Ink-Jet Texturing of Steel Rollers

Jonathan Muhl

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Declaration

I certify that the work presented in this thesis, except where explicitly credited to others, is of my own commission in both substance and composition.

Abstract

Over the past twenty years there has been increasing interest in the surface topography of sheet steel. Four processes are currently in commercial use to texture the rollers used in the production of the sheet and have been the subject of many studies. The aim of this project was to research the combination of ink jet printing technology and chemical and / or electro-chemical machining as an alternative process for the texturing of rollers for sheet steel production. This has resulted in a new process, termed *ink-jet texturing*.

Ink Jet Texturing is a subtractive process where a printer is used to deposit an ink mask on to the surface of the roller. This is followed by a chemical or electrochemical machining process which etches those areas not masked to a depth of several micro-metres. Chemical and electro-chemical processes have both been investigated. During the course of the study four pairs of rollers were treated for a commercial pilot rolling mill. Sheet samples produced by these rollers have been measured, analysed and discussed in the context of other technologies. The main challenges in the research concerned the accuracy and integrity of the ink mask, the reduction of waviness in the machined surfaces and the interaction between them.

The thesis starts with a technological proof of concept using a chemical machining process. The chemical process was subsequently replaced by an electro-chemical one for reasons of speed, cost and environmental responsibility. The majority of the research was concentrated on the electro-chemical texturing (ECT) which culminated with the production of samples of rolled sheet for analysis. Issues of texturing time, cost, wear and reliability have also been investigated to enable the commercial viability to be assessed. Apparatus has been designed, constructed and tested for both chemical and electro-chemical texturing and the results appraised in the context of existing processes.

Finally, the potential of the process to work in a commercial environment is examined. The ink jet method offers significant economic savings over competing technologies but real improvements would be required in the repeatability of both masking and machining operations.

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Notation

This section provides a brief description of the surface parameters and abbreviations used in this thesis.

Surface Parameters

R_a: The arithmetic average deviation of roughness from the centre line. Although not always the most suitable parameter this has been used extensively due to its universal acceptance in industry.

H: The distance between the top five percent of the data and the bottom ten, also known as the Swedish height parameter. This gives a good indicator of the depth of material removal during the texturing process and has been used extensively in this thesis.

Pc: Peak count, the number of local peaks which pass through a selectable band centred about the mean plane. For the assessment of Ink Jet Texturing this band was selected to be zero. This was justified by the bipolar nature of the surfaces where only true peaks would pass through the mean plane.

W_a: The arithmetic average deviation of waviness from the centre line. Usually used with a lower wavelength cut off of 0.8 mm. This is an important parameter as it is believed to have a strong influence on image clarity of painted sheets.

W_{ca}: As W_a above

rms: The root mean square average deviation from the centre line. More sensitive to extreme peaks and valleys than Ra is, but not so widely used.

PV: The distance between the highest peak and the lowest valley. Very sensitive to noise spikes or surface contamination and of little practical application.

R3z: The distance between the third highest peak and the third lowest valley. This and the following parameters are more robust than PV but still not so useful as H for evaluating the machining process.

Rz: The average distance between the five highest peaks and five lowest valleys, also known as the ten point height parameter.

Rtm: The average of highest peak to lowest valley in nine sampling areas.

Abbreviations

These are mainly related to machining and texturing processes.

CIJ: Continuous Ink Jet

DOD: Drop On Demand (ink jet)

EBT: Electron Beam Texturing

ECM: Electro-Chemical Machining

ECT: Electro-Chemical Texturing, also known as IJT

EDM: Electro-Discharge Machining

EDT: Electro-Discharge Texturing

IBT: Ion Beam Texturing

IJT: Ink Jet Texturing

MEK: Methyl Ethyl Ketone (solvent used in printing)

PCM: Photo-Chemical Machining

PCT: Photo-Chemical Texturing

1 Introduction

1.1 Introduction

This thesis chronicles the research and proof of concept of an entirely new process for the controlled texturing of steel rollers. It takes the work from the initial concept of using ink jet printers for surface masking, right through to the design, build and testing of a complete pre-prototype laboratory texturing system. The work has directly produced one refereed journal paper, two refereed conference papers and an international patent covering the concept [1,2,3,4]. In addition the surface metrology skills developed in the course of the work have resulted in a further two refereed conference papers in collaboration with other groups [5, 6] (these concern sheet metal formability in general but not the Ink Jet Texturing process). The main challenges in the research concerned the accuracy and integrity of the ink mask, the reduction of waviness in the machined surfaces and the interaction between them.

A broad range of skills were learned or developed in pursuit of this project. These have included a wide range of electronics, from high frequency power switching, through transducer instrumentation to design and programming of embedded micro-controllers. As well as the mechanical engineering there has also been an emphasis on materials engineering and in particular surface metrology. The latter has been essential to the understanding and characterisation of the work and has required the establishment of a metrology facility within the department, where none existed previously. Indeed it could be said that the financing of this was one of the more challenging aspects of the project.

Due to the scale of the project, and the commercial interest and involvement, the work has focussed on two main aims. These will be outlined in the subsections below.

Primary Aim

The primary aim of the research was to establish the technological feasibility of the process. This involved investigating whether ink could be a suitable masking material, the range of roughnesses and peak counts available and uniformity or waviness of the process.

There is a large but relevant gap between academic laboratory and industrial shop floor. This was also a significant part of the project.

Secondary Aim

As a proof of concept, a secondary aim had to be the investigation of the process in a commercial context. This involved the investigation of many areas such as the service life of the texture (roll wear), the reliability of the masking and the predicted cost of the process compared to its potential competitors.

Many of the problems encountered would provide sufficient material for theses in themselves if pursued to their conclusions. In these instances they have been followed only to a point where suitable solutions have been found to enable further progress to be made. The quest to develop the process has left many gaps and much potential for further study. Some of these have been too academic, others too commercial. In both cases they are left to those in the future who deem them worth while to continue. During the progress of the work a number of other applications of the process were briefly studied, including injection mould dies and tribological surfaces. Although interesting as case studies they contributed little or nothing to the advancement of the process. For this, and commercial considerations, they have been omitted from this thesis.

1.2 Background

Since the early 1980s there has been an increasing interest in the surface morphology of rolled steel sheet, primarily driven by the industries single largest market sector, the automobile manufacturer. This interest has been reflected in the quantity, and quality, of research in the subject and has ranged from characterisation and functional assessment through to the invention and development of methods for texture generation.

Texture can mean many things on many scales (even within the confines of strip rolling). Here it is a pattern of peaks and valleys, typically in the order of microns (thousandths of a millimetre) in height or depth, which is laid over the surface of the sheet in order to improve its functionality. The surface is where the sheet interfaces with its environment and as such much interest has stemmed from the influence of texture on the painted finish of the sheet as well as its formability in pressing. More recently the widespread introduction of coated sheet (primarily zinc) has led to other concerns, notable the effect of texture on adhesion.

The surface texture is rarely applied directly to the surface of the sheet, rather it is applied to rollers in the cold strip mill which then imprint it into the surface of the strip. The distinction is important, not least because the strip texture will be the mirror image of that applied to the roller. After hot rolling and annealing the strip enters the cold rolling mill where it is passed through a series of reducing rollers called the tandem mill. This would typically consist of four or five pairs of rollers and will reduce the strip to close to its required final thickness. Afterwards it is annealed to remove the work hardening before being passed through the final rolling stage, the temper or skin pass mill. This is used to set the mechanical properties of the steel and it is on these rollers that the final texture is applied. The reduction on the final stage is typically less than 1.5%. Annealing between the mills is traditionally done off line with the steel being coiled and then placed in ovens where it is heated in an inert atmosphere for a number of days. A texture is also applied to the strip at the final stand of the tandem mill. This helps to reduce sticking in the coil when annealing. More recently continuous annealing has been adopted in a number of mills. This brings its own requirements on the strip finish, particularly where combined with plating lines.

Throughout the thesis the rolling of a primary texture has been called tandem rolling while a secondary texture is referred to as temper.

1.3 Ink-jet texturing

The idea of texturing rollers for sheet steel production is far from new. The idea of applying a texture of controlled geometry is no more original, with lasers being developed for this purpose throughout the 1980's. Against that background the Ford Foundation funded work in the early 1990's to investigate the possibility of chemical or electro-chemical processes being used. Little had been done, other than some crude experiments to photo-chemically machine some flat sheets, when the project was inherited in mid 1992.

While trying to solve the problems of applying a high resolution photo mask to a large curved surface without any evidence of joining, the idea of printing directly onto the photo-resist occurred. If it could be done with an ink jet printer then the ink could even be used directly as the barrier to the etchant. It was from this reasoning that Ink Jet Texturing was born.

The early work led to a years funding extension by the Ford Foundation where a small rig for Ink Jet Texturing followed by chemical etching was developed. This was followed by two years funding from the EPSRC to investigate further, now using an electro-chemical process for the material removal. The latter work was supported by British Steel as an end user and Domino Printing Sciences Ltd as an ink jet manufacturer. The process was also included in an ECSC project with British Steel and Hoogovens to investigate the effects of surface texture on the adhesion of zinc coat. This project has provided the opportunity to texture larger rollers than would otherwise have been available. It also provided valuable funding for much of the latter part of this thesis.

1.4 Summary of chapters

Chapter one, this chapter, provides a general introduction to roller texturing, the origins of ink-jet texturing and the scope and structure of the thesis.

Chapter two contains the literature review. This is split into three topics, the main of which concerns roll texturing, existing methods and some other related areas such as functionality and characterisation. The secondary topics are the machining processes and ink jet printers. These are not intended to be definitive descriptions of their fields but concentrate instead on those areas where they impinge on this project.

Chapter three discusses experimental methods, in this instance surface metrology. This is the only unusual experimental technique employed in the investigation.

Chapter four covers the chemical texturing work. This is in effect from the beginning of the project up until the end of the Ford Foundation funding. The evolution of the process is charted and some experimental results presented.

Chapter five takes over with the electro-chemical stage of the project. This represents the bulk of the work and is therefore the largest section in the thesis. A full description of the system is developed at the start of the chapter. This represents the final form of the apparatus and it should be remembered that this was reached by a process of evolution and that not all sections were available for all experiments. Texturing experiments are described, starting with work on flat panels then progressing to a variety of sizes of roller. Data from rollers textured for the Hoogovens pilot mill enabled some investigation of roll wear as well as samples of rolled sheet. The last section of the chapter compares these with samples from other texturing processes, rolled on the same mill under the same conditions.

Chapter six discusses the results of the project in the context of the thesis. Does the process work in the laboratory and could it represent a possible commercial process? This latter part is assessed in the context of the existing processes and commercial practices. It finishes with a brief discussion of the relative merits of the chemical and electro-chemical methods.

Chapter seven presents the conclusions of the thesis. This is followed by a number of appendices, including three published papers of direct relevance to the work.

2 Literature Review

2.1 Introduction

Although this section represents the literature review of the field its structure is perhaps non-standard and in need of introduction. The main aim of this research was the proof, or disproof, of a new potential method for the texturing of steel rollers for sheet steel production. The existing roller texturing technologies are reviewed in section 2.2 with a view to establishing the main requirements of the new process and the benchmarks against which it will be assessed. This section represents a review of the field of operation of the project. Some consideration is also given to the functionality and metrology of the rolled sheet although a thorough study of these topics is the subject of many theses.

Although the process itself is new it represents the combination of a number of established technologies in previously unconnected applications. Sections 2.3 and 2.4 are not intended as critical reviews of these fields. Rather, their purpose is as a reference to the state of the art as it relates to the application of Ink Jet Texturing.

2.2 Roller Texturing

This section is intended to be a general comparison of all methods available for the texturing of rollers, either commercially or experimentally.

The processes will be characterised as non-deterministic, semi-deterministic and deterministic with a brief explanation of each. The processes will be described and then compared in terms of speed, cost and commercial availability. The main areas of texture influence will be identified, and related to the processes available.

2.2.1 Texturing Processes

The main methods of roll finishing identified are *mill roll (MR), shot blast (SBT), electro-discharge (EDT), laser (LT), electron beam (EBT), electro-chromium deposition (ECD), photo-chemical (PCT)* and *ion beam(IBT)*. These can be classified as follows.

Non-deterministic	Also known as random or stochastic, this includes the two most popular methods of roll finishing, shot blast and electro-discharge as well as the new process of electro-chromium deposition. It can also include electron beam and lasertex in psuedo-random operation. It should be emphasised that some methods are more repeatably random than others and that most still exhibit a small degree of directionality from the traverse of the texturing head.
Semi-deterministic	The classic example here is laser texturing, where the spacing of the craters is fixed around the circumference of the roller but with no registration lengthways from strip to strip. Mill finish could also be classed as semi-deterministic as the marks left from grinding are perpendicular to the length of the roller. This leads to anisotropy in the forming characteristics of the material.
Deterministic	This includes those processes which generate features with controlled spacing both normal and parallel to the direction of rolling. Electron beam texturing is currently the only commercially available process with photo-chemical texturing and ion beam texturing all at varying levels of development. Work has also been done on a deterministic EDT variant.

Hybrid	Some work has been done combining random and deterministic processes to attain the best properties of each. Primarily this has involved the combination of EBT and EDT but could of course use other processes.

The basic configuration of the different methods is fundamentally the same. It comprises of some form of machine to rotate the roller about its central axis, a machining head and a linear actuator to position the head along the length of the roller as shown in **Figure 1**. In some configurations (e.g. roll grinders) the head is stationary with the roller and rotary drive moved relative to it, but the basic principle is the same. The main exception to this is ECD which is done in large cylindrical plating tanks.

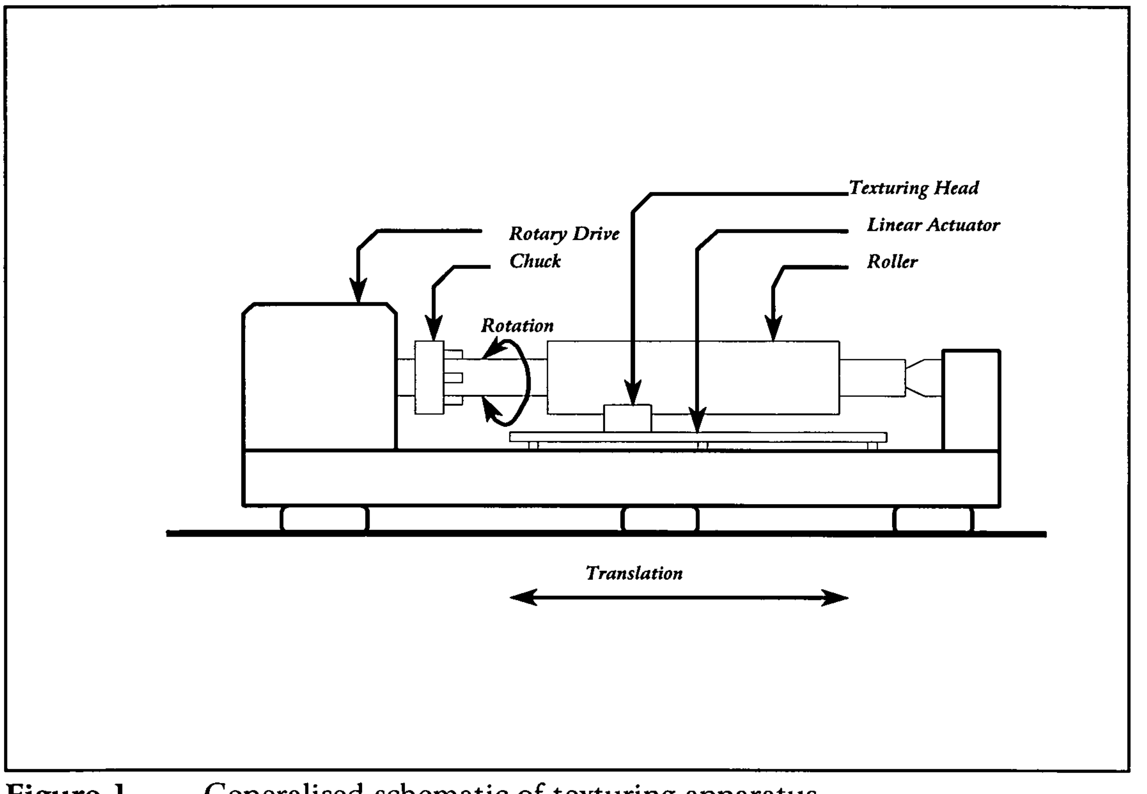


Figure 1 Generalised schematic of texturing apparatus

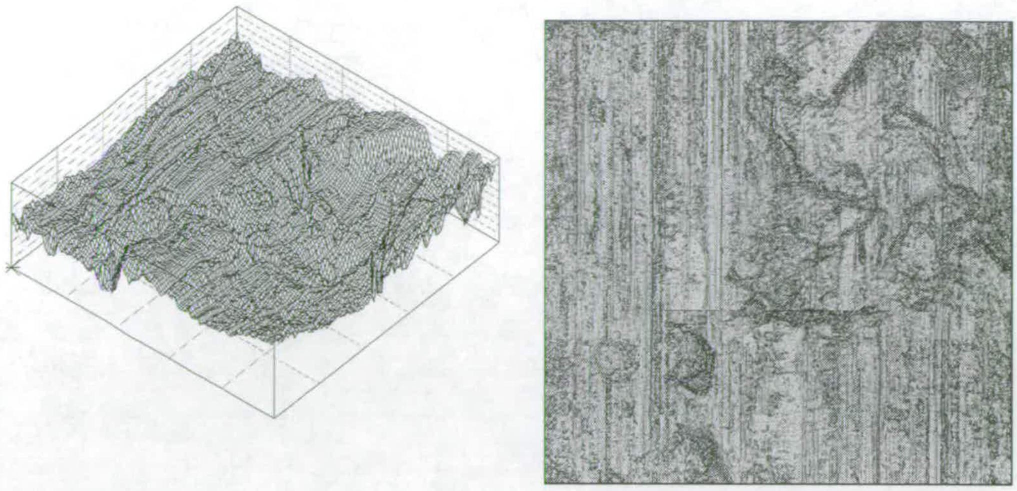
2.2.1.1 Mill Finish

This is the finish left from the grinding of the roller surface. It was the original finish on rolled sheet and although long surpassed for the majority of cold rolled steel production it is still common on hot rolled steel and on aluminium. While it is conventionally regarded as *untextured* this is not necessarily valid as the grinding marks lead to directionality of the coefficient of friction during press forming [7]. Grinding is also done as a precursor to the other texturing methods.

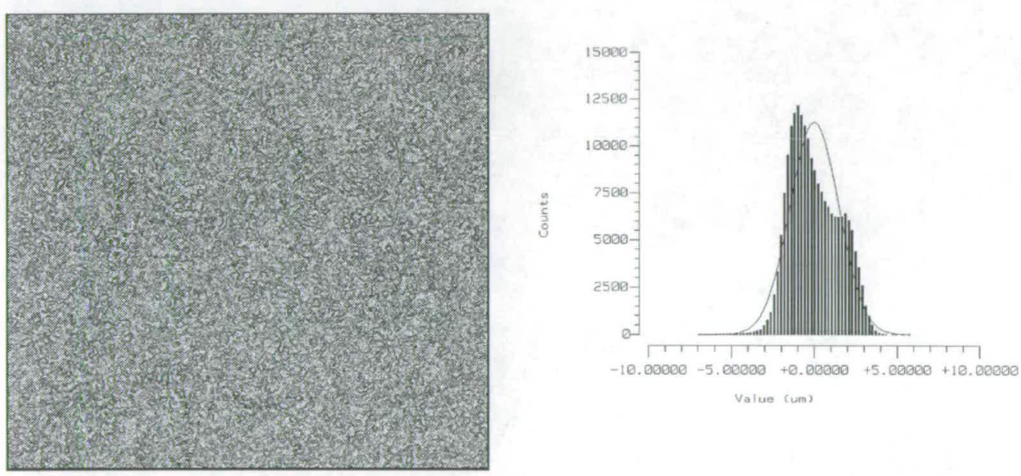
2.2.1.2 Shot Blast Texturing

Also referred to as shot peening or grit etching this involves firing hardened particles at the surface of the roller. This was the first process to replace grinding [8] and still has widespread use world wide. The texture produced is a random series of peaks and valleys with a roughly Gaussian distribution. The main limitations of the process are in poor control of roughness and a maximum work roll hardness set by the hardness of the shot media. It is also very difficult to control the waviness of the process, due largely to local variations in roll hardness causing variable deformation. Although the roll hardness is restricted further hardening at the surface occurs as a result of the plastic deformation during texturing. Equipment costs are relatively low - above £500,000 - but running costs are high. This is mainly due to the power consumption and the need to replace the shot at regular intervals. Another consideration is the life of the equipment as it is difficult to stop at least some degree of "self machining".

An example of a SBT rolled surface is shown in **Figure 2**. Note the almost Gaussian distribution of the histogram. The step on the high side of the height distribution is caused by the remains of the original ground surface of the hot rolled sheet. This shows that the transfer of the texture from roll to sheet has been less than 100%. This can also be seen in the high magnification view where the remains of the hot rolled texture are still visible to the left of the picture. The



Isometric and plan view of SBT sheet: 0.35 mm square



Plan view and height distribution of rolled SBT sheet: 8.0 mm square

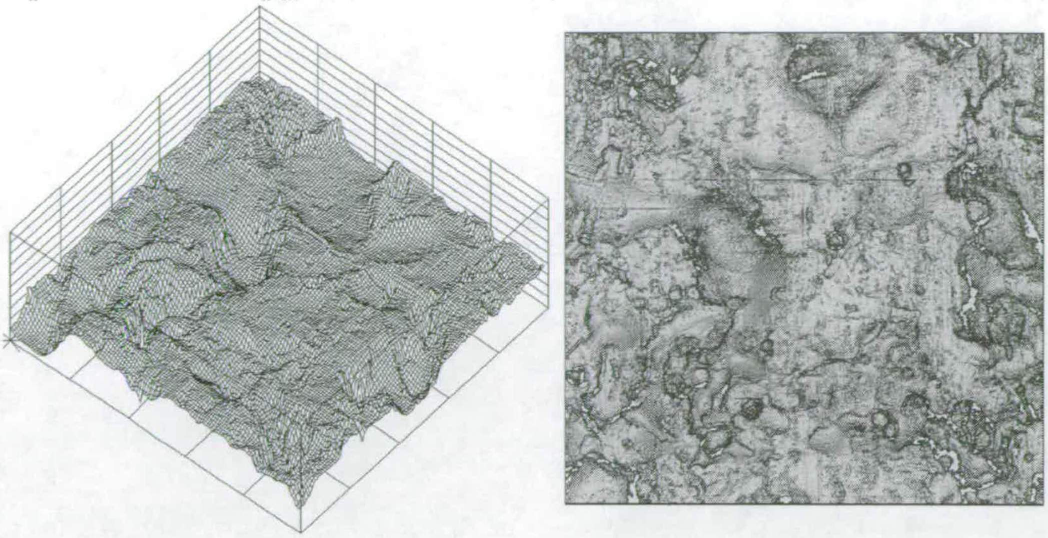
Figure 2 Shot blast textured sheet surface random nature of the process can be clearly seen in the large area plan view.

2.2.1.3 Electro-Discharge Texturing

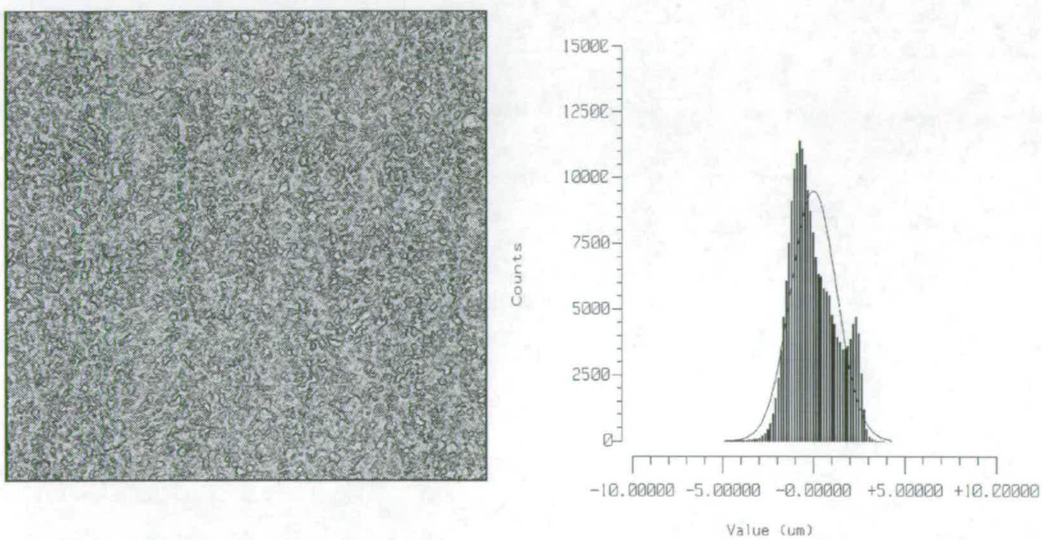
This is based on the process of electro-discharge machining, or spark erosion. The machining head consists of a series of one or more electrodes each mounted on servo actuators to maintain a constant gap between the electrode and the roller. A dielectric fluid such as paraffin is pumped through the gap to act as insulator, coolant and debris removal mechanism. A pulsed voltage is applied between tool and work leading to breakdown of the insulator and the onset of arcing. By controlling the frequency, magnitude and duration of the current the average roughness, R_a, and peak count, Pc, can be accurately controlled. The process is characterised by a random distribution of craters forming isolated peaks separated by interconnecting valleys. Some work has also been done using a modified EDT system to simulate laser texturing [9] but only at a laboratory level. Although a random process it can offer good control of roughness (R_a) and peak count (Pc) and is independent of roll hardness. Careful control of operating parameters can minimise waviness, or, in extreme cases, possibly even reduce it [10].

While the process is independent of roll hardness the energy of the removal process gives rise to modification of the surface layer with thermal hardening possible. A characteristic white layer has been reported. This was thought to be a carbide layer which would give vastly superior wear qualities [11] however this has since been questioned [12].

Equipment costs vary depending on the type of installation but a dedicated multi-electrode machine may cost in excess of £3 million. Texturing times will also depend on the type of installation but 10- 12 rolls per shift is possible. Theoretically EDT should be the fastest process as the number of electrodes can be increased to reduce the processing time.



Isometric and plan view of EDT sheet: 0.35 mm square



Plan view and height distribution of rolled EDT sheet: 8.0 mm square

Figure 3 Electro-discharge textured sheet surface

An example of EDT rolled sheet is shown in **Figure 3**. It is similar in structure to the SBT of **Figure 2** but a "more regular" random topography can be observed. Again the partial texture transfer can be seen.

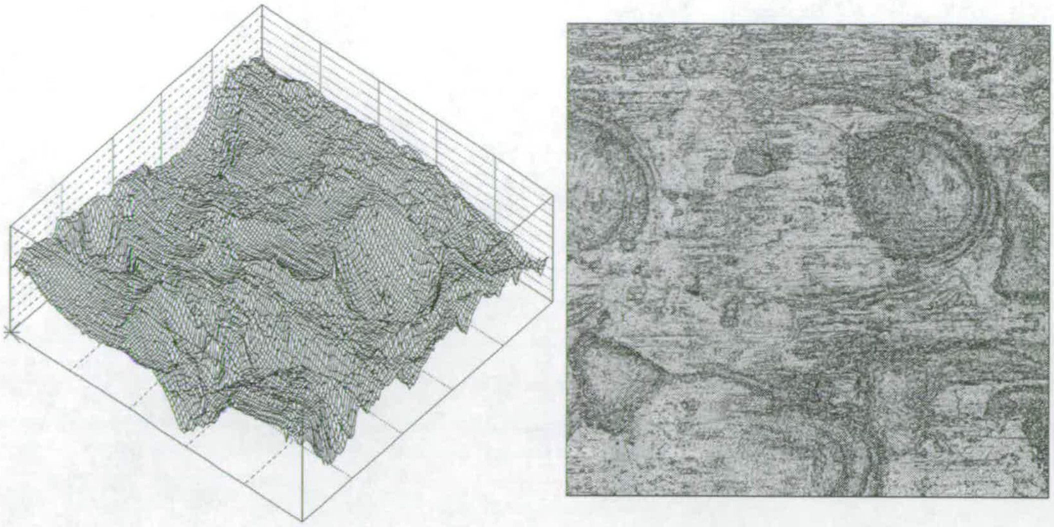
2.2.1.4 Laser Texturing

The process that was originally billed as the first deterministic texture, LaserTex uses a pulsed laser beam to machine microcavities into the surface of the roller. A helical pattern of craters is machined round the roller with the spacing set by the frequency of the chopper and the rotational speed of the roller. As the chopper is not synchronised to the rotation of the roll any variation in the speed of either will lead to a variation in the crater spacing. This means that the texture geometry is not fully controllable and as such the process is now classed as semi-deterministic. The craters are usually generated by CO_2 lasers in conjunction with a mechanical beam chopper [13], [14], although pulsed lasers have also been used [15]. The crater consists of a pit surrounded by a raised area of solidified melt pool.

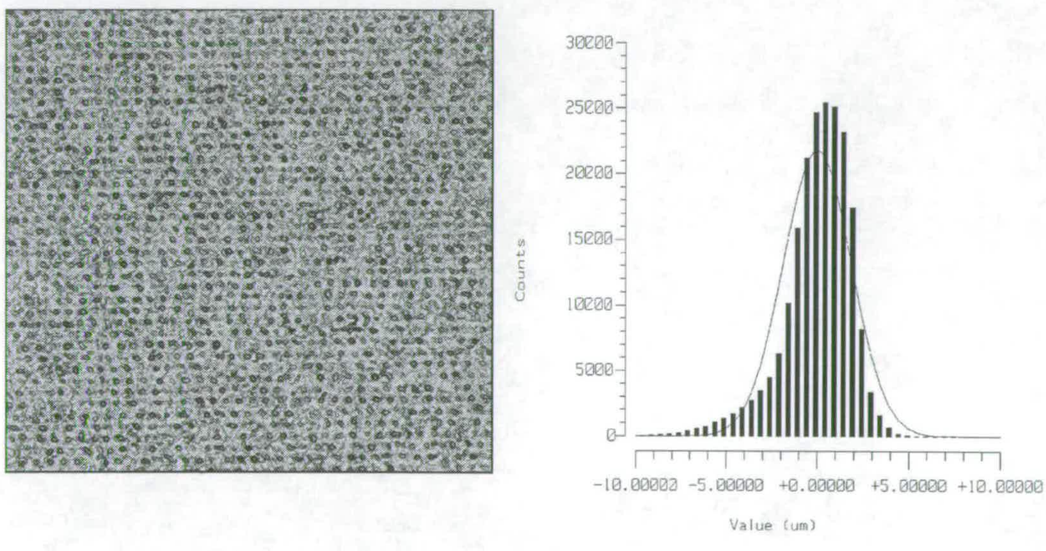
The process was claimed to have many advantages. Originally developed by CRM, Belgium, to give a higher quality deep drawing texture [16], [17], [18], other benefits were soon reported, notably improved paint appearance, increased roll life and reduced sticking during batch annealing [13]. As the waviness of the sheet was set by the grinding of the roll surface it tended to be less than that of a comparable stochastic process. This resulted in a steel that was reported to have extremely good painted performance, the so called "Laser Mirror" [19], [14],[13].

Although many companies invested in the technology, notably in Japan and in central Europe, its limitations have since become apparent. Anticipated improvements in processing time did not materialise with typically 2 - 4 rolls per 8 hour shift being achievable [20]; not helped by a relatively high scrap rate caused by poor quality control. In addition the long roll life predicted failed to materialise. This has been attributed to a number of factors, notably poor adhesion of the crater rim to the roll surface, and brittlement of the solidified melt caused by contamination from gasses when molten [21]. To form isolated craters on the sheet it is the crater rim that is rolled into the surface. With second generation lasertex this is carefully shaped by the gas flow into a single peak rather than a semi-toroid [22]. In addition to the brittleness mentioned above this also has the effect of reducing the bearing area and thus further increasing the wear rate.

Figure 4 and **Figure 5** show examples of both generation 1 and 2 Lasertex rolled sheet. The generation 2 craters can be seen to be significantly more uniform and more repeatably spaced although the lack of registration across the rolling direction can be clearly seen in both. The histograms show a significantly skewed distribution indicating a mainly plateaued surface although the spread of the lower values indicates a variation in the depth of the craters.

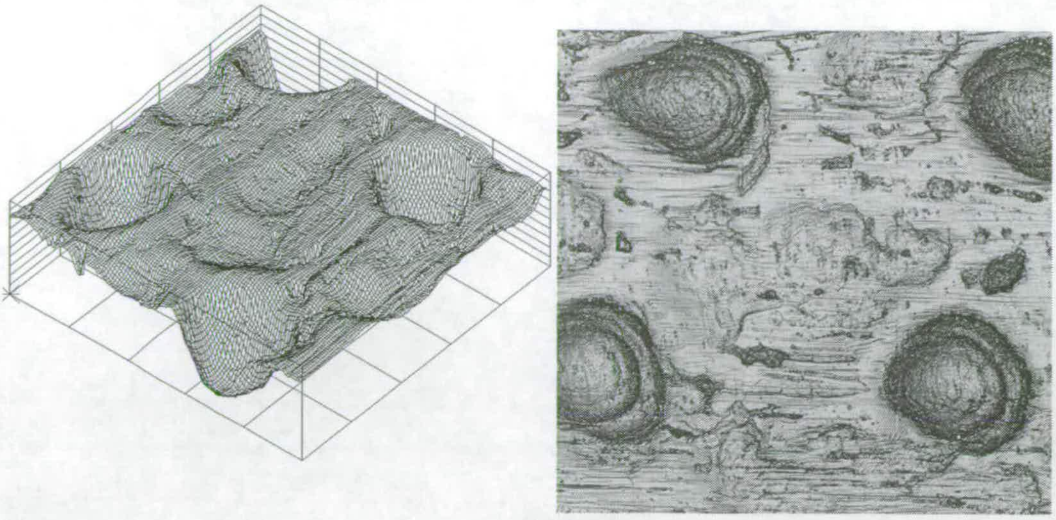


Isometric and plan view of LT1 sheet: 0.35 mm square

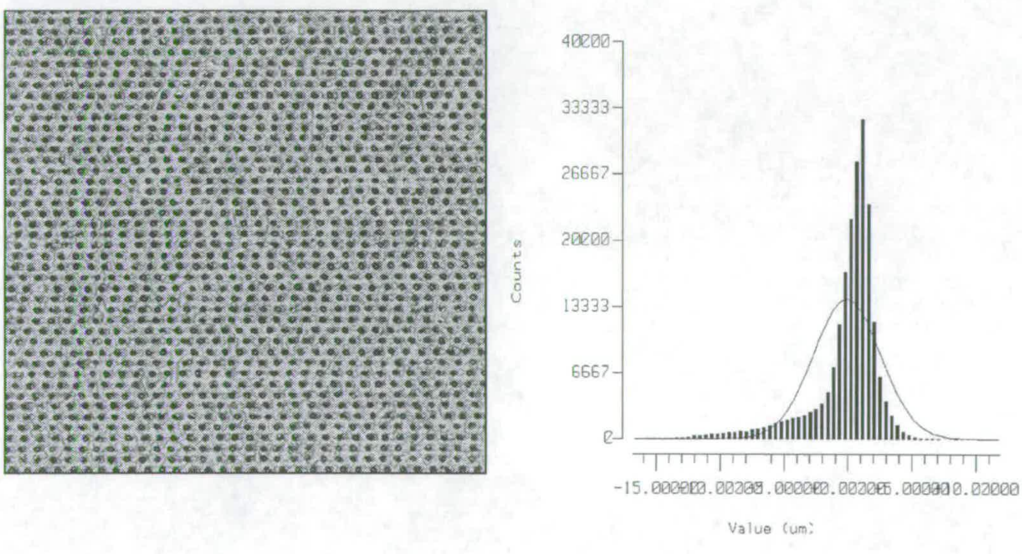


Plan view and height distribution of rolled LT1 sheet: 8.0 mm square

Figure 4 Generation 1 laser textured sheet surface



Isometric and plan view of LT2 sheet: 0.35 mm square



Plan view and height distribution of rolled LT2 sheet: 8.0 mm square

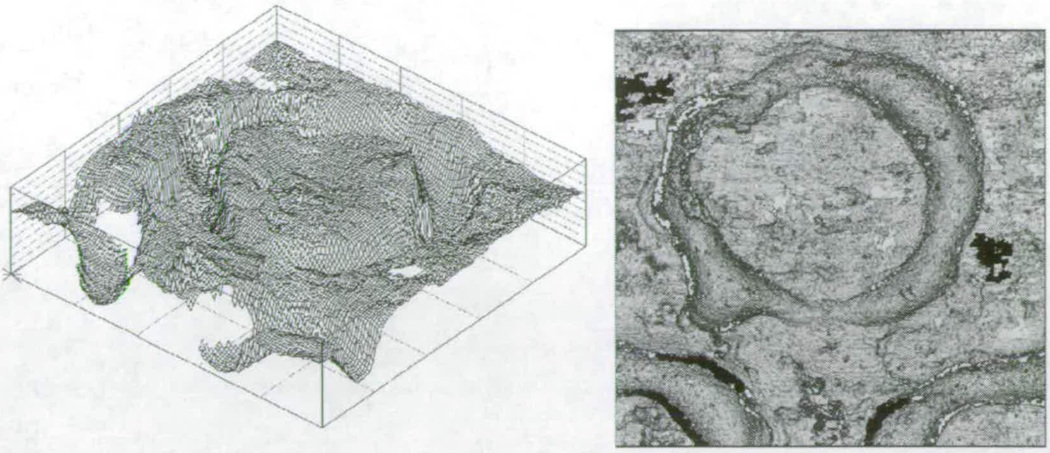
Figure 5 Generation 2 laser textured sheet surface

The combination of low productivity, high scrap rate and low roll life meant that Lasertex sheet was significantly more expensive to produce than by more conventional methods. This has lead to a decline in its use worldwide. Although it is now largely superseded by electron beam texturing, as the first commercial non-random process its significance should not be underestimated.

2.2.1.5 Electron Beam Texturing

The use of an electron beam to machine rollers was pioneered by Dr Ing. Rudolf Hell GmbH for the engraving of rotogravure printing rollers. The first laboratory tests of the process were conducted in 1961 but it was over twenty years before technology was available to control the process to within the strict tolerances demanded by the printing industry. A prototype production machine was built for demonstration in 1985. Sidmar, the Belgian steel manufacturer, saw the potential of the process to overcome many of the limitations of LT and initiated temper mill trials in 1986. These trials, and those of other steel producers were successful and led to the first order for a commercial EBT machine in 1991 [23].

With this process the laser is replaced by an electron beam; this has many advantages [24]. The electron beam is focused at the desired point on the surface and maintained there for a period necessary to create the required crater depth. Because rotation of the roller would cause an elongated pit the beam is electro-magnetically deflected to maintain the focus at the required position. After the required pulse length the beam is defocussed and directed to the location of the next crater. The process operates in a vacuum, this means that there is no contamination of the melt pool. The rim is formed by molten metal flowing from the crater under the pressure of the plasma, so no gas injection is required. The location of the crater is controlled by electromagnetic deflection of the electron beam - this means that textures are flexible in geometry and repeatable in operation. Finally the metallurgical properties of the rim can be controlled by varying the energy in the electron beam during the formation of the crater.



Isometric and plan view of rolled EBT crater: 0.35 mm square

Figure 6 Isolated crater on electron beam textured sheet

Although the beam creates a crater in the surface of the roller it is the raised rim of the `melt pool which is rolled into the surface of the sheet. An example of a crater is shown in **Figure 6**. This leaves a pattern of toroidal craters on the surface of the sheet. These are typically deterministic but by connecting the beam controls to random signal generators a stochastic pattern can be produced [23]. As with Lasertex the process does not impart any further waviness to the surface of the ground work roll. Because of the relatively low reductions during temper rolling it was not found possible to remove waviness generated on the sheet during tandem rolling, resulting in a subsequent loss of image clarity on the painted product. This was countered by utilising EBT at both temper and tandem mills, the resulting texture having the trade name SIBETEX (SIdmar BEam TEXtured Product) [24]. The overlapping of two deterministic patterns creates another problem, Moire interference patterns. By developing a mathematical model to predict Moire lines Sidmar claim to predict and counter this effect [20].

The process is fast with 8-10 rolls per shift being claimed. This is close to the rates obtained by EDT although it would appear difficult to add extra beams to the system to improve on this. Capital costs are high, 30 to 50% more than a top dedicated EDT system, although running costs are claimed to be the lowest of any process.

The EBT process is claimed to offer improved press performance, paint performance, galvaneal adhesion, roll life and processing time while giving a choice of random or deterministic textures. At time of writing a number of machines have been sold to companies world wide: the results of these independent programs are awaited with interest.

2.2.1.6 Electro-chromium Deposition

This is a very new process which has been jointly developed by the Fraunhofer IPA, Winterthurer WMV AG and Preussag Steel AG. It is also known by the trade names *PreTex* and *Topochrome*. Very little information is available with no technical papers published in English to date. The following information has been gleaned from the internet.

The process is based on hard chromium electro-deposition and gives a random surface texture which is spheroidal in nature. It is claimed to be repeatable to within 0.1 μm, although it is not clear whether this is an average or peak value. It is claimed to be capable of very high peak counts and low roughnesses giving good painted appearance. An installation is in operation at Preussag Steel which can process rollers of 600 mm diameter and 4.0 m total length. Grinding is not required and the chromium plating gives good wear characteristics and a long service lives. As a result a reduction in costs for sheet metal production of 10 - 15% has been claimed.

It should be remembered that the only source of this information has been the Fraunhofer web site which may be assumed to be not entirely objective. It is however included here for completeness.

2.2.1.7 Photo-chemical Texturing

This is derived from the process of photo-chemical machining. It is not known to be in commercial operation although a number of patents have been registered in Japan. These have involved coating the roll surface with a layer of acid resistant material, selectively removing sections and chemically etching the exposed areas. Traditionally the coating is a UV sensitive resin with the desired pattern projected onto the surface through a mask. The coating is then developed to expose the areas to be machined. With subsequent operations of etching resist stripping and post-processing there can be more than ten separate stages involved. This involves many man hours of operation in a dark-room environment and is not well suited to automation. As a result processing times have been too long to be of practical value.

Two processes have been described to counter these problems. One [25] sprays a UV curable resin onto the surface of the roll and exposes it to form a continuous hard coating. This is then selectively removed by a Q-switched YAG laser (5-100 W) to leave the surface ready for etching. The other [26] coats the roll with a homogeneous layer of visible light curing resin then selectively exposes it with a pulsed visible wavelength laser. In this instance the beam is pulsed by a mechanical chopper arrangement similar to that used in laser texturing.

In spite of these developments it is not known whether the processes described are currently being used in a production environment. It is interesting to note that both laser and Ink Jet Texturing have evolved out of early work on photo-chemical texturing.

2.2.1.8 Ion Beam Texturing

This is a very experimental process being researched at the RIKEN research institute in Japan. It uses ion beam milling to create a deterministic texture on the surface. The process is limited in that it can only create isolated valleys on the machined tool. Therefore to create isolated valleys on the sheet requires an intermediate forging technique to create isolated peaks on the roll.

The texture is created using a suspended mask method [27] where a metallic foil mask containing the desired pattern is suspended a small fixed distance above the surface to be machined. The spacing between mask and work has been varied between 2 - 10 μm to vary the amount of undercutting of the process. This also has the effect of varying the wall angle of the machined cavity. Crater depths of 55 μm have been achieved with a wall angle of 72^0 for an etching time of 24 hours [28].

Experiments have been conducted to transfer this texture to a roller using rotary coining or pressing. An obvious limitation here is that the material to be formed must be significantly softer than the etched WC-CO tool. A 20mm diameter roller of precipitation hardened aluminium with a tool steel core was pressed against the etched tool to form a deterministic pattern of isolated peaks. These were subsequently rolled into aluminium sheet to give strip textured with isolated lubricant pockets. No attempts appear to have been made at this stage to control the overlap of the pattern on the roller [29]. The process has also been applied directly to a small roller (20mm diameter, 37mm barrel length). This gives isolated valleys on the roll and peaks on the rolled sheet [30].

It is obvious that technology will need to progress significantly before Ion Beam Texturing can be seriously considered as a usable option. It should not be dismissed out of hand however as it may offer significant advantages over other processes as high peak densities and very controlled wall angles appear to be easily obtainable. The requirement for soft roll surfaces is major problem but already it is common commercial practice to apply hard chromium coatings to work rolls to increase their wear resistance [31] - future coatings may develop to solve these problems for IBT.

2.2.2 Rolling Considerations

Whatever texture is applied to the surface of the work roll, it is of very little use without some facility to transfer it to the end product, the sheet. This is done through a series of rolling mills. In a cold rolling mill the strip from the hot rolling mill will first pass through the *tandem mill*. This is where the dimensional reduction of the sheet occurs and will typically consist of a series of two to five mills or stands. As the sheet is reduced, so is the grain size, resulting in considerable material hardening by the end of tandem rolling. The steel then needs to be annealed to allow the sheet to recrystallise. This is traditionally done by batch annealing where the coiled sheet is left in a furnace at 700^{0}C for up to 10 days [32]. During this time contact welding can occur leading to surface defects, *sticker marks*, after uncoiling. To minimise this effect a texture is often applied to the last stand on to the tandem mill to reduce the contact area of the sheet. This is know as the tandem texture. An increasing number of plants are now replacing batch annealing with continuous annealing lines. Here the sheet is uncoiled and fed through a furnace at 900^{0}C, the whole process taking approximately 10 minutes. The annealed strip is finally passed through a temper mill to set its final material properties and it is here that the final surface texture is imparted on the sheet. Reductions at this stage are very low, typically 0.1 - 1.0%, and it is often referred to as skin passing.

We will now consider the nature of the texture required at the tandem and temper stages and also issues concerned with imparting that texture on the sheet.

Texture Transfer

This is the ratio of the roughness on the sheet to that on the roll, and is typically expressed as a percentage of the original roll roughness. It is dependent on a number of factors, most noticeably sheet material type, rolling load, texture type and presence or absence of lubricant. The latter factor can be expected to have a significant effect as fluid trapped in cavities will act as hydraulic reservoirs, resisting the deformation of the roll into the sheet. Although most steel producers will have investigated these factors, very little has been published. Work has been done to simulate tandem and temper transfer for EDT rolls on a pilot mill [33]. This shows 51% R_a transfer for tandem rolling with 3% reduction and 38% transfer for 1% temper reduction. It should be noted that these were for dry rolling, with lubrication these value would reduce accordingly. It was also observed that peak count transfer was significantly higher than R_a transfer although is not particularly surprising considering the nature of deformation.

A trial comparing the performance of SBT, EDT, LT and EBT for temper rolling of hot dipped galvanised sheet has also been conducted [34]. Only one set of work rolls was used for this trial with the different textures situated in axially adjacent bands. This ensures consistency of rolling parameters and roll material properties, but its possible influence on texture transfer is not discussed. The deterministic textures consist of features proud of the roll surface while the stochastic textures are below it. It seems likely that this will alter the transfer capability of the EDT and SBT strips at least in the vicinity of the outer edges. No information is given as to the width of the strips or the sequence of the textures so it is difficult to estimate any effects that may occur. Texture transfer is rated on a scale of 0 - 1 based on a technique called *substitute profile method*. This attempts to characterise the surface in terms of its fundamental geometry from a sufficiently high number of 2D stylus profiles. The method of calculating the transfer is not defined and it does not appear to correspond to the more conventional ratio of roughness on strip to roughness on roll but does show an interesting comparison between dry and wet temper rolling. Plotting degree of transfer against reduction SBT and EDT both show the same characteristic curve, albeit with reduced transfer. EBT and LT both show over 30% less transfer with wet lubricant due to the entrapment of lubricant within the closed crater formed by the melt ring.

Transfer for EDT rolls at approximately 0.6% temper reduction may typically be expected in the region of 35 - 40% [35], compared to the 75% predicted by [34].

For tandem rolling a sheet with a series of isolated peaks may be preferred. These would act as stand offs between adjacent layers of a coil and reduce the contact area and thus the tendency for sticker marks to appear

Roll Wear

During operation a work roll will be subjected to a constant process of erosion. Its ability to resist this wear will, at least in part, determine the economic viability of the texturing process. Typically rolls will be re-textured when they are no longer capable of imparting the desired roughness into the sheet, although they may also be changed prematurely due to the appearance of flaws on the roll surface or to changes in scheduling.

Shot blasting causes plastic deformation of the roll surface. This leads to work hardening of the surface and therefore improved wear resistance, although this is offset by the need to use softer rolls than for other processes. EDT, LT, and EBT all work on localised melting of the surface. EDT is reported to posses a white high carbon layer at the surface caused by diffusion of the carbon from the dielectric into the molten steel before being rapidly quenched by the surrounding fluid. Early work suggested large improvements in roll life could be achieved over SBT, in some cases up to five times better [11] although others claimed a more cautious 25% improvement [36]. Similar claims were also made for LT with a 50-100% increase in tonnage compared to SBT [13]. This was attributed to an increase in hardness of the roll surface but later reports claimed the process caused a brittle, badly adhered surface with subsequently poor roll life [21], [20]. EBT is claimed to have greatly improved wear characteristics due to use of the electron beam to control the heating and cooling of the melt zone and also the operation within a vacuum preventing contamination. It is even claimed that the "quasi stable" EBT texture may make chromium plating obsolete [24].

Recent years have seen the widespread introduction of chrome plating of work rolls. This is done after texturing to improve the wear resistance of the surface, attributable to increased hardness and corrosion resistance and reduced friction coefficient [31]. This has had the effect of increasing roll life irrespective of the texturing system used. A study using SBT and EDT on identical chrome plated rolls [37] comparing the decrease in roughness, R_a, and waviness, Wca, during rolling, concluded that shot blast could provide the greater wear resistance under certain conditions. Another study of SBT and EDT chrome plated rolls [38] found that, although EDT roughness decreased more quickly, the peak count was maintained considerably longer.

A comparative study of EBT, EDT, SBT and LT [34] concludes that "the wear characteristics of the work rolls is influenced by the thermal treatment during the texturing process". This is undoubtably true, but it may be that the wear is more influenced by the surface topography.

It is interesting to observe that each new texturing process is claimed to have significantly improved wear characteristics over its predecessors. A recent study on the functionality of different texturing systems [21] ranked them in terms of wear behaviour, from best to worst, EBT, SBT, EDT, and finally LT. It may also be that future developments in hard coatings, such as PVD, will make roll wear negligible and re-texturing will scheduled on the basis of changing production requirements. This may make more esoteric processes such as ion beam texturing viable options as the relative cost and time of texturing can be offset against considerably greater tonnage of steel.

2.2.3 Metrology of Sheet Metal

This is not intended to be a full discourse on surface metrology, rather a discussion of its relevance to the characterisation and functionality of sheet metal.

A surface can be considered as comprising of a mixture of high, medium and low frequency components. The following terms and wavelengths are in common usage and will be retained here. *Roughness* consists of high frequency components with a wavelength $\lambda_h \leq 0.8$ mm. Medium frequency or *waviness* components have wavelengths $0.8 \leq \lambda_w \leq 8.0$ mm. Wavelengths longer than 8.0 mm are called form. Since the 1960s equipment has been available to characterise engineering surfaces either visually or in terms of numerical parameters. This is done traditionally using stylus profilometers to measure a single trace across the surface. The parameters usually used in rolling are average roughness, R_a, and peak count, Pc. These are frequently used to characterise the roll and sheet surface to determine whether the product is within specification.

Two dimensional analysis, based on the average of multiple measurements, may give a valid representation of a random surface such as SBT or EDT although R_a and Pc alone may not be sufficient. They will not for example give a measure of the distribution of the material, for which the bearing area or Abbot-Firestone curve may be used. Similarly it is difficult to quantify functionality, for example lubricant retention during forming. Studies of EDT have questioned the ability of 2D metrology to describe the complexity of this random process, especially where surfaces are predominately plateau. Skewness, kurtosis, high spot count and summit curvature are amongst the parameters recommended by Aspinwall et al [12] . Although these works are concerned with the *roughness* of the surface there is increasing interest in *waviness* due to its effects on paintability of sheet. There is no industry standard procedure for the assessment of waviness but a study by Bastawro et al [39] recommends cut offs of 0.8 and 8.0mm and the use of digital filtering to minimise the influence of the form and roughness of the surface. Although this work is concerned with EDT and SBT the authors claim also to have achieved repeatable results with deterministic textures.

The advent of deterministic textures, in particular Lasertex, led to further questioning of the validity of the common 2D classifications. An early characterisation of laser textured sheet [40] found that R_a measurements, taken from an array of 10 profiles at 0.2mm intervals in the rolling direction varied by over 50% , presumably depending on whether the trace ran through the craters or the flatter plateau between them. By measuring at 45^0 to the rolling direction the variation was reduced to 13%, similar to that recorded with the shot blast sample. This is to be expected as it is unlikely that a trace in this orientation will either hit or miss all craters in a single profile. It is interesting to note that the deviation in R_a across the rolling direction is only 17%. As the craters are shown to be placed in a rectangular grid structure the deviation across the rolling direction would be expected to be of the same magnitude to the deviation with rolling. This suggests that there may have been a phase difference between adjacent rows of craters on the sample measured. By comparing the SBT and LT surfaces using conventional 2D analysis only skew and kurtosis showed any significant differences between the two surfaces. Although 3D analysis was used there was no attempt to extract statistical parameters from it, presumably due to the limitations of the computing available at the time. The work concluded that there were still problems in characterising the LT surface adequately for quality control.

The dramatic power increases and cost reductions of computing and metrology hardware over the last decade have led to an increase in the use of 3D analysis although it is only with the introduction of EBT that it ha been routinely used for production quality control. The first significant attempts to classify deterministic textures were again with lasertex. The texture description was broken down into features, craters, and flat area, the ground roll surface. By defining the dimensions of crater and rim and the pitch between features the surface can be described in 3D [41] although others were developing techniques of extracting this information from 2D roll measurements [22]. The semi-deterministic nature of LT will always complicate its classification but the repeatability of EBT, both in feature spacing and size has lead to claims of greatly simplified roll texture description [24]. Only four parameters are required to characterise the surface of the roll, pattern type and crater depth, diameter and spacing. It is unclear as to whether this method can be applied successfully to the surface of the sheet but variations in transfer rates caused by lubrication, roll load, substrate properties and initial sheet texture may make this difficult.

More generally, the recent evolution of 3D metrology has led to an absence of standardised 3D parameters, with most used being individual interpretations of existing 2D ones. To counter this an EC funded study has devised a set of 14 3D parameters which are proposed to form the basis of a new ISO standard [42]. These parameters have been evaluated in the context of EBT rolled sheet [43]. This concluded that, while 3D assessment was necessary, the proposed parameters could not fully describe the functionality of the texture, particularly in tribological behaviour. Two further parameters were proposed: relative oil recess volume, Vr, and wet ability ratio, Wr. Vr represents the thickness of an oil film derived from the volume of cavity retained lubricant divided by the area of the sheet. Wr is the ratio between the plan areas of the cavities (wet areas) and the plateau (dry area). These were found to relate well to the observed differences in tribological behaviour between different EBT structures. While these may not be applicable for random surfaces they may prove effective with other deterministic textures such as ECT, PCT and possibly LT.

Although parameters now exist to classify random and deterministic processes a major challenge still exists in trying to find methods which will enable accurate comparisons for both. Comparative studies of texturing types have tended to stay with conventional statistical parameters such as R_a [21] even though it has little significance on regular surfaces where one surface could have double the peak to valley height of another, while maintaining an identical R_a and Pc. Any breakthrough in this area can only come from assessing the functionality of the surface and then relating it back to its geometric properties. Until then the position of R_a is unlikely to be seriously challenged.

Similarly it may be some time before portable 3D measurement machines become cheap fast and rugged enough to enable their routine use in a production environment. Whatever its limitations, 2D metrology will dominate in roll shops until then.

2.2.4 Functional Properties of Sheet Steel

The ability to measure surfaces is only of any real importance if these measurements can be related to the functional properties of the part. For sheet steel this means establishing some relationships between the surface properties and the paintability and formability of the strip.

2.2.4.1 Paint Performance

It would be tempting to declare that there was an established relationship between surface roughness and the overall appearance of the painted sheet. Unfortunately this is not possible as there are a large number of interacting variables such as roughness, zinc coating, phosphate, primer, base coat, clear coat as well as random environmental influences such as contamination and un-even spraying. Even the orientation of the panels can have an effect [44]. Many different studies have been reported looking at the effects of surface roughness but direct comparison is made difficult through the use of different paint systems, a fact acknowledged by most authors. It is however possible to make some general observations which may be relevant when considering any new texturing process.

The three parameters most commonly studied in this context are roughness, R_a, waviness, Wa, and peak count, Pc. Waviness is generally accepted to have the greatest effect on paint appearance and is strongly implicated in the formation of orange peel, although it can be difficult to separate this from waviness induced by the paint process itself. One recent study [45] found waviness in the band 0.8mm to 3.0 mm had the most effect on orange peel (features below 0.5 mm were strongly attenuated by the paint film) although other bands have been suggested .

A high peak count, low roughness, surface has generally been considered best for high image clarity with one study [46] suggesting that low R_a (0.75 μm) and high Pc (7.4 ppmm) gave the best results for a 50 μm paint film. This theory has not been supported by studies investigating the EBT process which have generated acceptable finishes with high roughness and low peak count sheet. This is likely to be because conventional stochastic processes have a strong correlation between peak count roughness and waviness [35]. The specification of high Pc and low R_a implicitly meant a low waviness. With deterministic surfaces such as EBT this correlation is not as strong resulting in little difference in image clarity.

2.2.4.2 Press performance

This is a measure of how well the steel can be transformed from an area of rolled strip into a finished component by press forming. Advances in press technology have reduced the influence of surface texture for many applications but it is still a major factor in deep drawing applications. There the texture will influence the uniformity of the frictional behaviour and reduce the tendency for galling.

Many studies have been made on coated and uncoated strip using a wide variety of lubricants and test methods. Again there can be some problems in comparing data from different researches but this is not so much of a problem as with paint performance. Most studies report the most favourable results to be obtained by surfaces containing regularly spaced isolated lubricant pockets as are generated by LT and EBT. These act as lubricant supply reservoirs as well as providing hydrostatic load carrying. They also can trap small particles of contamination which might otherwise lead to scoring or seizure. Stochastic surfaces tend to have interconnected lubricant pockets which limits the build up of hydrostatic pressure by providing lubricant flow paths.

2.2.5 Texturing Review Summary

From the review of literature a number of key areas were identified. The waviness of the roller appears to be very important, particularly with regard to the final painted sheet. It is seen as one of the main advantages of the deterministic processes, especially EBT. Minimising the waviness on the roller was therefore identified as one of the core challenges of the project. Peak count was also seen to be important. An initial target of 3.5 peaks per mm was chosen. Although based on the available resolution of Lasertex at the start of the project, it also represented feature wavelengths comfortably shorter than those associated with paint defects. The average roughness of the roller was seen to be of less use due to the difficulties of comparison between different texturing processes. Notwithstanding, it is still the main method of assessment within industry so a target range of 1 - 10 μm was chosen.

Issues identified as core to the commercial viability of the process included the roller wear rate, texturing time and capital cost. All these combine to determine the economic feasibility of the process.

2.3 Material Removal

This section will present a general overview of chemical and electrochemical machining processes with consideration of their application to the texturing process

Ink Jet Texturing is fundamentally a combination of a masking process and a material removal technique. Through mask machining is well established, particularly in the production of electronic components and thin sheet parts. The masks are typically based on the exposure of a light sensitive surface film (photo-chemical machining) which is subsequently developed to reveal the surfaces to be removed. One variation on this is in the aerospace industry where a sheet rubber mask is used with a chemical etchant for bulk removal of structural components (chemical milling). This can create large weight saving cavities without the creation of stress raisers associated with conventional machining processes.

This section is not intended to be a comprehensive review of all material removal processes, rather it is intended to provide the necessary information on the two main processes of through-mask machining, chemical and electro-chemical etching. Although other methods are possible for through mask machining such as ion beam (see above) they have not been considered here.

2.3.1 Chemical Machining

Introduction

Wet chemical etching has been used for many centuries (one particularly early case was the use of a vinegar based etchant to decorate iron plate armour in the 15^{th} century). A variety of metals and etchants have been used but all work on the same basic principle. Exposed metal is oxidised by the solution which then removes the resulting dissolved solids (reaction products). At high flows the removal rate will be governed by the reactivity of the components, this is referred to as *activation controlled*. At low flow rates it is controlled by the rate at which the etchant at the surface can be refreshed, the *mass transfer rate*.

Wet etching of copper and steel is commercially well established with many applications including printed circuit boards, integrated circuit lead frames, ink jet nozzles, shadow-masks, machine tool scales and jewellery. The result of this is that there is little published research available concerning solutions and removal rate. Most information comes from one book [47] and from manufacturers publications.

Etchants

Although some metals require the use of concentrated acids as the oxidising agent, steel is well machined in ferric chloride solution. This is a much more user-friendly solution which gives high removal rates while still having relatively low toxicity. It will also etch any metal less reactive than titanium. The advantage of this is its ability to machine all grades of steel, including stainless. The disadvantage is that it restricts the choice of components available to construct the etching tanks.

The reaction mechanism for etching ferrous materials in $FeCl_3$ is a straightforward redox (reduction - oxidisation) process. Ferric chloride is reduced to ferrous chloride, with Fe^{3+} acting as the oxidant such that:

$$2FeCl_3 + Fe = 3FeCl_2$$

Although acids are rarely, if ever, used to etch steels they are sometimes added to the $FeCl_3$ solution. Perhaps most common is the controlled addition of HCl to ferric chloride when it is being used in high concentrations for the machining of some stainless steels. This is to inhibit the precipitation of iron hydroxide onto surface of the metal which would otherwise affect the etch rate. In practice the low levels of elements such as chromium in the tools steels used in this project mean that plain $FeCl_3$ is quite adequate.

Machining rates

The machining rates depend on both reaction and mass transport kinetics depending on the application. If the steel is immersed in the etchant then the removal rate is usually governed by mass transport and is typically in the range of 2 - 10 μm / min. If a spray is used then reaction kinetics will tend to dominate, etch rates of 10 - 50 μm / minute are typically achieved [48].

The reaction kinetics are sensitive to temperature and etchant concentration. The latter is usually expressed in terms of the Baumé index (°Bé). This allows concentrations to be expressed in whole numbers or, at most, to one decimal place. It is related to specific gravity (s.g.) as follows.

$$°Bé = 145\ (s.g. - 1)\ /\ s.g.$$

As concentration is decreased the reaction rate increases but the surface finish deteriorates. Below 40 °Bé the surface finish is very poor and the solution is no longer used[48].

Etching Geometries

Wet etching is often considered to be a two dimensional process, possibly because it is usually used to etch components out of sheet material. In practice this is not really true: the etchant acts isotropically, machining both the edges and bases of features uniformly. This would lead to a maximum achievable wall angle of 45 °. As mentioned above, reaction rates are also influenced by mass transfer and, by careful flow design, this can be used to provide some geometrical control. This is often employed to generate high aspect ratio features but can also give problems in the production of '3-dimensional' components [49]. It is also possible that this could be used to get some measure of control on the feature wall angle of textured rollers.

Environmental considerations

In use the etchant is being continually depleted until it is no longer suitable for its application. When this happens it needs to be recycled. Techniques exist for the recovery of copper and nickel and for the replenishment of the spent solution. Although this can be expensive compared to the original price of the etchant the disposal costs are such that it can be cost effective for large volume users.

When used for etching ferrous materials, depleted $FeCl_3$ can be regenerated by treating it with chlorine gas (provided that high percentages of alloying materials are not present). The reaction is:

$$3FeCl_2 + 1\tfrac{1}{2}Cl_2 \Rightarrow 3FeCl_3$$

This has the added advantage that 50% extra $FeCl_3$ is generated from the dissolved iron. This can lower costs by a factor of ten or more [50]

2.3.2 Electro-Chemical Machining

Introduction

Electro-chemical machining (ECM) is a dissolution process where the work piece represents the anode in an electrolytic cell. Removal rates are high compared to chemical and electro-discharge processes and are independent of material hardness. As with chemical machining, ECM has been in commercial use for many years. ECM has traditionally been used in applications where complex geometries are required to be produced from hard to machine materials. As such it initially found favour with the aerospace industry where these attributes, combined with a tendency to produce surfaces free of stress concentrations, made it suitable for components such as turbine blades. More recently it has been used for applications such as deburring, electro-polishing, fine hole drilling and micro-machining as well as the traditional bulk removal. As with chemical machining it ECM is as much black art as science, with most information on machining of conventional ferrous alloys coming from books [51,52,53] and manufacturers data.

The parameters and mechanisms involved in the electro-chemical machining process are quite complex and, as its application to surface texturing is new, an introduction may be beneficial.

Material removal rate

As an electrolytic process, the theoretical machining rates can be predicted from Faraday's laws which state:

1. The amount of chemical change produced by a current is proportional to the quantity of electricity passed.
2. The amount of substance dissolved by a given quantity of electricity is proportional to its weight.

These can be combined to give the amount of material electrolytically removed from the anode (workpiece) as:

$$m = \frac{A}{z}\frac{It}{F} \qquad (1)$$

where m = mass of metal removed (kg)

A = atomic weight of metal

z = valency of dissolving ions

I = machining current (A)

t = duration of current (s)

F = Faradays constant (= 96500 C)

This shows that the theoretical mass of material removed is directly proportional to both current and time, the other factors being constant for a given material. In practice the machining rate is influenced by many other parameters and these are often interdependent. Probably the most significant of these are related to the flow rate as Faraday assumes that the electrolyte is pure and of uniform properties.

In practice the electrolyte in the gap will be affected by hydrogen bubbles, contaminants, localised heating and ion build up on the surface of the anode, all caused by the electrochemical reaction. The machining will therefore be affected by the rate at which the electrolyte is refreshed, ie the flow rate. The nature of the flow, and the flow velocity, will also be affected by the separation of the electrodes, ie the gap height. This in turn will change the machining voltage for a given current.

The current density is related to the machining current, electrode area, and mask coverage ratio (the ratio of unmasked surface to total surface area). Machining current is also related to the machining voltage, electrolyte conductivity, and gap height. Electrolyte conductivity is related to its concentration, temperature and type.

Machining time, in the case where the electrode is moving parallel to the tool, will be the product of the time it takes for the electrode to pass over one point and the number of times it passes. This makes it dependent on the electrode length, surface speed, electrode width, and print height.

The machining rates and surface finishes will also be affected by the electrolyte type.

The interdependence of parameters is shown, at least in part, in **Figure 7**. From this it is necessary to select what will be the most dominant parameters and combinations.

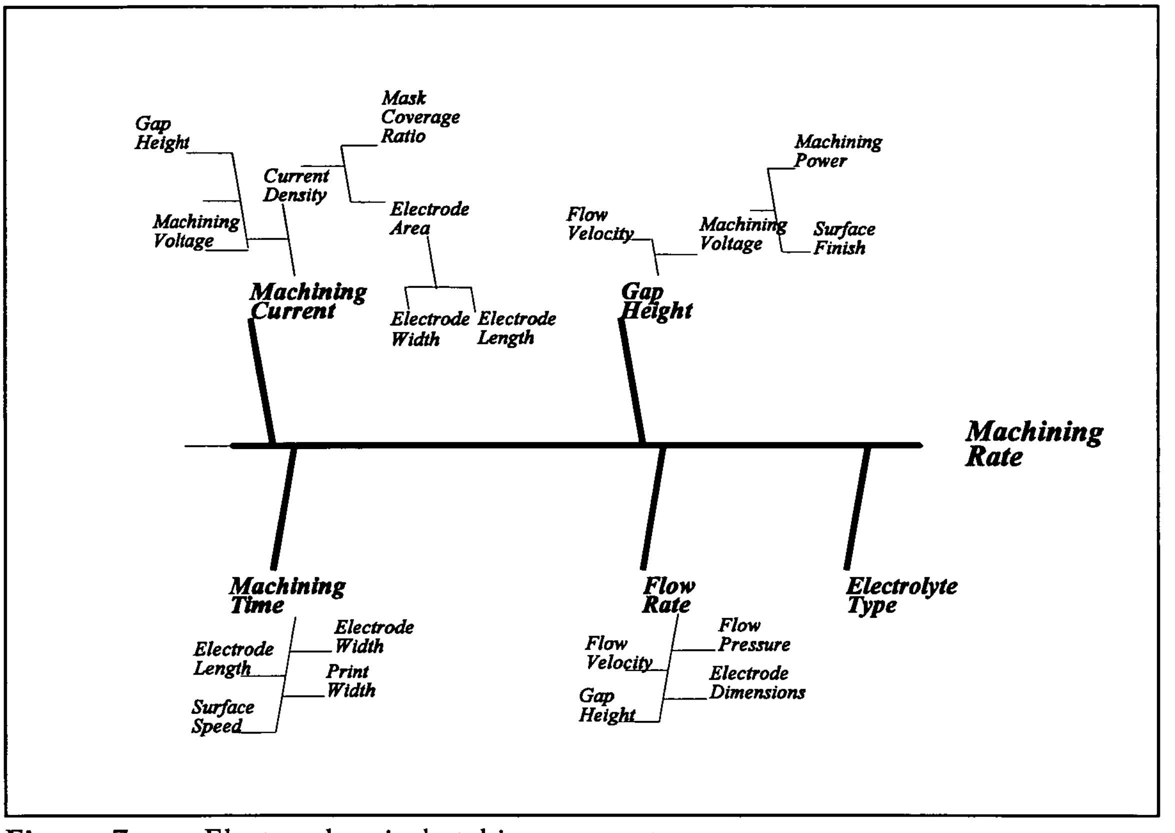


Figure 7 Electro-chemical etching parameters

Electrolytes

The electrolytes used in ECM can be classified as two distinct types, corrosive and passivating. With the rollers being a ferrous based alloy a pure salt solution should be adequate without any additives. Of the two most commonly used solutions one is corrosive and the other is passivating as outlined below.

1. Sodium Chloride (NaCl) (Corrosive)

   Safe, non-toxic and cheap, it has a good current efficiency over a wide range of current densities. It is also quite corrosive, conductivity is temperature sensitive and tends to leave a loose smutty deposit on the machined surface.

2. Sodium Nitrate ($NaNO_3$) (Passivating)

More expensive than sodium chloride, combustible and temperature sensitive but is non-corrosive and gives a better surface finish.

The sodium chloride will machine even at very low current densities and large gap separations but leaves a corrosive deposit on the surface requiring prompt removal. The sodium nitrate needs high current densities (>30A/cm^2) and small electrode gaps but leaves a passive surface layer after machining has ceased.

The ideal electrolyte for texturing would probably have the machining properties of chloride and the passivation of nitrate. It is obvious that the chosen solution will be a compromise.

Electro-chemical micro machining

Recent years have seen an increased use of ECM for high precision, low volume, material removal (particularly in the electronics industry). This has been termed electrochemical micro machining (EMM) and is well covered by a number of review publications [54,55,56]. Early EMM studies looked at applying traditional die-sinking methods to high precision applications. By combining passivating electrolytes ($NaNO_3$) and pulsed current, with an effective tool insulator (silicon carbide) significant improvements in dimensional accuracy were obtained [57].

The most relevant EMM studies to this project have involved the use of photoresists. This is a very recent area of ECM to be investigated and has been termed through-mask EMM or recessed electrode EMM. Initial studies concentrated on the effects of resist thickness and feature sizes on the field and current distribution [58, 59] and the effects of fluid flow [60, 61]. Although these were concerned with thin metallic films on insulating substrates (typical of the electronics industry) they do suggest two things. Firstly there will be an increased current density at the edge the mask (around the ink drops in IJT) which will cause an increased initial machining rate at these points. Secondly fluid flow will have a significant effect on the mass transfer of reaction products, especially in narrow or shallow cavities where recirculating eddies may form. A more recent study looked at the effect of the mask wall angle [62] and found that the primary current distribution at the initial electrode surface was very sensitive to changes in the angle. Acute wall angles were found to concentrate the current at the edge of the mask although, as the shape evolves the current becomes more uniform.

2.4 Ink-Jet Printing

Ink jet printers work by depositing a controlled quantity of medium (ink) onto a substrate which is typically moving relative to the print head. These have developed over the past 25 years to fill a number of mainstream applications. The most common use is as fast, cheap and quiet home and office printers, using a variety of papers and films as the substrate. The other main use is as production line coders. These are designed to print basic text, graphic and bar code information onto a variety of products as they pass by the print head. The primary requirements for these printers are speed and reliability. The last application is for commercial graphics production. These are intended to provide high quality images, often on large format media. An adaptation of this is the digital printing press where the ability to renew the image each revolution is beneficial [63].

2.4.1 Project requirements

For Ink Jet Texturing it was envisaged that printer would be marking directly onto the surface of the roll. This is effectively the same as a production line coder. The other requirements were speed, reliability, resolution and an ability to print onto metallic substrates. These strongly suggested the use of an industrial coder provided the resolution was high enough.

Speed

The surface area of a work roll is large in printing terms (approximately 1 - 6 m^2). If a conventional printer outputs one A4 pages every two minutes with graphics then the theoretical time to print one roller would be 12 - 72 minutes. Ink jet coders are designed to work with line speeds of up to 300 m / minute giving potentially much higher print rates.

Reliability

Unlike desk top printers, industrial coders are designed for continuous operation. Increasingly they are located at critical points in the production process - if all product must be coded then when the printer stops, so does the line. This has led to reliability being one of the most important concerns of the ink jet manufacturer. A bad reputation can be almost impossible for a company to recover from.

Resolution

Most printers have resolutions expressed in dots per inch (dpi) with 300 dpi being common in desk top ink jets at the commencement of this project. Texture 'resolution' is usually defined in peaks per millimetre (ppmm). Although with IJT each peak equates to one ink dot the two scales are not directly interchangeable. Printer resolution assumes that drops are overlapping while peak count requires them to be distinct. A better approximation can be had by halving the printer dpi.

From the available literature it was decided to aim for a peak count of 3 - 4 ppmm, the lower range of LT and EBT. This meant a printer resolution of at least 150 dpi would be required. This is easily attainable with desk top printers but not so with industrial coders. Because print is required to be easily readable (by machines and humans) the characters are typically large with 'resolution' usually expressed in terms of mm height rather than dpi. Fortunately a number of 'high resolution' machines have been introduced. These are designed to print legible text with characters less than 1 mm high, equating to resolutions of 150 - 170 dpi. Although at the lower limit of the texturing requirement it was felt that this would be acceptable.

Substrates

Most desk top ink jets print with a water based ink. This relies on some absorbsion into the substrate for drying. With paper this is easily achieved while transparency films require prior coating, often with a starch based medium. With a metallic substrate rapid drying and good bonding is very difficult to achieve and even if it were, the ink may still be soluble in an etching solution.

While some industrial ink jets use water based inks many are equipped to print onto non-porous media. These use hot melt, solvent or UV curable inks.

2.4.2 Printer types

A full review of ink jet technologies is not warranted here, but the following reviews are recommended as they make fascinating reading [64, 65].

Ink jets can be classified into two basic categories, continuous-ink-jet (CIJ) and drop-on-demand.

Continuous ink jet

CIJ consists of a continuous stream of ink drops which are individually charged before passing between high voltage deflector plates. Two main types are used. With a binary deflection system the charged drops are deflected into a gutter or catcher while the uncharged ones travel straight ahead onto the substrate. A multiple deflection system is analogous in operation to a cathode ray tube. Drops are variably charged depending on their desired position on the substrate, with the uncharged drops going straight ahead into the gutter. In both instances the ink collected in the gutter is pumped back into the main reservoir for re-use.

CIJ had its origins in the last century when Lord Raleigh first described the mechanism by which a stream of ink breaks into drops [66]. The first devices to use this were patented in the 1950s with the first successful computer ink jet printer (the IBM 4640) introduced in 1976. Although the complexity of CIJ deflection systems ensured that they never really became established as desk top printers, the 1980s and 90s have seen the wide spread adoption of single jet multiple deflection systems for production line coding. The continuous formation of drops means high print speeds can be obtained, while the constant flow of ink through the nozzle deters blocking, thus improving reliability. Many companies now make CIJ coders including Domino, Videojet, Lynx, Imaje, Willets and Marsh.

Pressure from emerging applications such as postal services (addressing and personalised mailings) has led to a desire for printers which can match existing line speeds (300 m / minute +) while providing a wider, higher resolution print band. While Imaje has tackled this by introducing a four nozzle multiple deflection system, Domino and Videojet have developed large binary deflection arrays. An example is the Domino BitJet which has 128 nozzles drilled into a stainless steel plate for a 25 mm print band. This approach is being taken even further by the Technical University of Berlin. After developing a 600 dpi drop-on-demand semiconductor print head [67], they are now developing a 1440 dpi binary deflection head micromachined out of silicon [68]. Although still some way off production, this could provide a significant breakthrough in ink jet technology in the future.

Drop-on-demand

These devices consist of an array of nozzles which only eject ink drops at such times as they are required on the substrate. This was seen as a way of avoiding the complexities of charging and deflection that plagued early attempts at CIJ. After an uncertain start where problems of clogged nozzles and poor image quality were rife, they have developed into the widest selling form of computer printer. Again there are two main technology variants.

The first DOD printers used a piezo electric element to eject the ink drop. As either a tube leading to the nozzle, or a plate at the back of the ink chamber, the element deflects one way to eject the ink then flips back. This creates a vacuum which then draws more ink in. The first DOD printers used this principle but suffered from poor reliability and were largely superceded. One company in particular, EPSON, has remained faithful to piezo technology and has recently launched a very successful range of printers based on it. The shear-mode piezo design is now being developed by XAAR for use in high end digital presses and copiers where its ability to deliver very small volumes of ink at reasonable speeds can justify its increased costs.

The other type of DOD printer is the thermal inkjet or bubble jet. This works by heating the ink behind the nozzle until a bubble of water vapour is formed. The bubble grows and ejects the ink through the nozzle, before bursting to create a vacuum in the ink chamber. This then draws in fresh ink for the next drop. The process was first invented by Canon, reputedly after a capillary of ink was accidentally touched by a soldering iron, although Hewlett-Packard claim to have invented it independently at the same time or slightly later.

DOD printers have revolutionised computer printing, particularly through the ability to provide reasonable quality colour output at low cost and high resolution (up to 1440 dpi for piezo printers). They have not been so successful in the industrial coding industry where print speeds are too low and reliability (often from blocked nozzles) is suspect.

2.4.3 Ink Types

Three main ink types are available depending on the printer being used.

Water based

The most common type and used in all thermal ink jets and some piezoelectrics and CIJs. The ink dries by a combination of adsorption into the paper and evaporation. Formulations are closely guarded but tend to include pigments, surfactants and biocides.

Solvent based

These rely on the evaporation of the solvent to dry the ink. In this way they are suitable for printing onto non-porous substrates and are commonly used in CIJ printers. Methyl-ethyl-ketone (MEK) is a popular base as it will dry in less than one second, making it suitable for high speed printing. As MEK is likely to be phased out in the future, due to safety and environmental concerns, other solvents such as ethanol are becoming more popular. Solvent based inks are generally unsuitable for use in DOD printers due to a tendency to evaporate in nozzles, thus causing blockages.

Ultra-Violet (UV) cured

These inks rely on exposure to a strong UV light source for curing. Cure times are currently long compared to other inks but the subsequent bond strength and solvent resistance is very good. This has led to increasing use for "permanent" marking of components in the automotive and aerospace industries where traceability is required. Initial only available for CIJs they are now being developed for DODs as a way of printing onto non-porous substrates.

Solid ink

This is also referred to as hot melt or phase change ink. It is used in some DOD systems where it leaves the nozzle as a liquid but quickly solidifies on contact with the substrate. With little spreading or adsorption this gives high resolutions and strong colours. One drawback is said to poor substrate adhesion, leading to the development of the offset drum printer by Tektronix. This effectively rolls the ink into the paper afer printing.

2.4.4 Other Applications

The versatility of inkjets has led to their use for a number of different applications, although only three references have been found to their use in generating etch masks. All of these are related to printed circuit manufacture.

The first was concerned with depositing masks onto copper coated boards for printed circuit manufacture [69]. The work was very experimental and used paraffin as the masking fluid. The second concerned inkjet sprayed masks for the rapid prototyping of leadframes for integrated circuits [70]. In this case a liquid photoresist was found to give the best results but the work then had to be baked before etching to allow the resist to harden. The third case was a patent for a combined printer-etcher[71]. This consisted of a printhead which coated a copper foil with the desired mask. The foil, installed in coil form, then passed through a bath of ferric chloride before being manually removed for laminating onto the backing board. None of works represented technology which could be readily adapted for the etching of rollers.

Other ink jet applications have included 3D rapid prototyping [72, 73] and the printing of metal films for hybrid circuits [74] and solder for IC production and ball grid arrays. They have also been used in a variety of biological and medical applications for precisely controlled dosing.

2.4.5 Ink Jet Summary

The comparison of various ink jet technologies suggested that a continuous ink jet represented the most suitable technology at the time. This decision was made on the grounds of speed and reliability. A further advantage was the ability to vary the spacing of the printed drops: not an option with a drop-on-demand type head.

The most suitable ink appeared to be MEK based. This would give the fast drying times needed to print onto the non-absorbent steel surface. Solid inks were not an option due to the choice of printer.

3 Experimental Techniques

3.1 Introduction

The majority of the work in this project involved the use of standard engineering techniques and equipment as would be found in any mechanical, electrical or electronic laboratory. The one non-standard technique used was surface metrology and in particular the three dimensional characterisation of topography. This section is intended to provide a general introduction to the equipment and methods used for this measurement, and in particular to the machines used in this thesis. Although surface metrology is a wide area of research in itself, in this project is has been utilised primarily as a tool for the characterisation of the texturing process. More comprehensive reviews of the field can be found in the following books [75, 42] .

Many different techniques exist for the characterisation and inspection of surfaces although most can be classed as either qualitative or quantitative. Examples of the former include both optical and electron microscopes. These are very useful for visualising surfaces but can provide only limited data for further analysis. In order to assess the effects of modification processes it was necessary to obtain both horizontal and vertical data for the surfaces after machining.

Qualitative instruments are capable of providing either 2D or 3D measurements of the surface by a variety of different techniques. They can be primarily classified as either contact or non-contact systems depending on the method of measuring. The original, contact, instruments consist of an inductive stylus probe (similar to a Gramophone needle) which is dragged over the surface to create a 2D surface profile. By combining this with a precision translation stage a series of parallel traces can be combined to create a 3D surface map. Non-contact systems typically use one of two optical methods to measure the surface. The first is similar to the contact method in that the surface is moved under an optical probe by a translation stage. The second and most recent uses interferometry to create a 3D map of the surface.

There is a further family of instrument called scanning probe microscopes (SPMs). These have a mechanical stylus which is actively driven in one of a number of different measurement modes. These can include scanning with a fixed potential between stylus tip and the measured surface (non-contact) or driving the tip downwards until it contacts the surface. The machines are very accurate and have high vertical and horizontal resolution but are limited to a very small measurement area, typically 0.1mm square. This makes them unsuitable for general roll texture analysis and they will not be considered further here.

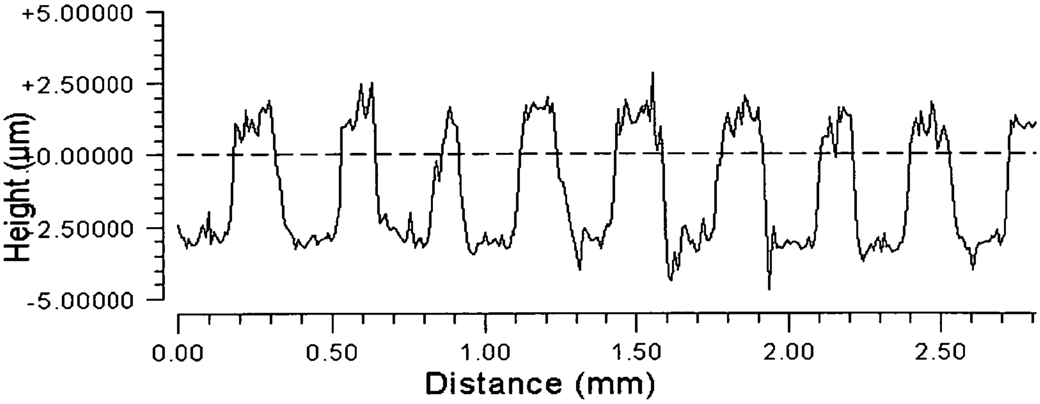
As with most things each method has its own strengths and weaknesses which have to be considered with the intended application in mind. Stylus systems will give a measurement from almost all types of surface, are less sensitive to surface contamination but may damage soft surfaces and have an inherent filtering effect due to the geometry of the stylus. Optical probes will not damage the surface but may fail to measure objects of low reflectivity or high slope angles (note that contact instruments will always give a measurement irrespective of slope angle, though it may not always be correct). Interferometric machines have much better vertical resolution and may be considerably faster but are more expensive, have fixed lateral sampling intervals (dependent on the overall system magnification and the camera resolution) and smaller vertical ranges (typically up to 0.1mm).

Three different machines have been used for surface measurement during the course of this project. These will now be described in more detail.

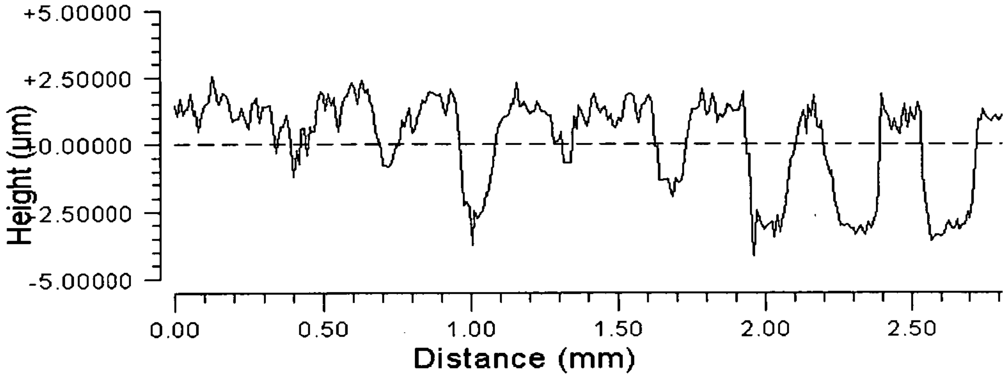
3.2 Taylor Hobson Talysurf 4

This is an early example of a 2D stylus profilometer, capable of providing either a thermal paper trace or an R_a value, but not both simultaneously. This was used during first stage of the project but was limited by its inability to provide a full 3D picture of the surface. While a single profile may give a representative picture of a stochastic surface, as would be generated by shot blasting or electro-discharge texturing for example, it is not possible to build an accurate picture of a deterministic surface by this method. This is due partly to the difficulty of aligning the trace accurately with the features of interest. **Figure 8** shows three traces taken from a 3D data set. One passes through all the peaks, one passes through some and the other misses them completely. This can give misleading information on the spacial location of features, wall angles, etch depths and mask integrity, thus making deterministic characterisation very difficult.

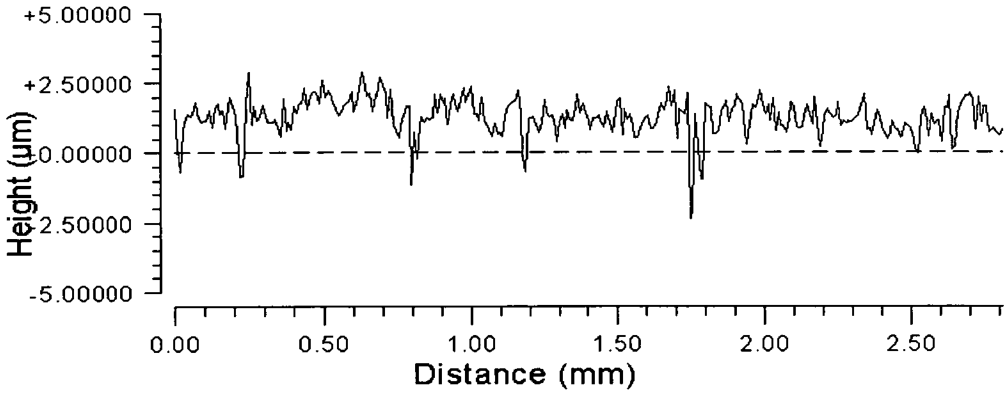
Some modifications were made to the machine to enable the data to be output to a computer for further analysis. Unfortunately attempts to convert it into a 3D system were less successful. The lack of any repeatable reference for the traversing arm meant that the stylus would have to be used in conjunction with an X-Y stage. The cost of a stage with suitable precision and flatness was such that upgrading to 3D would not have been cost effective.



Profile through all peaks



Profile through some peaks



Profile through no peaks

Figure 8 2D traces demonstrating misleading information

When the second phase of the project was being formulated it was apparent that some form of 3D instrument would be required. A number of different types of instrument were evaluated before purchasing an interferometer based machine.

3.3 Zygo NewView 100

This machine uses a technique called scanning white light interferometry (SWLI) to combine the high vertical resolution and speed of a conventional phase shifting interferometer (PSI) with an increased vertical range. Because PSIs use a filtered light source they are limited to measuring surface features up to a quarter wavelength. Beyond this wavelength the interference becomes ambiguous due to the periodic nature of the light source [76]. The instrument is shown in **Figure** 8.

The measurement area and lateral resolution in given by the objective power and camera resolution, although a zoom facility is now available to vary the magnification of any give objective. Vertical range is limited to 100μm by the piezo actuator used to scan the objective, though an extended scan option is now available.

With a 2.5x objective the measurement area is 2.84mm x 2.13mm with a spacial resolution of 8.8μm. This is sufficient for measurement of surface roughness and general visualisation but is more limited when looking at waviness and of no use when evaluating surface form. Long form wavelengths are of little interest in roll texturing but waviness is becoming increasingly critical as it is associated with deterioration of paint appearance. It is possible to increase the measured area by the combination of a precision x-y stage and "image stitching software". This enables adjacent overlapping scans to be combined into one large data set. An added advantage of this approach is that each measurement is aligned to match its neighbours so any flatness errors in the stage travel are removed, giving rise to more accurate measurement of waviness and form over large areas. In certain circumstances it may be necessary to compensate for curvature in the optics by

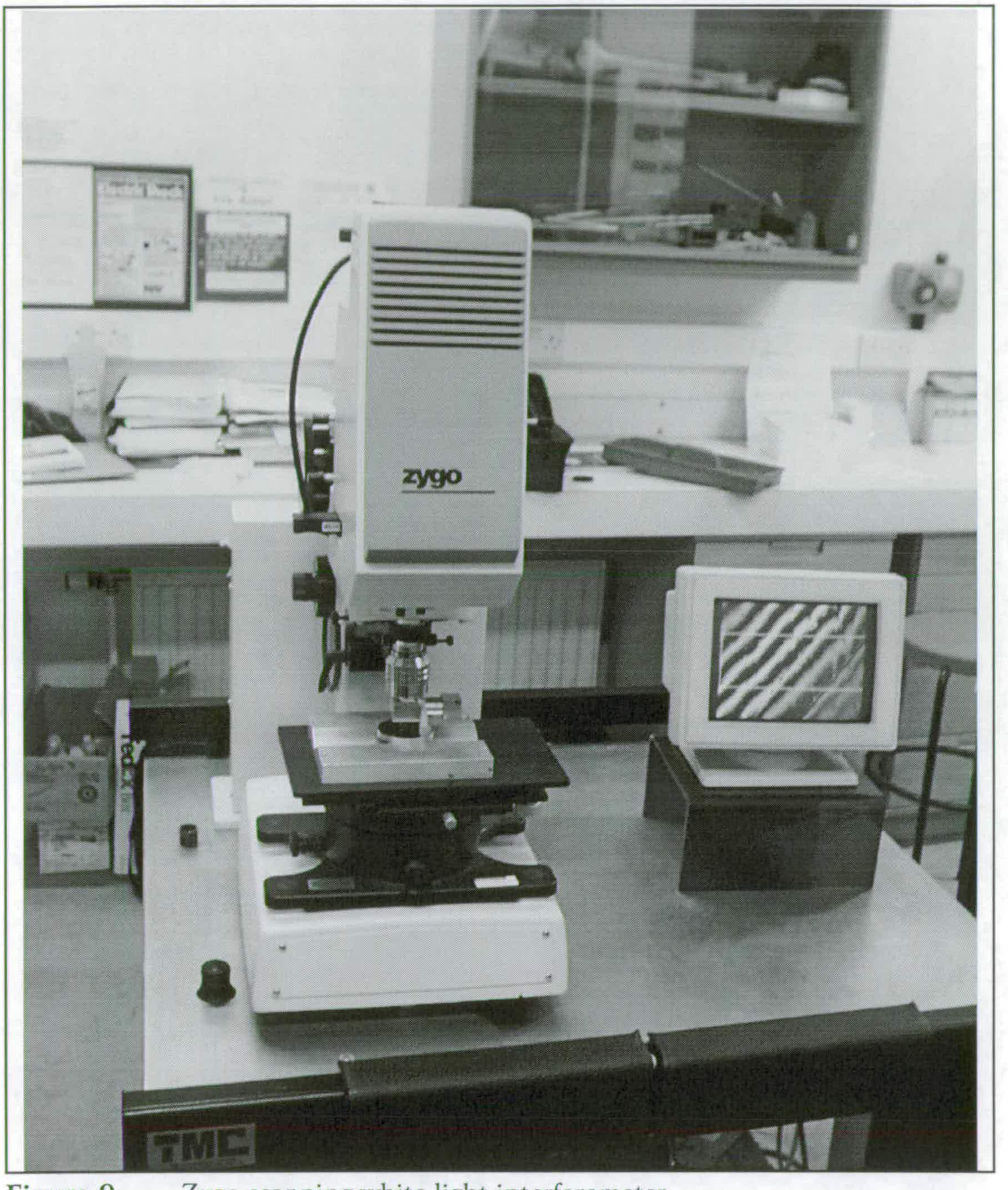


Figure 9 Zygo scanning white light interferometer

way of a system calibration file. A measurement is taken on an optical flat which can then be subtracted from subsequent measurements to remove the effect of optical distortion.

Although the image stitching option has not been purchased a demonstration system has been used to acquire some large area scans used in this work.

3.4 Scantron Proscan 1000

This scanning optical probe machine was acquired towards the end of the project. Although the vertical resolution is lower (± 30 nm best case) than the NewView (0.1 nm) the vertical range is greater (400 μm), as is the measured area. The instrument is shown in **Figure 10**.

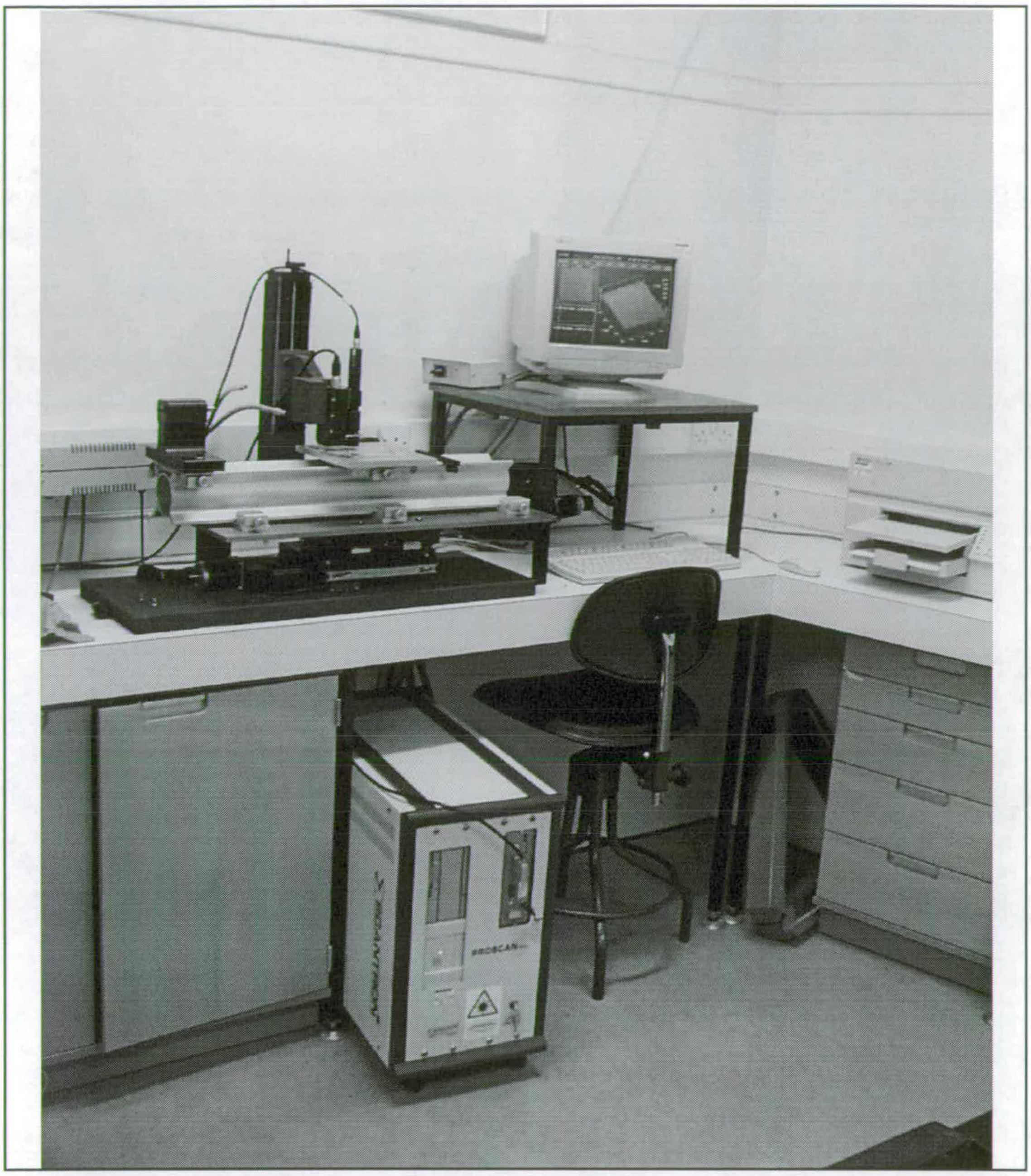


Figure 10 Scantron Proscan 1000 scanning laser triangulation machine

The Proscan uses a laser triangulation sensor which can give artifacts when measuring high slope angles, although not as badly as a laser focusing sensor. One, less obvious, problem with the triangulation sensor is that the spot size varies with surface height, e.g. 12 μm diameter in mid range but increasing to 35 μm at the extremes. As the surface height is a (weighted) average over the spot area this leads to a filtering of high frequency components which will vary with surface height. Because of the spot size the highest realistic sampling interval is 10 μm. Applying the Nyquist criteria to this means that the highest frequency component measurable has a wavelength of 20 μm or 50 cycles per mm. With deterministic textures having peak counts typically between 3 - 10 peaks per mm this is not a major limitation but EDT surfaces may have 20 -30 ppmm or even higher. In these instances there may be a significant loss of data in regions of interest. Another source of error is the translation stage. Any variation in the flatness of the slides will appear as changes in the height of the surface being measured. Although generally significant over a small area it could give problems if measuring waviness over a large area (eg 25 mm square or greater). It should be noted that none of these effects need be a barrier to accurate measurements but that they must be understood and accounted for if necessary.

3.5 Replication of surfaces

One problem with measurement of rollers is that they tend to be too bulky or heavy to fit underneath a surface measurement device. One solution to this is to remove sections of the roll for analysis by EDM wire erosion, sawing or other similar processes. This has a number of limitations. Firstly the roller may be too large to fit under the sectioning device but perhaps more importantly the technique is destructive and results in its end as a functional item. Academically this means that the evolution of surface texture during rolling cannot be studied. Financially even a small set of rollers for a pilot mill may cost in excess of £15k making it a very expensive way to make measurements.

The way round this is to use some form of casting material to make replicas of the surface. In this way surfaces of even very large objects can be accurately measured. The measured surface is the negative of the surface of interest but the data can be easily inverted in most software packages. In some cases it is even possible to apply a scaling factor to account for any shrinkage of the replica if needed.

All replicas used in this thesis have been made with a two part hard setting material called Kulzer Technovit 3040. This has a quoted accuracy of 0.1μm R_a but work done at Birmingham University on artificial hip joints suggests that it is capable of resolving features much smaller than this [77].

The replicating solution worked well but experience showed that the solution had to be made up thinner than recommended by the manufacturers data sheet. This was to allow any air bubbles formed to rise from the surface before the material set. To assist this process a thin layer of solution is desirable but if less than approximately 3 mm thick some form distortion was observable in the finished replica.

The data sheet also recommended the application of a thin film of oil as a mould release on the surface to be replicated. This proved to be undesirable as some of the finer roughness features seem to be obscured by it. The best technique appeared to be to degrease the surface thoroughly prior to replication. The resulting cast, although firmly attached, comes away cleanly with a sharp tap with no apparent damage to the replica. By this method many rollers have been characterised which would not otherwise have been measurable.

3.6 Metrology Summary

In this chapter the techniques used for surface measurement have been presented. The two optical machines should be seen as complementary and used where appropriate. Although the speed, software and accuracy of the Zygo have seen it used most, its measurement area is barely large enough to give a true picture of the uniformity of the texture. At 2.8 mm it is not wide enough to measure across more than one complete print band. As the Scantron can measure much larger areas it has been used to assess the uniformity of texture on the rolled sheet, typically over areas 8 mm x 8 mm. It is not so suited to measuring rollers however. The curved surface means that the measurement area is limited by the sensor range. In addition the bands of higher slope along the edges of the scan are contaminated by noise spikes and other measurement artefacts.

Almost as important as the measurement machines was the replication process. Without it many of the rollers would have been impossible to characterise. Although many different techniques exist the compound chosen was found to be quick, cheap, accurate and sold specifically for the purpose. It is also becoming an industry standard allowing easier comparison with samples from other sources.

4 Chemical Texturing

This chapter covers from the initial research in Ink Jet Texturing through to the conclusion of the experiments using chemical etchants. Subsequent research involves a different machining process (ECM) and a different printer and is described in chapter 5.

Chapter 4 starts by describing the research inherited at the start of the project then proceeds to outline the stages leading to the conception of ink jet masking. Initial experiments involving steel shim material led to the design an testing of the first system to print and etch rollers. Subsequently a second generation etch tank was built and formed the basis for most of the chemical experiments described. The main aim of this stage of the work was to investigate whether ink masks could be successfully applied to a roller to form an effective mask. Further details of the first and second generation texturing systems can be found in appendices A and B respectively.

Prior to the start of this project some investigations of chemical and electro-chemical texturing had been made by other researchers within the department. Experiments to electro-chemically machine flat plates were deemed unsuccessful as the textures produced were of low average roughness and peak count. This is perhaps unsurprising given the copying nature of the NaCl electrolyte and high current densities used. Although a rougher surface can be obtained by machining at low current densities this does not appear to have been attempted. Also investigated was a hybrid process where an EDM pass was followed by an ECM process. The intention was to smooth the high frequency components of the EDM surface but results and the reasoning behind it are unclear. The third process to be investigated was photo-etching, or photo-chemical machining. This approach seemed more promising as it was capable of producing deterministic patterns. Unfortunately the results achieved again appear to be disappointing. Experiments were restricted to flat samples with the smallest resolved features greater than 3 mm.

After reviewing the work outlined above it was decided to start this project concentrating on the photo-chemical approach as being perhaps the more feasible for two reasons. Firstly, much of the technology already existed, and secondly the user would have complete control on the final pattern printed onto the roller. The photochemical approach can be summarised as the following stages.

4.1 Photo-chemical machining

The basic stages of photo-chemical machining are described in chapter 2. To apply it to the texturing of rollers, the following basic steps would be involved:

(1) the rollers must be coated evenly and repeatably with a light sensitive chemical called photoresist;

(2) the image, or reverse image, must be projected onto the roller to expose the photoresist. To do this the pattern must first be created on a mask, similar to a photographic slide or plate;

(3) the exposed photoresist must be developed by immersion in a chemical bath;

(4) the roller may now be etched where it is not covered by exposed photoresist

(5) A final wash is now needed to remove the remaining photoresist residues.

These stages will now be described in more detail.

4.1.1 Photoresist

Obtaining a suitable photoresist would be unlikely to provide a problem as a large number of companies - e.g. BASF, Hoescht, Shipley, etc - manufacture a wide range of commercial photoresists. Similarly the coating of the rollers could be done using one of a number of commercial techniques such as dip coating, spraying or rolling. While the processes may be feasible they may be slow and expensive to apply to a large roller, not least due to the need to coat away from sensitising light sources.

4.1.2 Developing

Standard developers would be available, along with the resists. The development of the rollers could prove more difficult, due to their size and the need to ensure an even development over the whole surface but again it is likely that this technology is already available commercially. Otherwise it would be possible to use a chemical bath with the roller rotating on the surface.

4.1.3 Etching

The same problems apply at this stage as apply above and it is likely that the solution would be similar. Ferric chloride is a commonly used etchant for parts such as coordinate measuring machine scales and could be applied as above, by immersion or even by spraying.

4.1.4 Image projection and mask generation

This is the area where the main difficulties would occur. A significant technological problem exists in attempting to expose an image onto the curved surface of the roller. Contact printing would be infeasible due to the large size of mask required and the difficulties in maintaining it in complete contact over the entire surface of the drum. It would also be very difficult to achieve a 'seamless' join of the pattern on the drum. Other methods such as proximity printing would be difficult due to the varying gap over the area of exposure, caused by the curvature of the roller. These problems should not be insoluble but would greatly influence the complexity and cost effectiveness of the final solution.

What was required was a more continuous method of applying the mask to the photo-resist.

4.1.5 Ink jet mask printing

One idea developed as a solution to the problems highlighted above was to write the mask directly onto the surface of the photo resist, thus bypassing the optical difficulties. This idea evolved to writing directly onto the surface of the roller and using the ink as a barrier to the etch. By doing this all the steps connected with the coating, exposure, development and removal of the photo-resist can be eliminated leading to many fewer processing steps.

4.2 Preliminary Ink Jet Experiments

The concept was tested very simply using a standard office ink-jet printer (Hewlett-Packard Deskjet 500) and some mild steel shim. This arrangement was less than satisfactory for two reasons; firstly the printer is designed to print paper, not steel, and secondly it uses a water-based ink which relies on the absorption of the paper to dry.

The printer was set to print a strip of 50% shading. When the printer had loaded the paper but before printing, it was taken off-line and a piece of shim inserted over the top of the paper. The on-line was reset and the strip printed onto the steel. The steel was then etched in a solution of ferric chloride for a fixed period of time. After etching it was rinsed, dried and then measured under the Talysurf.

Convincing results were obtained by degreasing and heating the shim before printing. Some samples were also heated after printing as a form of post-baking. The results of these experiments are noted below in **Table 1**.

Sample	Preparation	Etch time	Comments
1	None	15 s	Print quality poor with ink coalescing into larger drops. Poor adhesion during and after etching
2	Degreased	30 s	Ink still forming larger drops but resolution is better. Adhesion during etch still poor but good resistance noted with well defined 1μm peaks observed
3	Degreased Post baked	45 s	Ink smeared before heating to give a continuous film over surface. Ink adhesion improved but with evidence of etching through the mask
4	Pre baked Degreased Post baked	60 s	Reasonably good resolution of image and good adhesion but evidence of etch penetration. Etch depths similar to those after 15 seconds
5	Pre baked Degreased Post baked	90 s	Not well resolved on Talysurf although image is clearly visible
6	Pre baked Degreased Post baked	105 s	As above, suggesting that peaks are being corroded through the mask at long etch times

Table 1 Preliminary ink jet results

The profiles indicate that the ink remained resistant to the etch for up to 30 seconds. Other research, the etching of high resolution markings on coordinate measuring machines, shows etch rates of 20μm/minute to be achievable [78]. This suggested that the ink resistance should be adequate to etch features at least 10 microns deep.

It was noticed that the solvent based ink used to label the samples was still forming a strong barrier to the etch after two minutes immersion. The following points were concluded:

1. Degreasing of the surface was essential
2. Preheating of the substrate improved print quality
3. Post heating of the substrate improved ink adhesion
4. Ink was resistant to etch penetration for at least 30 seconds
5. The ink used to number the samples showed excellent etch resistance, even after two minutes immersion, suggesting different inks could improve etch performance
6. The process showed definite potential if more suitable inks could be found

4.3 Solvent based ink experiments

Following on from the success of the first experiments it was decided to test some solvent based inks. Two samples were provided by Coates Electrographics, the inkjet division of Coates International. These were sufficient to determine the general chemical resistance of the solvent based inks.

It had been hoped to use these inks in empty Deskjet cartridges. This had some potential problems however. Firstly, it was suspected that the solvents in the inks may have a detrimental effect on the plastic casing of the ink cartridge. The other problem is one of solvent based inks in general. Because they are quick drying there is a far greater tendency for the ink to clog in the nozzles of the printhead.

In practice the two inks tested appeared to have no effect on the cartridge. The inks were applied to both the casing of a cartridge and the foam inside. They were then left to dry with no observable effect on the case or foam. Unfortunately all attempts to print the inks using the Deskjet cartridges failed. Various techniques were employed to clear the nozzles but they inevitably clogged again after a short time interval. This lead to the conclusion that the ink was indeed drying in the jets.

Samples were coated by dabbing ink on with a fine sponge to give quite a fine, random pattern. These were then etched as per the first samples. The solvent based ink showed a very good etch resistance. Inspection under the Talysurf showed no discernable etch penetration even after two minutes exposure.

These tests confirmed the findings of the first tests that the ink was a suitable masking material against the ferric chloride etchant.

4.4 Printer Evaluation

The problem of printing solvent based ink was overcome by the discovery of a high resolution industrial inkjet printer, the Videojet Excel Hr. This was designed to print a variety of ink types onto a moving substrate at 170dpi resolution. Videojet UK kindly agreed to provide a machine on loan to enable some evaluation experiments to be made. The print head has a nozzle diameter of 36 microns and a drop frequency of 80 KHz. Although the actual dot size on the surface of the roller would be larger than the nozzle size it should still be acceptably small. It was connected to the control unit via a 2m umbilical allowing easy mounting onto a lathe.

4.4.1 Machine Evaluation

This involved mounting the print head of the above machine onto the tool post of a small precision lathe. The "rollers" were made from 50 mm diameter steel tubing. This enabled them to be etched in a standard printed circuit board etching tank with bubble agitation. First results of printing were encouraging. There was little difficulty in printing onto the surface of the roller, even with character heights of less than 1mm (and thus dot sizes considerably smaller). It was not possible to program the machine with graphics but a semi-random texture was obtained from printing text strings.

It was possible for the machine to print up to three lines of text simultaneously. It was also possible to program the machine to print those lines repeatedly, or even to alternate the text being printed. By doing this with the pitch of the tool post feed set to ensure the lines overlap, it was possible to get a pattern of random appearance similar to that printed on the inside of certain confidential envelopes.

First attempts at etching the rollers were not quite so successful, suggesting that the development of a suitable etching system was a high priority. The printer, however, appeared to be ideally suited to the application and was subsequently ordered.

4.4.2 Ink Evaluation

After deciding on the choice of printer it was necessary to select the most suitable type of ink. Samples of 3 mm steel plate were surface ground then sent to Videojet UK for printing with a selection of different inks. Due to delays in the returning of the samples there was a wait of over one month between printing the first inks and etching the samples.

4.4.2.1 Methodology

Three sample plates were coated with four different ink types. Only one ink type was applied by a HR printer, the others being printed by a standard resolution version of the same machine. Etching was done in a tank of ferric chloride solution, temperature 50°C (+2°C, -1°C), strength 43°Bé. Agitation was provided by resting the bottom end of the plate on the base of the tank and gently rocking the top end. Plate one was etched for two minutes, plate two for four minutes. The third was left as a control and in case further tests were needed.

After etching the plates were rinsed under cold running water and scrubbed with a Scotchbrite type pan scourer. In addition to cleaning the samples this facilitated a qualitative appraisal of the ink adhesion. Samples were then examined under the Talysurf and an optical microscope to assess etch depths and ink penetration.

4.4.2.2 Results

The results of the ink etch resistance experiments are shown in **Table 2**.

Ink Type	Etch Time	Etch Depth	Comments
8600	2 min	2-3μm	Ink adhesion good with no evidence of etch penetration
8600	4 min	3-4μm	Adhesion still good with scrubbing needed to remove
8200	2 min	3μm	Ink adhesion excellent with firm scrubbing needed to remove. No evidence of etch penetration
8200	4 min	3-4μm	Adhesion still very good but now evidence of significant etch penetration on Talysurf and microscope
5600	2 min	3μm	Adhesion only medium with ink coming off with a firm finger rub. Slight evidence of penetration
5600	4 min	3-4μm	Adhesion now poor with ink lifting off. Evidence of severe etch penetration
8510	2 min	4μm	Very poor adhesion with ink lifting under running water. Etch resistance good where ink is still firmly attached
8510	4 min	5-6μm	Adhesion still poor but good etch depths. Where ink has remained there is evidence of penetration in the centre of characters

Table 2 Ink etch resistance results

4.4.2.3 Discussion

There were some problems with this trial. Firstly it proved impossible to get any information out of the manufacturers as to when each ink was applied. This is important if the ink matures with age. If all the coating was done over a week prior to etching then this should not be a problem but if one ink was applied immediately before despatch then it would be less than 36 hours old at time of etching. This may explain differences in adhesion of ink 5600. Ink 5600 is different in two ways. Firstly it was the only one applied by the high resolution printer. This will result in a smaller drop volume, giving less contact area and a thinner ink layer. The second difference is that it is intended to be used with a high temperature post bake (3 hours at 300°C) to give it MIL specification abrasion resistance. A post baked ink was not tested as it would be very difficult to apply on a small roller, and would significantly increase the processing time.

Both 8600 and 8200 had good adhesion even after four minutes. The etch resistance of 8200 was worse than 8600, even though its adhesion was slightly better. For this reason it was decided to try ink 8600 in the new machine.

The primary aim of this test was to select the most suitable ink formulation with etching rates being of limited interest. It can be seen however that etch rates are quite slow for most samples over the first two minutes, and with little further etching after four minutes. This is most likely to be attributed to poor circulation of the etchant giving poor replenishment of the depleted etchant on the surface of the plate. Most print samples were located near the base of the tank with only 8510 near the top. The greater etch depths associated with this ink can be attributed to increased motion during agitation.

4.5 Roller Processing - Generation I

The next stage of the development was to build and test a system to print and etch steel rollers. This would involve rotating the roll at constant velocity around its central axis while a print head traversed along its length. A small jeweller's rolling mill was purchased in the hope that it could be used to provide a crude method of producing rolled sheet for demonstration. These rollers were 51.5 mm diameter with 120 mm barrel length. The original rolls were grooved at one end for reducing wires so replacement sets were made from EN31A (water quenched). These rollers were used as the standard Edinburgh roller for experimental work and the texturing equipment was designed around their dimensions. Because these were time consuming and expensive to make a number of smaller rollers were also produced. These were the same diameter and material as the main rollers but only 25 mm wide, with a tapped hole in the centre for mounting. Although not suitable for rolling these were produced in numbers for machining experiments.

4.5.1 Printing

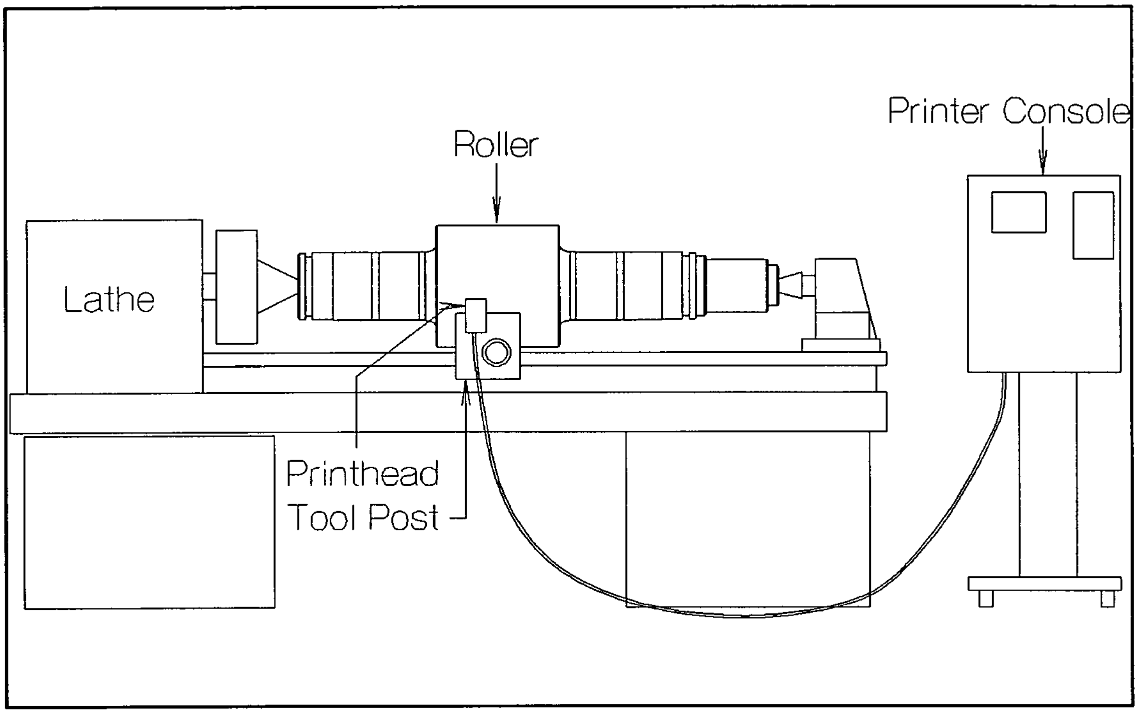


Figure 11 First generation roller printing

The rollers were mounted between centres on a small tool makers lathe as shown in **Figure 11**. Full sized jeweller's mill rollers were mounted directly with the small disk rollers screwed onto a holding shaft. This gave the potential for some eccentricity but was compensated for by reduced costs and the ease of processing for multiple tests. The print head was mounted on the tool post of the lathe with the screw cutting drive used as the actuator. The circumferential drop spacing was set by the combination of roller surface speed and the speed setting of the printer.

The axial drop spacing was set as print height on the printer and adjusted by varying the gap between the print head and the roller.

As the roller rotates the print head is traversed. The mask is thus printed in a helical pattern across the roller surface. Here the print head is mounted on the lathe tool post. The pitch of the helix is set using the machines screw cutting mode with the print height being adjusted to ensure accurate butting between strips.

The dot patterns used were created using the font generator facility which is accessible through the printer keyboard. This allowed the creation of custom characters by the selective addition or removal of points in a matrix of dots. Although easily accessible the fonts created consist of single characters and are therefore separated by spaces. As the main aim was to investigate the printing and etching process this approach was sufficient for a first test of pattern transfer. Two types of dot pattern were used. Isolated drops gives isolated peaks on the roller and ultimately isolated valleys or craters on the rolled sheet. The inverse of this has overlapping drops with isolated spaces between them. This gives craters on the roller and peaks on the sheet.

To provide a semi-random pattern which masked the gap between logos the pitch was sometimes set to provide overlaps between adjacent strips.

4.5.2 Etching

Having applied a mask to the surface of the roller, the next stage was to remove the exposed surfaces. The etching process had to be capable of meeting three main criteria:

(1) It must be capable of etching to the required depth without complete undercutting of the mask.

(2) It must maintain the integrity of the ink mask for the duration of the etch.

(3) It had to be suitable for use within a laboratory environment

To do this an etching rig was designed to enable the following parameters to be controlled.

(1) Etch time.

(2) Etch concentration.

(3) Etch temperature.

(4) Agitation/circulation of etchant.

(5) Delay time between mask printing and etching.

Ferric chloride solution, $FeCl_3$, was chosen as a readily available, effective etchant which is also relatively harmless to work with. The aggressive nature of this fluid influenced many of the design decisions. Risk of fluid splashes or leaks meant that the etching would have to be executed in purpose built equipment located away from the lathe. Similarly the etchant had to be kept away from all areas of the roller apart from the rolling face, that is the face to be textured.

There is little data available on materials compatibility. Some data is available on metals compatibility but plastics are less well understood. Commercial etching machines tend to be constructed from PVC. This gives a temperature limit of approximately 55°C so where higher temperatures are required the tanks are fabricated from Titanium sheet at considerable cost. Although etch rate of steels increases with temperature so does the surface roughness. With these considerations it was decided to limit the design temperature to 55°C.

With this information the system in **Figure 12** was built. The etch level in the tray - set by the height of the drain plug and the flow rate of the fluid - is adjusted such that it just touches the underside of the roller. The roller rotates, thereby refreshing the etchant on every revolution. With the pump switched off the fluid level drops and the roller may be removed for rinsing. The system allows temperature control via heaters and thermal sensor; circulation via the pump flow rate and agitation via the rotational speed of the roller.

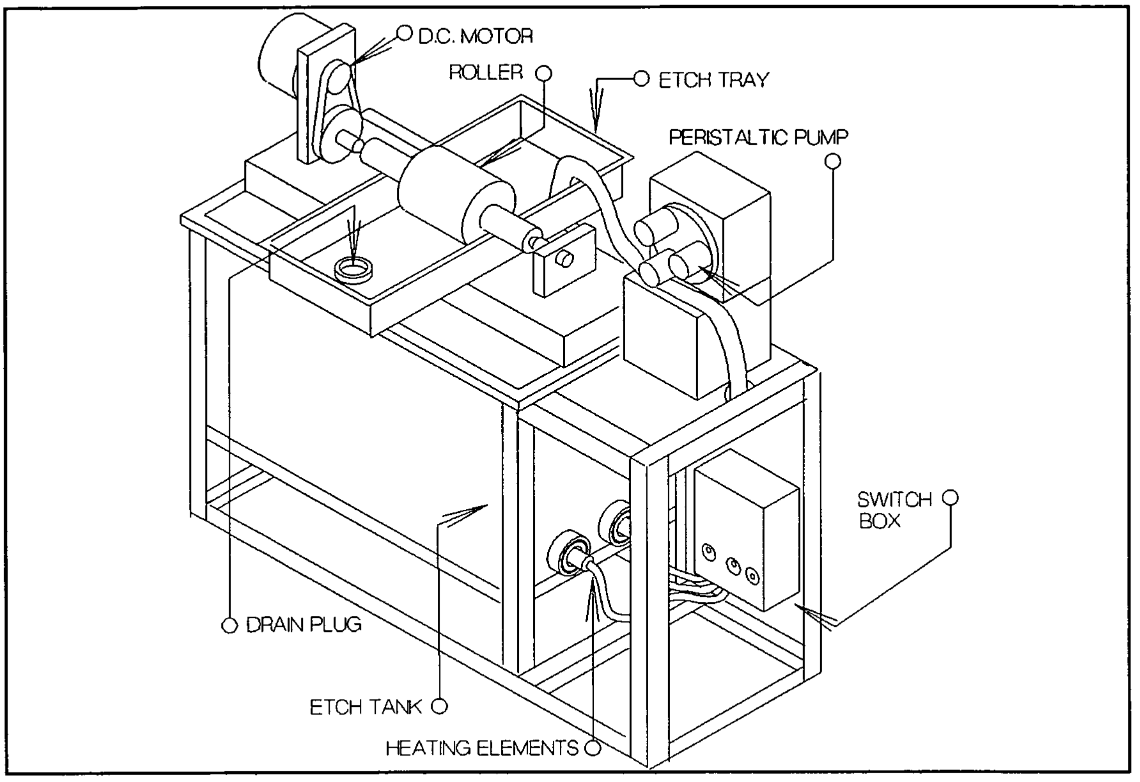


Figure 12 First generation etching tank

Fluid was circulated by a peristaltic pump chosen for its lack of wetted parts. The main limitations of these pumps are low flow rates, low delivery pressures and slight ripple in the flow rate. None of these represent a problem in this application. The fluid was heated by three *Red Rod* glass sheathed heaters with suitable chemical resistance. These are shown mounted through the side of the tank in PVC bushes. Sealing disks were secured with screws turned from Vitrex PEEK after Nylon screws expanded and snapped. The heaters were originally mounted in a Perspex column but this became badly cracked after repeated exposure to the etchant. Each heater is individually switched enabling all to be used to bring the tank to temperature then just one used to maintain it. As the temperature controller is a simple on-off configuration this reduces the overshoot from 7 to 3°C at 50°C.

With the roller fitted and rotating the pump is switched on and the level in the tray starts to rise. After an allotted period of time the pump is reversed to drain the tray. Timing starts when the fluid first touches the roller and finishes when it finally clears it. There is a delay of 30 seconds (±5 seconds) between reversing the pump and the roller clearing the fluid. Until this happens it cannot be removed for rinsing and even then it is coated in etchant until it reaches the water. The removal and transport typically takes 20-30 seconds. It is assumed that by the time the roller is removed the etchant on the surface has depleted and further machining is negligible but this cannot be confirmed.

4.5.3 Results

The first disks etched were sponge coated with Jetstream E ink from Coates Electrographics. This method gives a large variety of exposed areas and ink film thicknesses. The rollers were etched for 90 and 180 seconds giving typical etch depths of 3 - 5μm and 6 - 8 μm respectively. There appeared to be a good correlation between crater width and etch depth suggesting that depleted etchant was less likely to be replenished in narrower craters. There were also shallow craters (typically 1 - 2 μm) which did not fit this observation. It is believed that these were the result of etch penetration in areas of the mask where the ink layer is thinner. Ink adhesion was good at both etch durations but there some areas of the rollers showed evidence of etch penetration. It should be noted however that this is very difficult to confirm with a random mask as there is no geometrical reference to compare it to. By comparison, with a surface covered in a geometric pattern of regularly sized and spaced circles it is easy to spot any areas of failure.

Many of these uncertainties were clarified by the etching of rollers coated by the ink jet printer. Disks were printed to give a peak count of approximately 4ppmm and etched under identical conditions within 24 hours. After one minute craters were etched to 3 - 4 μm with no signs of mask failure. A good uniformity of etch depth between the peaks supported the theory that etching was being inhibited in small gaps by poor circulation. After two minutes etching the mask had failed but a roller coated four weeks earlier survived for three minutes with no sign of deterioration. This indicated that the ink was not fully mature after 12 hours, a source of some concern. The three minute etch gave 6 -7 μm craters suggesting that etch rate is also a function of depth. It was not feasible to use smaller time intervals or to accurately compare etch rates between rollers due to timing variations introduced by the apparatus, as mentioned above.

4.6 Roller processing - Generation 2

Having demonstrated that the rollers could be printed and etched with some success a number of modifications were needed to enable the process to be further evaluated. These include printing more continuous patterns onto the jeweller's mill rollers to enable rolled sheet samples to be produced. A more controllable etching rig was also needed to enable accurate timing of the process. In addition the first prototype incorporated existing laboratory equipment which was starting to corrode on exposed metal parts, even with anti-corrosion wax coating applied. This was due to corrosive vapour from the heated fluid in the tank. It was prudent to design a fully dedicated system using as much plastic componentry as possible.

4.6.1 Printing

The font editor was sufficient to look at the effects of dot patterns on etching but did not give a very convincing demonstration of the process. To do this it was desired to lay continuous dot patterns on the surface of the roller. This requirement was predicted when ordering the printer and it was advised that what was needed to do this was a piece of software called the *extended serial interface*.

When delivered it appeared that all this consisted of was a piece of firmware (EPROM) which enabled most of the machine control to be done remotely and a basic manual which did not even refer to the HR machine. This meant that the PC interface software had to be written before the graphics generation facility.

The dot patterns were generated in HP Basic for Windows on an IBM PC and down loaded into the printer as graphical logos. The process of generating the logos was complex and time consuming. The logo size was machine limited to 14 drops high by 255 drops long. This was not anticipated to be a problem as most texture patterns repeat within four strokes. It should be possible to define a short pattern then print it repeatedly.

Although it was possible to print multiple logos there was still a gap between them. When Videojet were questioned about this they said that the delay was needed for the machine to do phasing checks. These are so that the drop charging can be adjusted to take account of the inks changing electrical properties. Although it had been informed that the machine would be capable of continuously coating a full sized roller it now appeared that this was not going to be possible. There was no way to disable this phasing check without obtaining a significant rewrite of the printers operating system and, even if this was available, it would be unlikely to print for more than 20 seconds before quality became unacceptable.

It became apparent that there would be significant problems in using this particular printer to texture commercial mill rolls as there was no way of providing a continuous pattern. Even if the pattern was printed as adjacent bands instead of a helix, the message length would not be sufficient to print a one metre circumference. This printer would be adequate for the laboratory trials but alternatives were needed for further development.

Figure 11 on page 69 shows the lathe and printer, with a close up of a roller being printed in **Figure 13**.

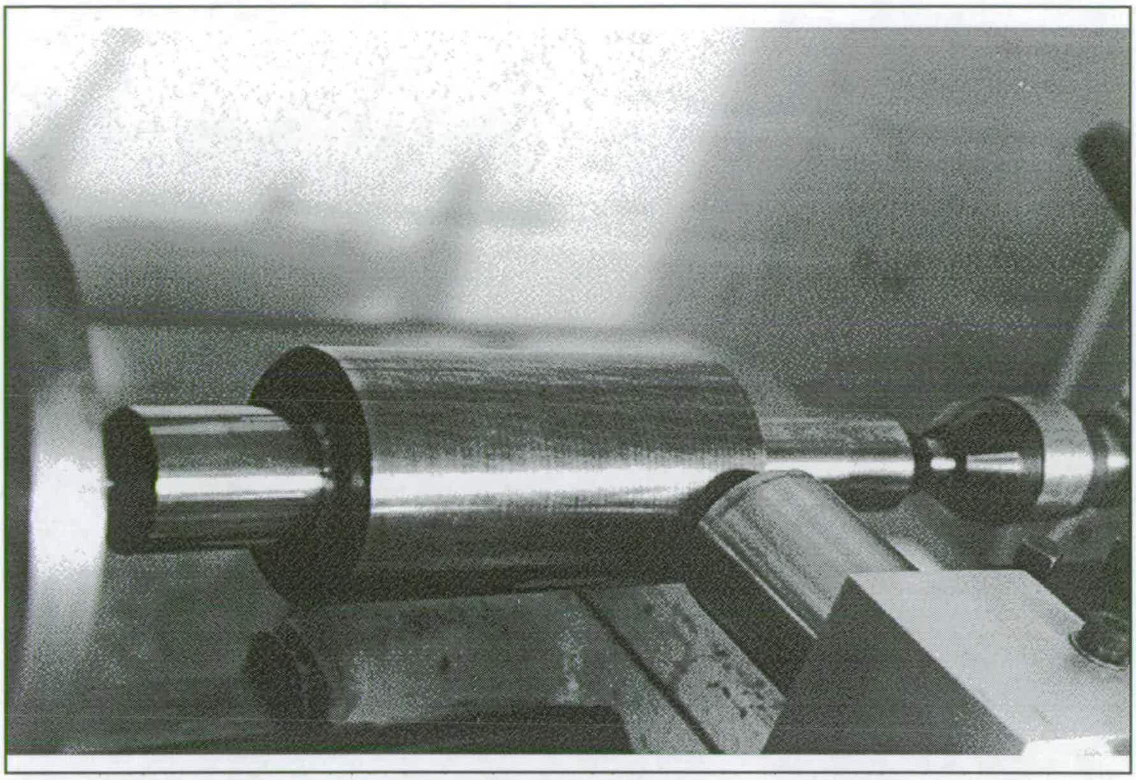


Figure 13 Close up of roller and print head

Concerning the printing it was found possible to get good butting between adjacent revolutions of the helix by adjustment of the print height. It was more difficult to match the registration of the drops so the pattern was continuous along the length of the roll. This was done by fine adjustment of the print speed to match the roller speed. As there was no direct synchronisation between the printer and the roller there could be no compensation for variations of machine speed. Similarly any change of diameter, as would be found in crowned work rolls, could not be accommodated. These problems were more applicable to commercial rolls and would be tackled at a subsequent stage of the work. A final problem with the printing was a discontinuity in the centre of the stroke, as shown in **Figure 14**. It was not certain what caused this but it seems to be a problem with the stroke raster. This determines the voltage to be applied to a particular drop to give it a particular position in the printed stroke. It has to take account of the likely charge levels on adjacent drops and will be optimised to print the installed font with the highest quality possible. The custom logos will have different stroke formations from those in normal use.

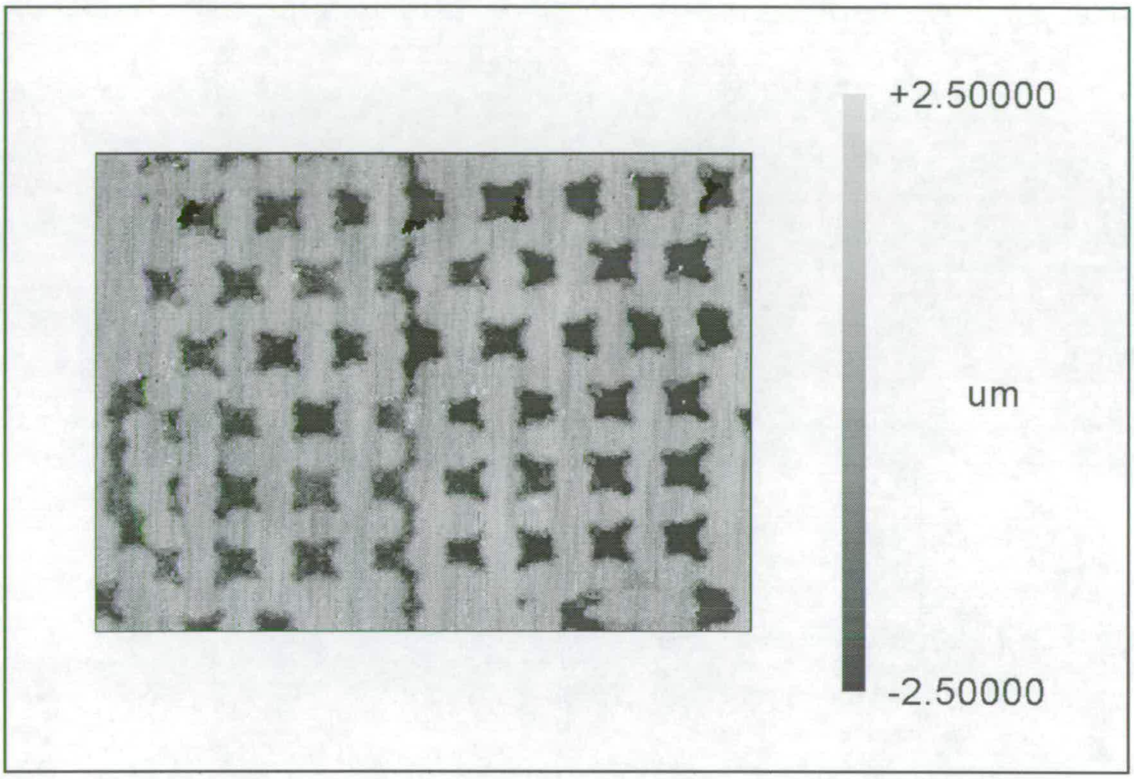


Figure 14 Surface plot of print discontinuity after etching

Two basic dot patterns were generated, one with isolated peaks, the other with isolated valleys, as described before. In addition it was possible to generate more complex patterns so textures containing the corporate logos of the project sponsors, Ford and British Steel, were developed. By printing these reversed on the roller it was possible to roll recognisable logos onto steel strip. An example of a rolled Ford logo is shown in **Figure 15**.

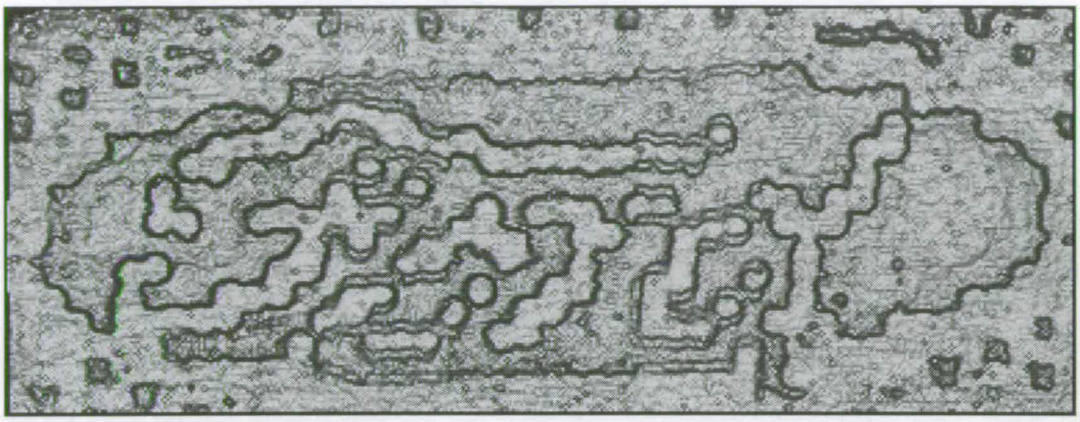


Figure 15 Solid plot of rolled Ford logo

4.6.2 Etching

When designing the new tank the possibility of incorporating rollers from the British Steel 9" Hille mini mill was investigated. Although it would have been possible the costs involved were high, particularly as many components were not standard at that size. As these rollers would only need textured occasionally, if ever, it was decided to etch them on an old lathe well coated in corrosion inhibitor.

The following design factors were considered for the new etch rig.

1. Good control of etchant level
2. Fast removal of etchant after machining
3. In situ rinsing of roller without dilution of etchant

4. Fast removal after rinsing
5. Dedicated rig needing minimum external equipment
6. Minimal exposed metal work
7. Minimal exposed etchant to limit the escape of corrosive vapour

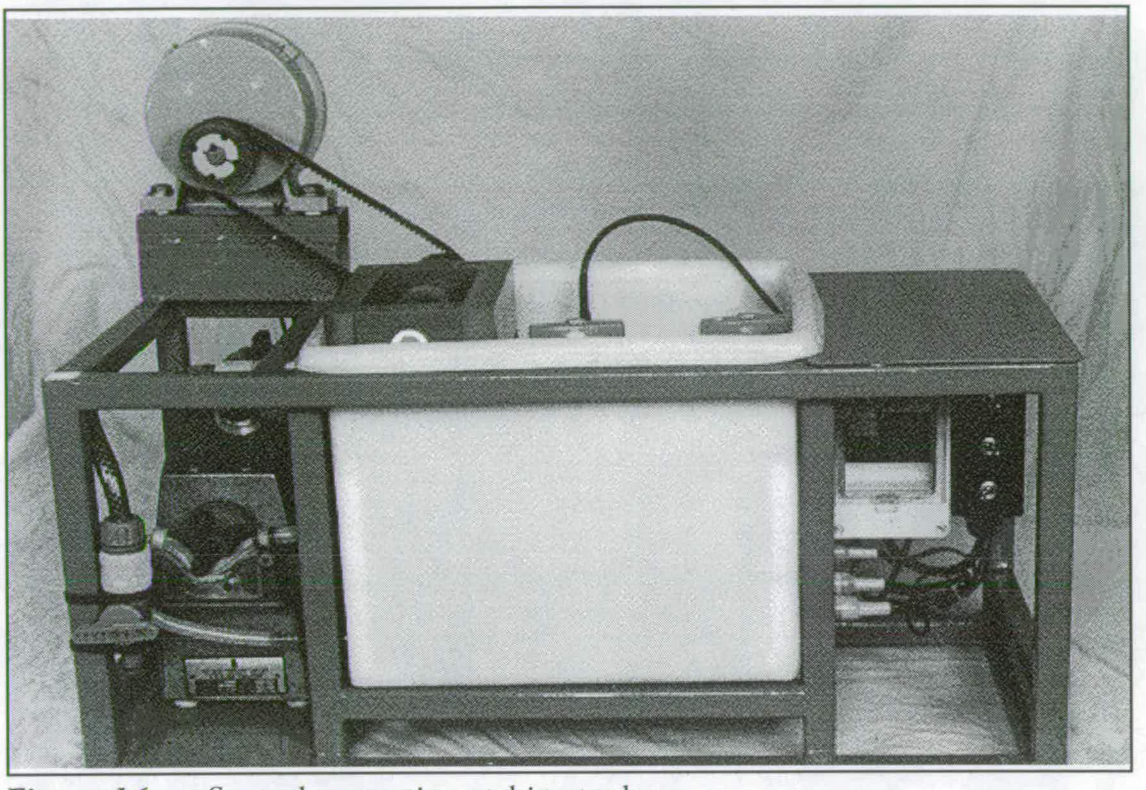


Figure 16 Second generation etching tank

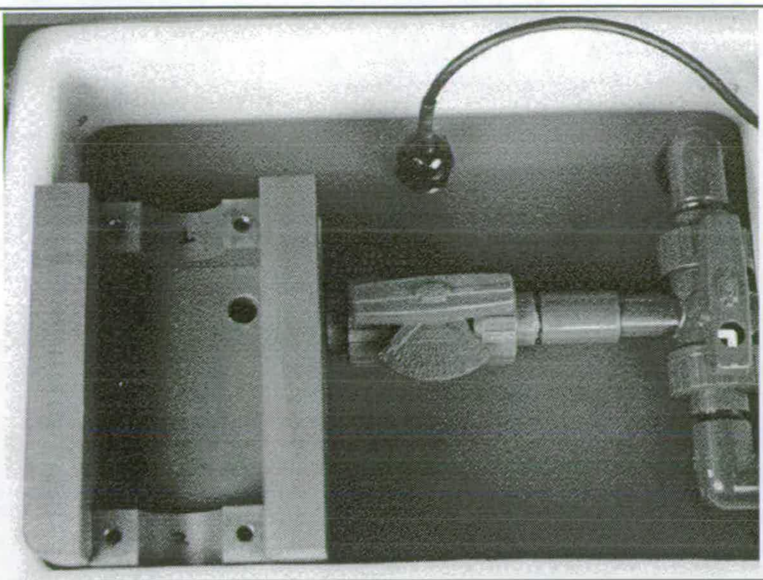


Figure 17 Second generation etch tank: inner sanctum

The final design is shown in **Figure 16** and **Figure 17**. The tank, pump and heating are common to the previous design. A PVC false floor is fitted over the top of the tank supported on pillars going to the base. This contains most of the etchant evaporation and acts as a base for the etching chamber. The roller is mounted in the chamber in Tufnol bushes with PVC clamping blocks to hold them in place. The clamps are secured with stainless steel cap screws, a M8 thread was chosen as its longer pitch requires less turns to remove.

The chamber has two inlets, one attached to the pump, the other via a ball valve to the mains water supply. There is one outlet which goes to a fine metering ball valve. This sets the back pressure in the outlet and thus, with the pump flow rate, enables the level in the chamber to be controlled. The outlet from this goes to a T valve where the etchant can be returned to the tank or the rinse water sent to the drain. The surface area of the chamber has been minimised to restrict evaporation. The chamber floor is designed to be only 5mm below a roller of nominal diameter thus reducing the volume of fluid to be utilised. This enables the chamber to be emptied very quickly when the pump is reversed.

The roller is driven by a geared DC motor via a timing belt. A geared motor was not used because of any high load requirements but because the low drive load means it would be difficult to drive a normal DC motor at low speeds without a closed loop controller. The configuration used meant the only external equipment required is a laboratory power supply.

Operation of the tank is as follows. The roller is fitted with the Tufnol bushes and belt drive wheel then located in the chamber and clamped in place. The motor is connected to the power supply and the roller rotated at the required speed. The pump is switched on and the etchant rises to the required level in the chamber, usually just touching the roller. After the required time the pump is reversed to clear the chamber then switched off. The T valve is set to drain and the rinse water inlet valve is opened. With the roller rinsed the motor and water supplies are turned off. The roll can then be removed for thorough cleaning elsewhere.

4.6.3 Results

The first jeweller's roll was printed using an overlapping helix of isolated peaks to give a pseudo random continuous pattern. This was then etched in the new tank under standard conditions for 90 seconds. The mask resisted the etchant well and a variety of features were measured. Etch depths of 8 μm (± 2 μm) with peak counts of 3 - 4 ppmm were generated as shown in **Figure 18**.

The roller was fitted into the jeweller's mill and strips of annealed last were passed through with a variety of reductions. The texture transferred well with and without lubrication. This was reassuring as some doubts had been raised as to the chances of getting any texture transfer with the mill [79]. This work is also described in [4] and reproduced in appendix B.

A further jeweller's roll was textured to demonstrate the different patterns that it was possible to produce with the technique. This contained sections of isolated peaks, isolated valleys, logos and text. Sheet samples were rolled from this as above. Surface plots of both sheet and roll are shown in **Figure 18** and **Figure 19**. Good uniformity of peak / valley height and spacing can be seen on both roll and sheet. Further measurements are given in appendix B where a very low level of waviness can be seen, comparable to sheet rolled with a ground roller on the same system. This suggested that the waviness present was generated by the grinding of the roller rather than the texturing process. It also appears to be independent of the EDT generated tandem mill texture on the annealed last strip. This can be seen to have an average waviness over three times greater.

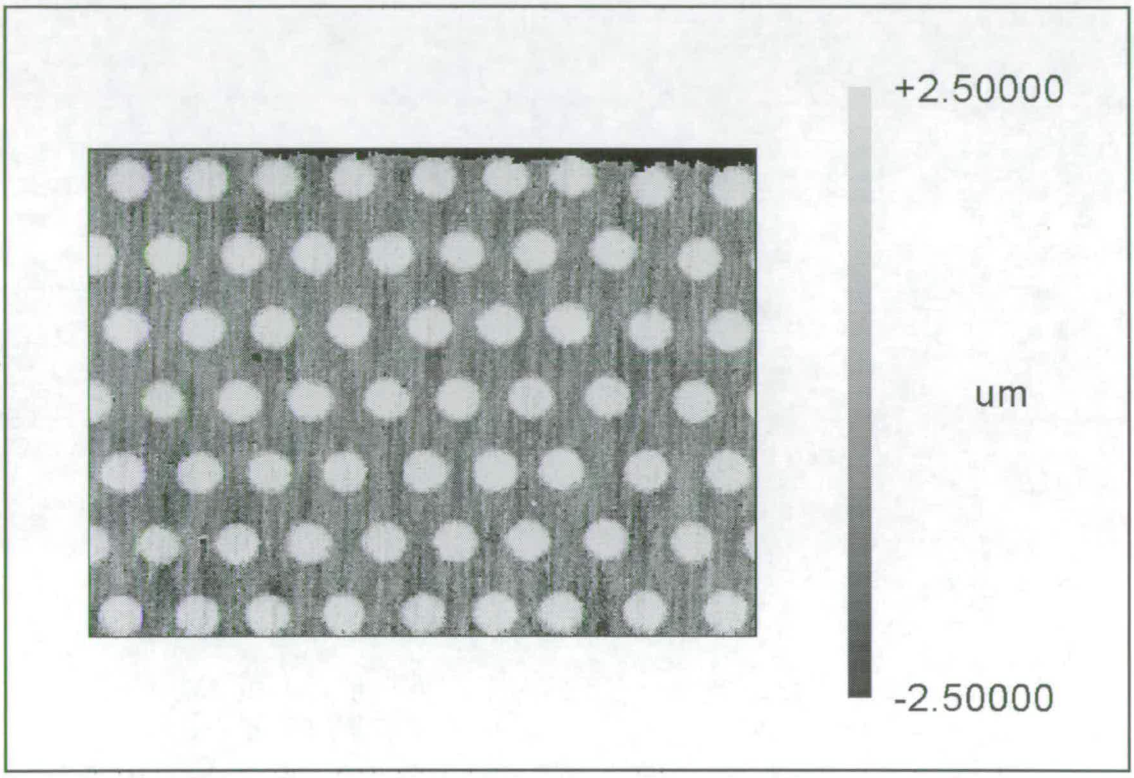


Figure 18 Chemically etched roller with isolated peaks

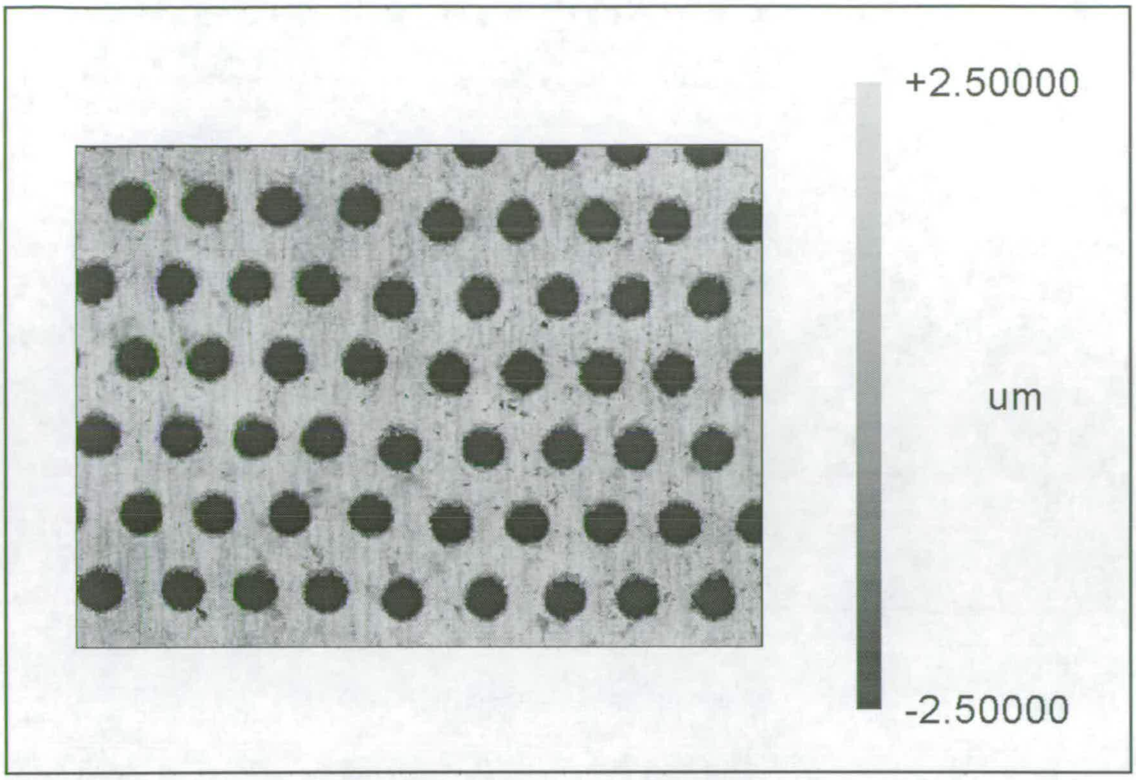


Figure 19 Ink jet textured sheet with isolated valleys

4.7 Chapter Summary

Although the new tank gave uniform etching problems with mask adhesion remained and 90 seconds appeared to be the exposure limit for recently (within 12 hours) printed ink. In addition even where longer etch times were successful it was difficult to obtain etch depths greater than about 10μm. To procede further with the process both printing and etching technologies needed to be reviewed.

5 Electro-Chemical Texturing

The second stage of the project replaced the chemical etching process with an electro-chemical one. This chapter will give an introduction to the electro-chemical texturing research before describing the printing and machining equipment used. The electrochemical experiments will then be described in chapter 6.

The first stage of the project tested the feasibility of the ink masking as a laboratory process. This showed that it was possible to use ink jet masking to apply controlled textures to the surface of a curved object but with certain limitations. The second stage was to assess its potential as a commercial process for texturing mill rolls - a pre-prototype phase in effect. This involved tackling the following problem areas.

Etching

The laboratory-scale rollers were etched by partial immersion in a tank of fluid. Immersion etching is limited by the refresh rate of the fluid at the surface of the roller. One way to improve this would be to apply the etchant as a spray so that the old fluid does not become trapped in the cavities forming on the surface. While this would improve the metal removal rate it would be difficult to etch uniformly along the full length of the roller simultaneously due to the spray distribution. This could be countered by having a spray jet following the print head as it traverses the roller, the overlapping of the fan helping to counter etch rate variations. This would increase the amount of airborne etch vapour and would require complex sealing and cleaning arrangements. Spraying may also increase the problems with the mask failure with a tendency to lift off any poorly adhered ink.

Another method, which may offer ultimate control, is electro-chemical etching. This has faster machining rates than spray etching and etch rates could be controlled by limiting the machining current allowing good control of surface roughness. Further advantages include cheaper, less corrosive chemicals and less disposal costs. This would help to make the texturing process cleaner, cheaper and quicker. The machine would be similar to the conventional printing system shown in **Figure 11** on page 69 but with the tool-post / print head arrangement supplemented by an etching pad as shown in **Figure 20**.

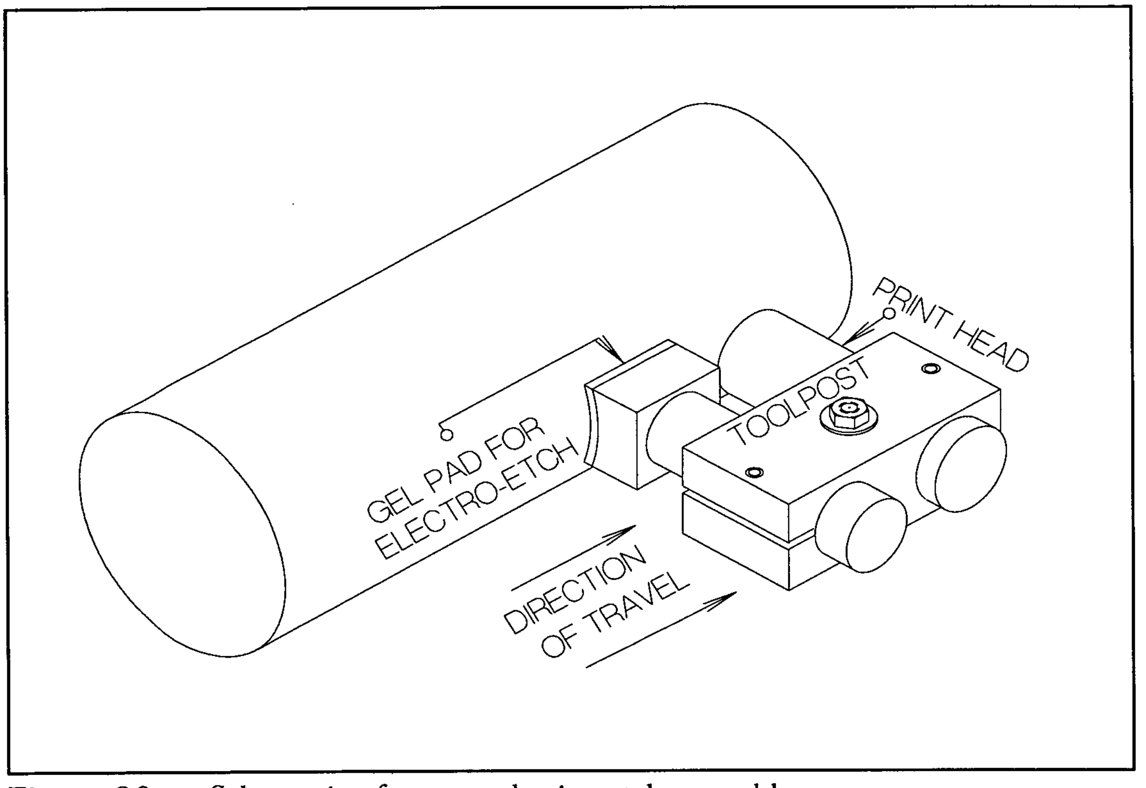


Figure 20 Schematic of proposed print-etch assembly

It was decided to try the electrochemical approach for the second stage of development.

Printing

When the project started the Videojet HR printer was the only high resolution industrial ink jet available and seemed ideally suited to the process. By the end of the first stage the limitations were becoming apparent, particularly the gap in the printing. It was obvious that this would be totally unacceptable on a commercial work roll meaning either it had to be resolved or a different method of printing needed to be sourced. Discussions with Videojet showed little interest in tackling the issue as it is not a problem in their main market, product coding. This meant investigating other options.

Two possibilities were available. Industrial drop on demand print heads were starting to become available with a US manufacturer selling 150 dpi heads and with 400 dpi under development. These printed hot melt inks which would work on non-absorbent substrates. The other alternative was a UK company, Domino Printing Sciences, who were about to launch a high resolution continuous ink jet as a competitor to the Videojet machine. Technical discussions with them suggested that phasing checks could be inhibited allowing continuous printing for a longer period. A willingness to cooperate in the research, and the contribution of a Domino Solo 6 Pinpoint printer were the deciding factors in the choice of this printer for the next stage of the project.

5.1 Mask Printing

5.1.1 General Description

The mask is deposited by a Domino Pinpoint high resolution industrial ink jet printer using a solvent based ink. This has 40μm diameter nozzle and is capable of creating textures with peak counts up to approximately 3.5 peaks/mm. Texture patterns are generated on a personal computer then stored on EPROM for loading into the printer.

5.1.2 Rasters

As mentioned previously the raster is what transforms the continuous stream of ink drops into a line, or stroke, of dots on the printed surface. It sets the number of drops in the stroke as well as their relative spacing. The standard rasters are 7, 14, 16 and 21 printed drops. The printer was shipped with a 21 drop stroke and this was used for the majority of this work. This has had some effect on the quality of the print.

The larger the stroke the greater the difference in flight time between first and last drops. This is due to the increasing path length of the deflected drops and has two main effects. As the solvent is continuously evaporating the greater the deflection of the drop, the higher its viscosity when it hits the surface. This in turn will limit the spread of the drop giving a smaller drop diameter. The second effect is a reduction in print speed. The longer the flight, the greater the influence between charged drops and therefore the more space needs to be inserted between them. This is done by introducing uncharged drops into the matrix. These are not deflected and therefore are not printed but take an equal time to generate and therefore significantly reduce the stroke rate.
A further defect in printing was a reduced gap between drops in the centre of the stroke. This was similar to the problem encountered with the Videojet printer and was thought to be a product of the charge levels in the installed matrix. An improved version of this has since been fitted and shows a significant advance in print quality.

5.1.3 Ink

The Domino Pinpoint machine was supplied with a standard general purpose ink, BK0101. This has a ketone base and is suitable for printing onto most substrates. During experiments three problems were observed.

1. Ink adhesion to substrate

2. Ink breakdown during machining
3. Print quality of drops

5.1.3.1 Adhesion

The most significant factor in the adhesion of the BK0101 ink seems to be the surface cleanliness. Adhesion to an oil contaminated surface is very poor with ink often removable by touch. It was possible to ensure that the substrate is degreased when working with small samples in laboratory conditions but much more difficult on large rollers in a production environment. Stripping the oil film also reduces the surfaces resistance to corrosion. A more corrosive ink has been developed (BK2301) which has a reduced sensitivity to surface contamination but would have required machine modification to test. The standard printer has a gear pump impeller and other wetted parts constructed out of stainless steel. These are attacked by BK2301 and would have needed replacing by coated components at a cost in excess of £1000 for trials to take place. Issues relevant to cleaning are discussed later in this section.

When machining the ink has been observed to lift off at high flow rates and at high current densities. On samples where the ink has survived machining it can usually be removed by touch. It may be that the ink is loosened by the machining process then washed off by the high flows.(It should be noted that the term high flow is relative, being around 1l/min.)

The effect of current may be due to localised heating, abrasion by removed particles, or possibly hydrogen evolution on the surface. Of these heating is likely to be the most significant as the lack of adhesion is also observed in sodium nitrate solutions at low current densities. In this case there is very little machining, the energy going to heat the electrolyte in the gap.

5.1.3.2 Breakdown

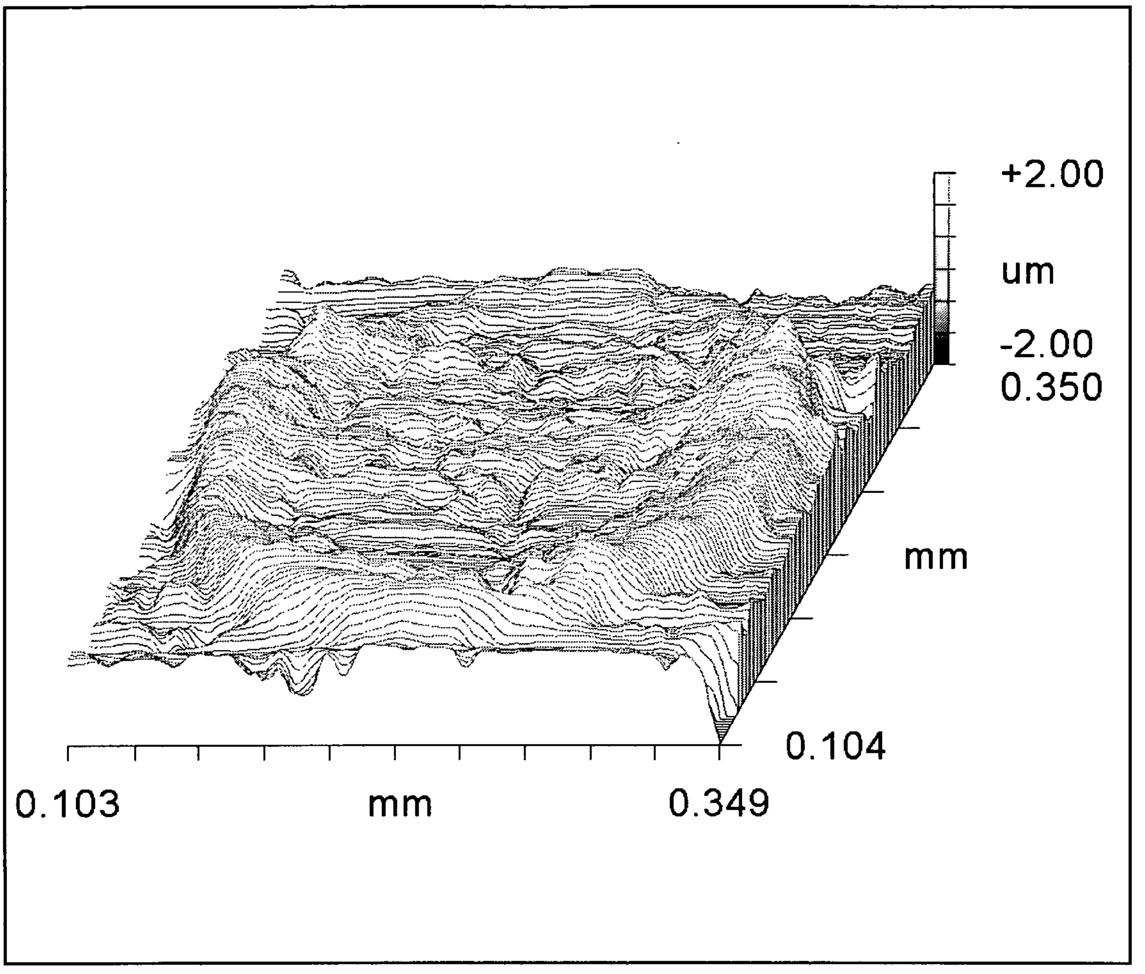


Figure 21 Surface plot of BK0101 ink drop, area 0.35 mm by 0.35 mm

Assuming the ink is adhering to the surface correctly, there will come a point during the machining process when the mask starts to break down. The ink layer in the centre of the dots is thinner due to the drying process on the surface. **Figure 21** shows a drop of BK0101. The ink is approximately 0.3 μm thick in the centre, rising to 0.8 μm towards the perimeter. The coldness of the steel, combined with its lack of absorption, means that the solvent takes a significant time to evaporate. During this period the ink will dry first at the edges where it is thinnest, it will also spread leaving the dried drop consisting of a thick outer rim with a thinner coating in the centre. This central region is an obvious weak point in the mask and is typically observed to be the site at which a well adhered ink layer breaks down. This is shown in section 6.1 in more detail.

A "different" ink type was later delivered and is discussed further at relevant points in section 6.2. The ink, BK0701, is in fact the same formulation as BK0101 but is programmed to be run at a higher viscosity. This reduces the spread of ink on the surface resulting in a smaller diameter drop of more uniform thickness. The only perceived drawback of this is a slightly slower (approximately 1 second) drying time which is unlikely to be a problem at slow surface speeds.

5.1.3.3 Print quality of drops

The uniformity of the printed drops has generally been good. Where there have been problems they have been due to the raster (see section **5.1.2** above) or to deterioration of the ink.

Under normal operation the ink is circulated from a central reservoir. When the conductivity drops more ink is added automatically from a separate cartridge and when viscosity rises a special solvent/ink solution called make-up is introduced. In this way the properties of the ink should remain constant over time. Each time the machine is switched off neat MEK is pumped through the nozzle to clean it. This introduces slight contamination into the reservoir. Further contamination comes from airborne particles and moisture being sucked into the ink return line. Eventually the reservoir will deteriorate and need to be replaced. At this time the ink may show strange effects such as jet instability, poor charge retention and even ovality of printed drops (see **Figure 40** on page 152) but all seem to disappear when the reservoir is changed.

Each reservoir contains an EEPROM which stores information on the operational life and stops the machine when it is time expired. This is based on a production machine in permanent operation and is not accurate when used intermittently in a laboratory environment.

5.1.4 Substrate cleaning

The problem of roller cleanliness is one which will have to be fully addressed for the IJT/ECT process to proceed to an industrial scale. It can be broken down into two distinct areas, degreasing prior to printing and general cleaning after machining.

5.1.4.1 Pre-cleaning

The ink mask will tend to adhere to what ever it is printed onto, be it steel, oil or dirt. If it is steel then there is very little problem, but either of the latter will cause the mask to come away during the machining stage. This can leave blemishes or imperfections machined into the surface of the roller which would then be repeated at regular intervals on the rolled steel sheet. As this is liable to be unacceptable to the end user it is likely that the roll will be rejected and sent for re-grinding and re-texturing. The degree of de-greasing required is not certain but does depend to an extent on the formulation of ink used. The standard Domino ink, BK0101, has been shown to require highly cleaned surfaces for reliable operation but other, more aggressive, formulations are less sensitive to a small amount of surface contamination.

Cleaning the rolls in the laboratory has been a manual process using multiple wipes of lint free tissues soaked in MEK de-greasant. It is time consuming and not suited to automation due to the frequent need to change tissues and to assess when the surface is actually clean. For a commercial application ensuring cleanliness would be difficult over a large work roll. There is also the health and safety concerns of using solvents for cleaning, an issue likely to become increasingly dominant in the future.

5.1.4.2 Post-cleaning

After machining the roller needs to be thoroughly cleaned. Salt solutions must be removed to prevent rapid corrosion of the newly textured surface while ink and loose deposits may cause contamination of the rolled sheet if allowed to remain. This requires a four stage cleaning process.

1. Wipe to remove excess fluids from surface
2. Rinse with water to remove salt residues
3. Wipe with MEK to remove ink
4. Dry to inhibit corrosion

Again, this has all been done manually. After drying, laboratory rollers are removed for inspection and measurement before being coated for storage or being sent for re-grinding. During the Hoogovens pilot mill trials, the rollers were dried with Kimwipes then coated in a thick layer of corrosion inhibitor. The rollers were to be stored for several days before use so corrosion inhibition was particularly important.

As with the pre-cleaning this is a manually intensive operation, dependent on the operator and difficult to automate. It is also heavily dependent on the use of solvent cleaners.

5.1.4.3 Other Cleaning Methods

The problem of surface cleanliness is by no means unique to this application. Within the steel industry it is important prior to coating processes, such as chromium plating. In other industries examples would include injection moulding and printing.

On a visit to a chrome plating shop, a manual system was in use comprising of an electrolytic cleaning tank and a manual wash tank where each roller was scrubbed with a solution of household detergent. As well as cleaning this gives the opportunity for manual inspection of the roll after texturing. Although the system has low capital costs it does have running costs in solutions, power and man-hours as well as involving extra handling of the rolls. It also requires more space on the shop floor. For ECT it would be most applicable after machining where the opportunity for visual inspection would be beneficial, though the time delay between starting machining and cleaning would be a concern, particularly on a large work roll.

A further possibility is laser cleaning. Quantel make a system called the Laserblast which has been used for some time for cleaning buildings and artwork and is now being promoted for industrial applications by Lambda Photometrics. It is non-contact and is claimed to leave the substrate free from damage.

5.1.4.4 Quantel Laserblast

The Laserblast comes as a self contained unit comprising of a pulsed Nd:Yag laser and a fibre-optic beam delivery system. It is available in pulse rates of 25Hz, 50Hz and 100Hz with a fibre length of up to 30m. Prices are £39K and £49K for the 25Hz and 50Hz systems respectively though OEM discounts are available. Alternatively Lambda will supply a kit of laser and associated equipment for approximately half this cost if the fibre delivery and robustness is not so important.

It was arranged for the system to be demonstrated in Edinburgh by Adrian Haxel on 4th July 1996. A heavily oiled 50mm diameter roll was mounted on the lathe for him to attempt to clean. Lambda do not yet have a Laserblast for demonstration purposes so were using a 10Hz Quantel Brilliant laser with a swinging arm delivery system designed for tattoo removal.

A number of problems were noted, most of which may be peculiar to the system being used.

1. At low powers it did not do much to remove the oil and at high intensities damage was observed on the roll surface. This may be connected to poor beam uniformity.
2. The pulse rate of 10Hz was too slow resulting in missed patches each revolution.
3. Contamination quickly built up on the surface of the delivery lens, causing reduced power output. This seemed to be made up of oil vapour coming off the surface and could be limited by the use of an extraction system.
4. It was very difficult to get the surface completely clean due to some of the oil mist from the area being cleaned landing on the areas already treated. Again this would be improved by an extraction system.

Noting the points above it was difficult to assess the outcome of the trial. The system demonstrated was not capable of cleaning the rollers satisfactorily but neither was it truly representative of a Laserblast. Indeed it is possible that the laser demonstrated would have been adequate had it been a higher pulse frequency -25Hz or better - and been combined with a simple vapour extraction system.

The laser was effective at removing dried on deposits and even the smutty residues left by electro-chemical machining at low current densities. It also removed the ink mask very effectively, suggesting that it may also be suitable for cleaning after texturing.

Another approach which may improve the performance would be to combine it with some form of heat source to harden the oil before cleaning. This was discussed with the sales engineer who agreed that it would clean more effectively in such a state. The airborne deposits would then be removed by vacuum extraction. If needed an air knife or similar could be used to clean the any last remains of particulate off the surface immediately prior to printing.

The same setup could be used for post processing of the roller, i.e. cleaning after machining. Here it is a mixture of electrolyte and metallic contaminants that need to be removed. After sucking off most of the liquid the remaining layer could be evaporated to leave the surface suitable for laser cleaning, again with extraction system to remove particulates.

For operation consisting of a printing pass followed by a machining pass the same equipment could be used for both. If a combined printing and etching stage was required then it would be possible to use a Brilliant laser combined with a beam splitter to provide both cleaning beams from a single unit. It would of course also be possible to use two Laserblast units but with a corresponding increase in cost.

In conclusion the possibilities of using the Laserblast seem encouraging but the high cost of the unit makes it essential for a proper trial with a demonstration unit before any commitment to purchase could be made.

5.1.5 Printer Registration

Having established a method of printing reliably the next stage is to print a continuous pattern over the surface of the roller. This section will outline the options for controlling the mask deposition both around the circumference (rotational registration) and along the length (translational registration) of the roller.

5.1.5.1 Rotational registration

When printing the mask round the circumference of the roller it is essential that the lines of drops match from one rotation to the next. That is to say that there should be no phase error between adjacent strips. This means that each revolution must contain an evenly spaced number of dots.

A number of methods were considered for this purpose.

1. Optical Tracking

   An optical, probably reflective, sensor would be used to detect the presence of the dots in the previous strip. It leaves the problem of getting the first strip printed correctly before it can work.

2. Encoder and Wheel

   An incremental encoder attached to a small wheel running on the surface of the roller. The encoder output can go straight into the printer to trigger the print head. By using a wheel we get a fixed number of pulses per millimetre as defined by the wheel circumference and the encoder resolution. This is an advantage in that the number of pulses per revolution increases as the roller diameter increases. The drawback is in determining how many pulses per dot are required to get an exact number of dots around the circumference. This involves knowing the precise circumferences of both roll and wheel, or being able to count the number of pulses in one roll revolution. One possible way of doing this would be to have a cheap low resolution encoder directly coupled to the roller to provide an index pulse.

3. Direct Coupled Encoder

   The incremental encoder is directly coupled to the spindle of the lathe or grinder. This means that the encoder does exactly one revolution per roller revolution, independent of the diameter. This means that the number of pulses per revolution remains constant with the danger of phase errors almost eliminated. The downside is that the dot spacings, and hence peaks per mm, become more and more limited as the roll diameter increases.

From the above discussion the direct coupled encoder seemed to be the most promising approach provided that an encoder could be obtained with a high enough resolution. If not then it may be desirable to employ the encoder and wheel approach with the modification suggested in footnote one.

Encoder Technology

Two types of optical encoder are available, incremental and absolute. Incremental gives a steady stream of pulses as output, thus giving a relative measure of rotation but not an absolute one. Absolute encoders, as the name implies, output the absolute position in the form of a binary word. Although these are available in very high resolutions they usually have a dead zone between 359° and 0°. This makes them unsuitable for this application.

Many incremental encoders have a quadrature disk which is used to indicate the direction of rotation. With suitable use of logic these can be used to give an output on each edge, thus giving four pulses for every line of the encoder. As this also multiplies any errors in the encoder pattern it should be used with caution, but it may well be suitable for this application.

For clarity the true line count of the encoder - without interpolation - will be referred to as the resolution and the interpolated output as pseudo-resolution.

The required resolution will depend on the roller diameter and peak count required. This was calculated for a selection of rollers that may have been used during the project.

Encoder Resolution

It is important to consider at this stage how the printer deals with the encoder. The pinpoint supplies +5 and +12 volt rails for the encoder and has a 12V npn open collector input. When the print-go is enabled one stroke will be printed per encoder pulse. No quadrature decoding is available nor is there a facility to reduce the stroke rate (e.g. printing one stroke every two encoder pulses).

Another consideration is the repeat length of the pattern, its pitch. This is the number of strokes before the dot pattern repeats itself. It could vary between two, for a very simple pattern, up to a hundred or more for complex logo's or text. This shall be defined as a block. The pattern can now be defined in terms of strokes per block (*s/b*), strokes per revolution (*s/rev*) and blocks per revolution (*b/rev*).

$$s/rev = b/rev \cdot s/b$$

To avoid phase errors *b/rev* must be an integer. Encoder resolution can be defined as pulses per revolution (*p/rev*) which leads to the number of pulses per stroke (*p/s*), again an integer.

$$p/s = \frac{p/rev}{b/rev \cdot s/b}$$

This will give valid values of b/rev and thus s/rev. We can then divide the circumference of the roll by the number of strokes and get the physical spacing of the dots in terms of peaks per mm.

Printer Setup

The maximum encoder input frequency is set by the stroke rate of the printer. For a Pinpoint with a 21 dot matrix this is typically 2048 Hz. Note that this is the absolute maximum and has no margin for error. An operating frequency of 90% maximum would be the fastest normally used.

The number of strokes per revolution for the three roll sizes under consideration for trials were calculated. The rollers are detailed below.

1. The Birmingham Stanat-Mann four high mill.
   Roll diameter - 38mm
   Roll circumference - 120mm

2. The Edinburgh jeweller's mill.
   Roll diameter - 51.5mm
   Roll circumference - 160mm

3. The Hoogovens pilot mill, four high configuration.
   Roll diameter - 140mm
   Roll circumference - 440mm

	Birmingham			Edinburgh			Hoogovens		
ppmm	1	3	5	1	3	5	1	3	5
strokes per rev	120	360	600	160	480	800	400	1200	2000
divide for 10K line encoder	83	28	17	62	21	12	25	8	5

Table 3 Encoder divides for different rollers and peak counts

Although the values in (3) are approximate they do show that the printer input frequency would not be a problem when texturing the above rollers. It also suggested that a divide ratio of at least 100:1 would be needed to get any flexibility in the peak count.

If the divide could be done by a proprietary product then that would be the preferred route. If not it would be a fairly easy job to do on a PIC or similar microcontroller. Standard CMOS divide counters tend to have binary divides, i.e. by a factor of two, and would not be much use.

Encoder bandwidth limits on roll speed

As the maximum bandwidth for most encoders is 100KHz for a 6000 line encoder this would give a maximum rotational speed of 16.7 rps or 1000 rpm (300 rpm for 20,000 line). From this we can conclude that the encoder bandwidth is unlikely to be a limiting factor in the maximum texturing speed.

Pinpoint stroke rate limits on roll speed

For a 21 drop stroke the maximum stroke frequency is 2048Hz. From Table 1 the minimum number of strokes per revolution predicted is 120. This would give an absolute maximum roll speed of 1024 rpm. With a factor of safety of two the roll speed would be 500rpm. For a more realistic pattern, e.g. an Edinburgh roller with 3 dpmm, the maximum speed , without factor of safety, becomes 256 (128 rpm with FOS).

This suggested that the Pinpoint would be the limiting factor on printing speed, particularly with large diameter rollers.

5.1.5.2 Translation registration

The purpose of the translation stage was to ensure perfect matching of the pattern from one revolution to the next. It had to be possible to vary the feed of the stage to take into account different print stroke widths, and different lathe speeds. Two possible modes of operation were envisaged.

1. Continuous print (Velocity control)

   In this situation the stage will travel at a constant rate, thus printing a helix on the surface of the roll. This will be the quickest method of printing the mask as there will be no delay in the process. The down side is that the texture will have a definite slant to it, caused by the helix. This will be quite pronounced on small rollers, e.g. 25mm diameter, but less obvious on large rolls, e.g. 300mm diameter. It would require a two axis servo-controller with a software gearbox facility. The printer would be required to operate without phasing for the duration of the printing. This may give problems on larger rollers.

2. Step and print (position control)

   With this method the stage would be stationary while one strip was printed. During the next revolution the stage is repositioned for the next strip, which is then printed on the subsequent revolution. It would be slower than continuous printing, but would remove the problem of slant. This increased time would also increase the etch time for combined print-etch operations. As any phasing checks could be done during repositioning this method would be less demanding on the printer. An indexing pulse would also be required to trigger the printer at the start of each revolution.

The simplest of these to implement would probably be mode 1, but mode 2 may be the more desirable in terms of functionality. While press performance is unlikely to be seriously compromised by the slant it may be that its directionality will be visible through the painted finish. It would be interesting to evaluate both techniques to determine what, if any, variation there is in the performance of the finished product but that is beyond the scope of this work.

A translation system which allowed both modes of operation was desirable.

Translation Systems

Two types of system were under consideration.

1. Machine Based

   This means utilising the existing traversing mechanism on the lathe or grinder. This is quick to set up and is available for no extra cost. It is limited by the accuracy of the machine, the pitches available and would require an involved process of recalibration each time the peak count was changed or the equipment was installed on a new machine. It is also restricted to operational mode 1.

2. Retro-fit

   The existing traverse mechanism is ignored and a linear translation stage is fitted to the machine bed to take the texturing head. Although taking longer to install initially the ability to control the feed rate in software, with synchronisation to the roller rotation via the encoder, will mean that setting the print pitch can be done quickly and without adjustment to the peak count. Peak count could be accurately set by programming the pitch to be the product of required count and number of dots in stroke. The accuracy is no longer dependent on the machine (which may be long overdue for retirement!). It is easier to upgrade if required and is capable of operating in both modes (depending on controller).

Although system 1 may provide an economical solution for industrial use, the flexibility of system 2 makes it the preferred choice for an experimental machine.

Translation length

The stage must be at least as long as the longest rolling face to be textured plus enough length for the texturing head to run over at both ends. If we say that the longest face will be 300 mm and the texture head is 100mm this gives a minimum requirement of 500mm. Too long a stage should be avoided as it will cost more and may give fitting problems on smaller machines.

Positional accuracy

If the tightest pattern was to be 5 dots per mm then, assuming the dot size to be 100μm, the space between dots will be 100μm. If a 10% error is acceptable then the stage should be accurate to 10μm. Note that as the stage will only be travelling in one direction while printing, backlash should not be a problem. The only exception to this would be with position control if there was any overshoot, and even that could be avoided with increased damping.

5.1.5.3 Practical Implementation

The following system was used. Rotational registration comes from a 5,000 ppr quadrature encoder with marker pulse (Hohner Automation). This is directly coupled to the spindle of the lathe as shown in **Figure 22**. The encoder signals go into a proprietary interface card. This has quadrature decoding, giving a pseudo-resolution of 20,000 ppr, and a count down divider. Output is divided by a factor of between 1 and 100, set by thumb wheel switches on the front panel. This enables the required peak count to be set to within the resolution of the encoder. The output of the interface card is buffered and then passed directly to the servo controller and, via opto isolators, to the printer encoder input.

The linear actuator is a DC linear motor made by Linear Drives Ltd. Position feedback comes from a Renishaw linear encoder strip mounted along the length of the actuator. This is an incremental encoder with 5 μm resolution. The servo controller is a Quin Ratio_er. This is designed for use as a software gearbox but is also fully programable for mode 2 operation. Parameters are easily down loaded from a PC via an RS-232 interface although it can also be run from the front panel.

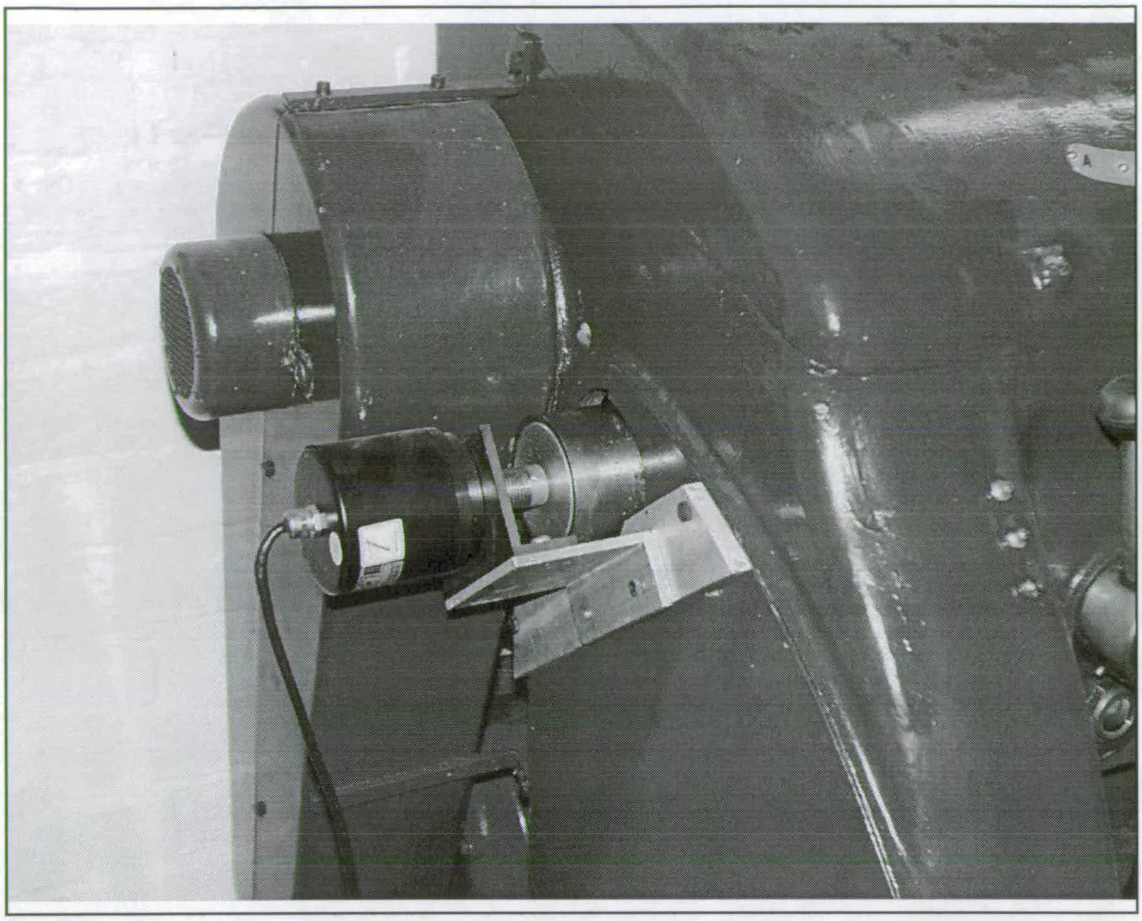


Figure 22 Encoder mounting on lathe

5.1.6 Print height sensitivity

The ability of the translation system to print a well registered pattern depends on the uniformity of the height of the printed strokes. This is dependent on the following factors.

1. Drop charge voltage

   Deflection is proportional to the charge applied to the drop.

2. Deflection plate voltage

Deflection is also proportional to the potential of the high voltage deflector plates.

3. Ink pressure

   The higher the ink pressure the faster the drop velocity will be and the lower the drop deflection will be.

4. Print gap

   As the gap between print head and substrate increases so does the spacing between drops and therefore the stroke height.

Items one to three are controlled directly by the machine or the operator but should have negligible variation over one print run. Item four is dependent on the head setup and could conceivably change while printing. This may be due to variations in roll diameter, as with a crowned work roll, eccentricity of the work on the lathe or misalignment of the actuator relative to the axis of rotation. Variations in flatness or straightness along the length of the actuator would also have this effect.

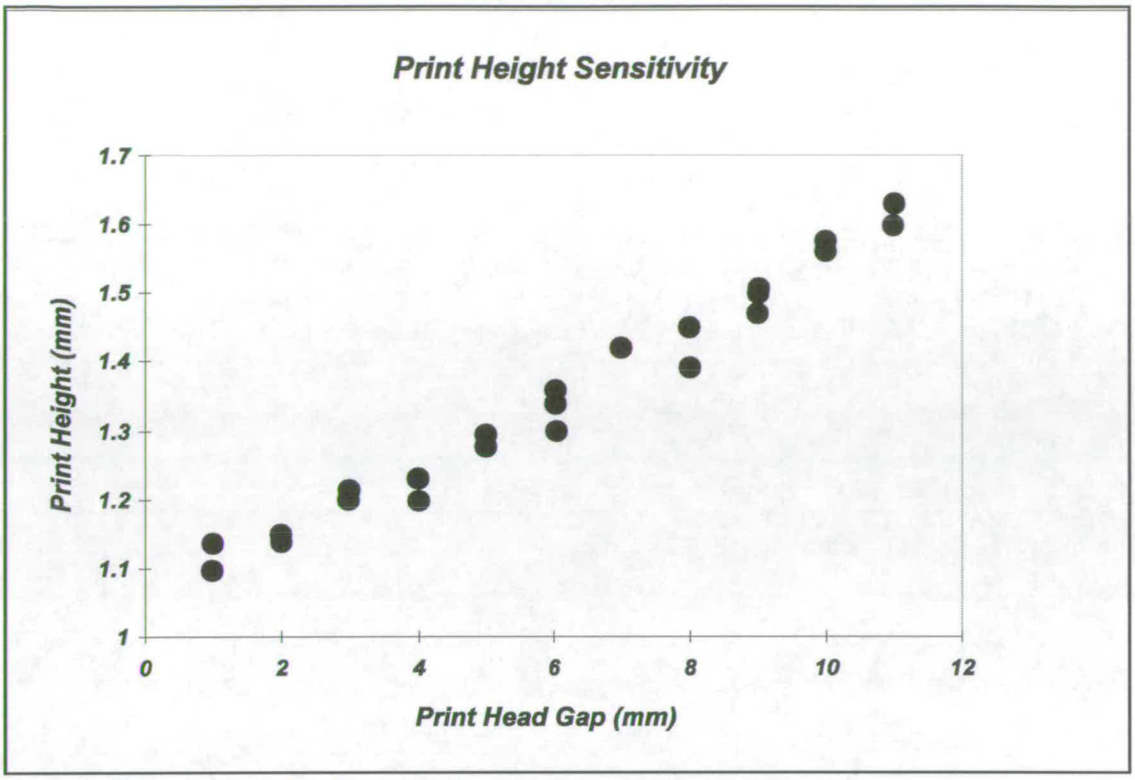


Figure 23 Print height sensitivity

An experiment was set up to quantify this variation. The print head was held a fixed height above a steel sheet with the gap set by gauge blocks between head and sheet. Ink pressure and print height were set to the middle of their normal operating ranges. At each height three strokes of dots were printed, each being a ! character seven drops high. The height of the strokes were measured on the Zygo Newview and are plotted in **Figure 23**. Note that only two data points are shown at some heights. This was due to triggering difficulties during the experiment.

The print height can be seen to increase almost linearly with gap width although the gradient seems less at low gaps. This may be explained by the drop trajectory but may also be due to increased relative errors at this level.

Selection of gap height is a complex issue. Although it may seem sensible to have a minimal gap this requires using a much higher charge level to get the required drop spacing. This in turn increases the likelihood of charge interaction between adjacent drops in the stroke. It also reduces the flight time allowing less solvent evaporation and therefore larger drops on the surface. Conversely a large gap will increase the chance of air disturbance affecting the drop trajectory and printed quality.

For most printing a nominal gap of 3.5 mm was used. This seemed to give the most reliable printing.

5.2 Machining Equipment

5.2.1 General description

The machining equipment consists of power supply, electrolyte supply and control circuits housed in a standard 19" rack cabinet as shown in **Figure 24** and **Figure 25**.

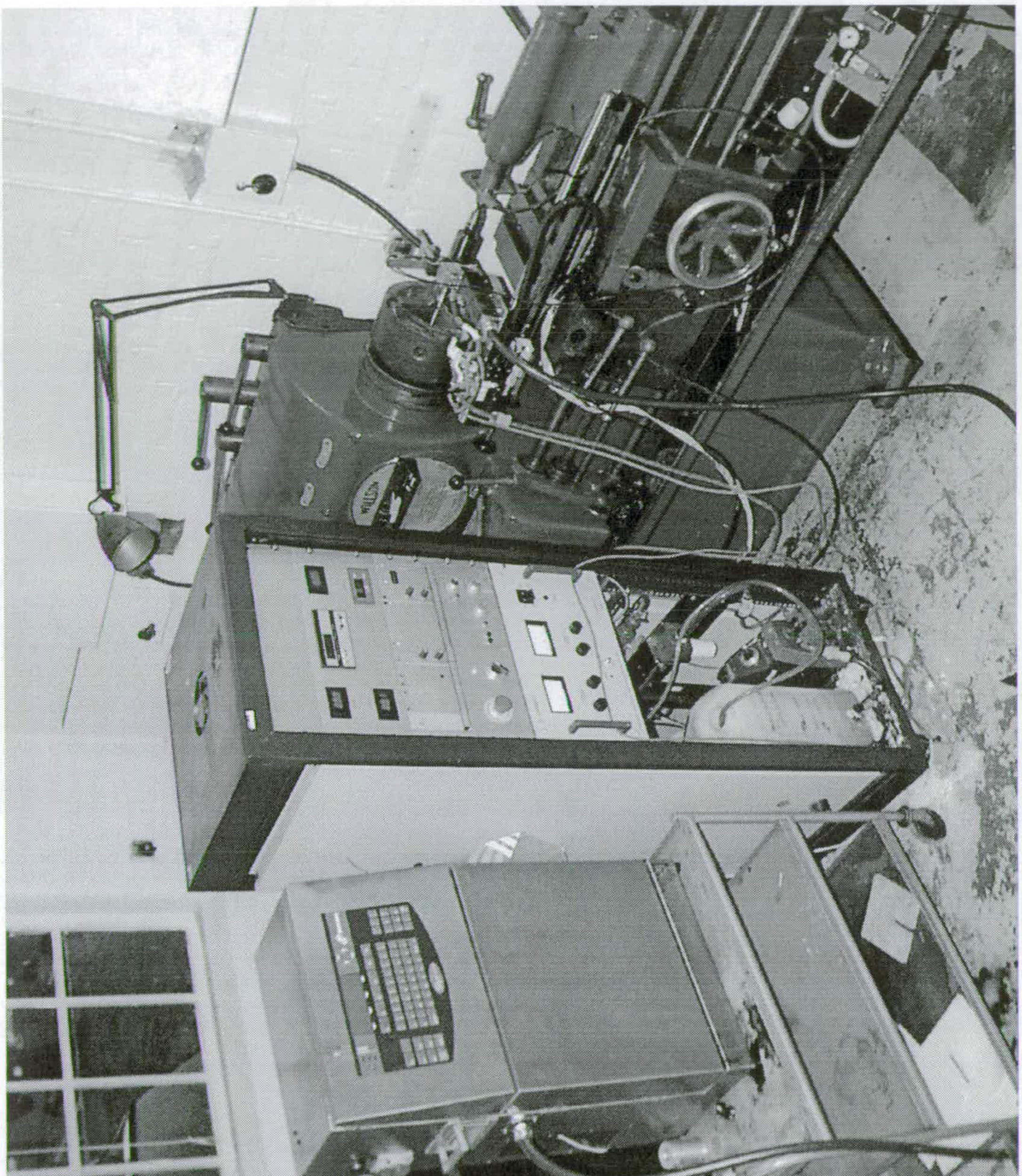


Figure 24 Front view of electro-chemical texturing

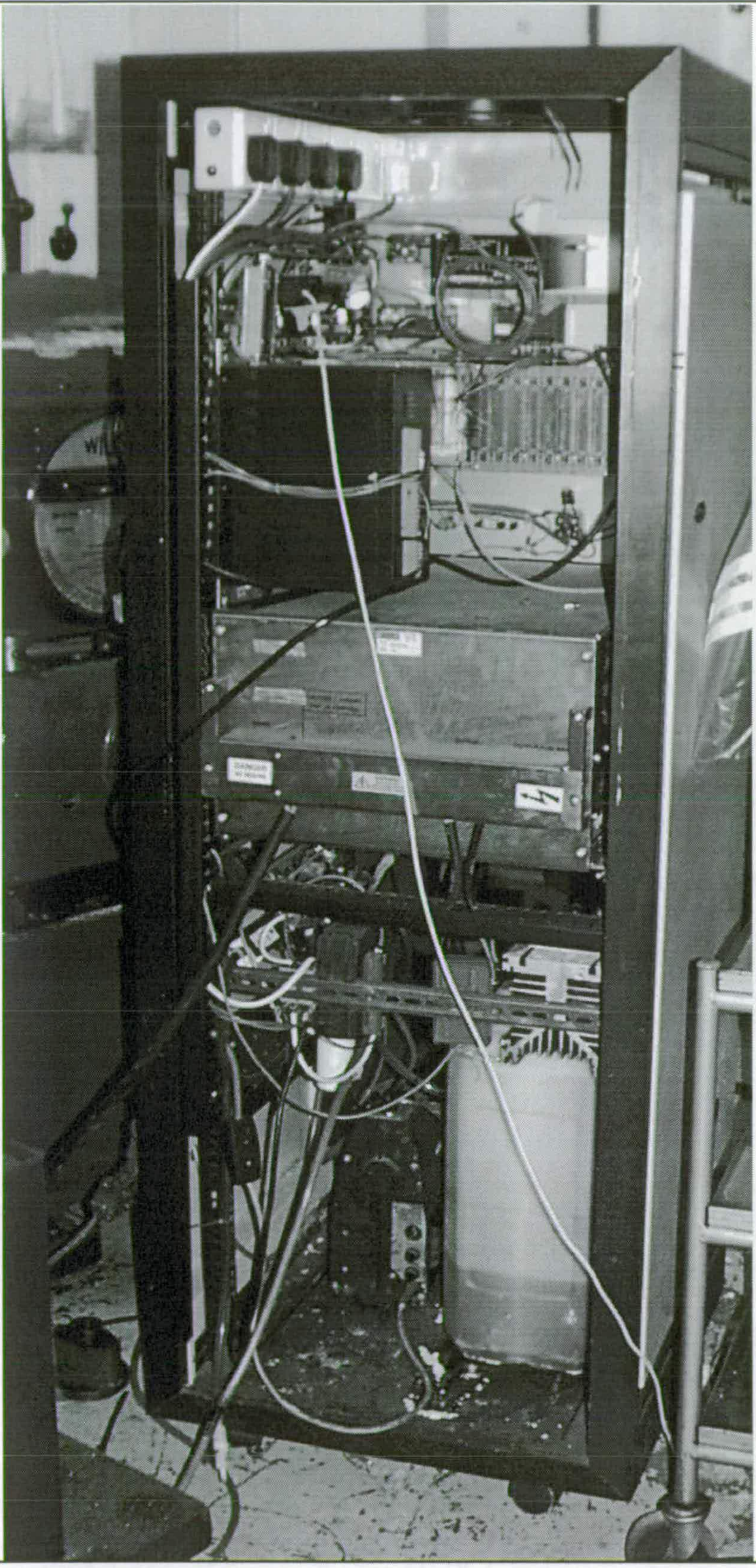


Figure 25 Rear view of electro-chemical texturing unit

The electrolyte is contained in a 25 litre canister in the base of the cabinet, allowing for fast and economical changes of solution. This is fed, via a self-priming stainless steel centrifugal pump through an in line filter to remove contaminants then through a fine metering valve, a flow transducer, pressure transducer and solenoid valve before leaving the cabinet to go to the machining head. The used fluid is returned to the canister assisted by a small centrifugal pump in the return line. Flow is switched on and of by a button on the front panel which activates the solenoid valve.

The machining power supply is a Farnell H30/100. This can operate as constant current or constant voltage, is short circuit protected and can output up to 100A at 30V. For ease of switching the output is wired through a power MOSFET module which is controlled by a switch on the front panel. This can be pulsed at frequencies from D.C. through to 1KHz with duty cycles from 10% through to 90%. The pulse generator is microcontroller based and is mounted in the main electronics rack. The electrode gap is monitored by a LVDT connected to a conditioning unit and panel meter in the control rack. The electronics rack also contains conditioning for the encoder and transducers. Current, voltage, flow rate, pressure and gap height are displayed on the instrument panel.

The servo controller and drive amplifier are also housed within the cabinet with connections going to the translation stage on the lathe.

The individual components will now be described in more detail.

5.2.2 Electrolyte circuit

This describes the general electrolyte storage, dispense and return circuits for the electrochemical texturing unit . All equipment is housed in the 19" rack cabinet with the power supplies and instrumentation. All fittings were chosen to be compatible with 15% NaCl solution. Although corrosive this presented significantly fewer problems than ferric chloride as stainless steel could be used.

5.2.2.1 Reservoir

The electrolyte is stored in a 25 litre "jerican" container. This fits into the base of the rack unit to enable quick and easy changes of solutions. Fluid outlet comes from a tap (with short hose and quick connect coupling) just above the base of the canister, thus giving room for settlement of sediment in the bottom. The fluid return is through the top of the can.

Level is monitored by a float switch (normally open, so closes on float rise). If the level drops (e.g. a leak prevents fluid returning to the tank) the switch will open, cutting the supply to a relay coil (N/O). This breaks the a.c. supply to the pumps to prevent them running dry.

To change electrolyte the old canister is disconnected and removed. A new canister of clean water is then connected and pumped through to flush the system. This can be repeated as required until the system is clean. Finally the rinse water is removed and the new can of electrolyte installed. This enables solutions to be made up and disposed of away from the equipment.

5.2.2.2 Fluid Supply

The fluid is drawn from the canister by the supply pump. This was originally a stainless steel self priming centrifugal pump controlled by a hydrostat (pressure switch). The fluid is then pumped through an inline cartridge filter, to protect the valves and transducers from contamination, before reaching a fine metering valve. This control valve is used to set the flow rate to the tool. After the control valve the electrolyte passes through a flow transducer, pressure transducer and solenoid valve before leaving the cabinet, through quick connect fittings to go to the machining head.

With the solenoid valve closed the system pressure rises until the trip pressure of the hydrostat is reach. This then switches off the pump. When the solenoid is opened, activated by a button on the front panel, the pressure drops and the pump is switched on again.

The supply pump was specified for predicted flow rates in the range of one to two litres per minute. This was considered too high for a peristaltic pump, resulting in the choice of the centrifugal pump. Experimental work has since shown that the optimum flow rate for the electrode configurations used is around 0.2 l/min. The original configuration was unsuited to this with the pump being continually cycled by the hydrostat. The solution was to replace it with the peristaltic pump from the chemical machining rig.

It was thought that this pump could be used to control the flow rate directly but at low flow rates the supply ripple was significant. When machining under flow limited conditions these fluctuations also caused variation in machining current and therefore etch rate. This was countered by running the pump at full speed and controlling flow rate via the metering valve, as before.

Used fluid is returned to the tank via the fluid return line. This pipe connects the electrode or collection tray, depending on configuration, to the canister through an in line assist pump. This was originally a small centrifugal pump which needed to be primed before each operation. When used with a collection tank it worked reasonably well but performance was unsatisfactory when used with a "sealed" electrode. This was due to air being sucked into the return line and de-priming the pump. Again this was eventually solved by replacing it with a peristaltic pump. An additional advantage is that no priming is required as air can be pumped to create the initial vacuum in the return line. As with the fluid out circuit connections to the cabinet are through quick release couplings.

5.2.3 Machining power supply

This is at the core of the texturing unit. The main component is a 30V 100A power supply (Farnell H30/100). Although this is a high power rack mounting unit it is functionally very similar to a bench top supply. It can operate as constant voltage or constant current and the current limiting facility gives good protection in the event of an electrode short circuit. The supply uses a separate single phase connection (230V 32A) to minimise any effects of supply loading to the rest of the unit.

The output is switched by a high current power MOSFET transistor (IRFK4H100). Originally this was driven directly from a button on the front panel but it was later adapted to facilitate supply pulsing.

5.2.3.1 Pulsed machining

The first machining done was D.C. constant current at low current densities (0.5 - 50 A/cm2). There were a number of reasons why higher current densities were desirable.

1. Passivating electrolytes will reduce the risk of corrosion of the work after machining by leaving an inert film on the surface, thereby simplifying the cleaning process. Experiments with sodium nitrate showed very little machining below about 30A/cm^2, with the energy being dissipated instead through boiling in the gap. This has been verified by existing work which reports very low current efficiencies at low current densities. To counter this higher current densities are required.

2. Although sodium chloride solution will machine at very low current densities the surface finish of the machined part improves with increasing current density. A higher potential across the gap will reduce the effect of different anode potentials on the surface. This would reduce the effect of any preferential machining, along grain boundaries for example, which may affect the wear of the surface.

Unfortunately machining at high current densities had a number of problems. Some of these are common to electro-chemical machining in general while others were specific to this application.

1. Increased current density requires a corresponding increase in flow rate to clear the contaminated electrolyte from the gap. Ink adhesion was been seen to deteriorate significantly at high flow rates.
2. The increased machining rate increases the gap temperature which again causes problems with adhesion.
3. The machining rate may in fact be greater than required leaving too deep a texture on the roller surface.

All these points could be addressed by using a high current pulsed supply. The advantages of high current densities could be achieved but at lower power levels, thus reducing heating (this is particularly true of the passivating solutions where the increased current efficiency will also reduce the heating) and machining rate. It also meant lower flow rates could be used as the electrolyte has time to clear the gap between pulses.

An additional application of pulsing would be to use the duty cycle to vary the machining rate while keeping other factors constant.

5.2.3.2 Pulse Generator

It was decided to drive the output switch directly from a pulse generator unit. This was required to have two modes of operation. Firstly as a free running pulse generator for continuous operation but also as a single shot timer capable of generating a single pulse of known duration. The user would select the period, duty cycle and mode of operation from the front panel. The low frequencies required limited the range of technologies available. Conventional analogue timers require very large capacitors at low frequencies making them quite inaccurate while a digital timer requires a high clock rate for the higher frequencies and therefore a large divide on the clock to generate the low frequencies. It was also desired to have the unit integrated into the main electronics rack with an opto isolated output driving the switch directly. No suitable commercial pulse unit could be found so it was decided to design and build a board specially.

The final solution was based on an 8 bit microcontroller, the PIC16C61, made by Arizona Microchip. The user inputs came from BCD switches with timings generated from the controllers internal 1MHz clock. It was decided to restrict the available duty and frequency ranges to minimise variation the between experiments. Frequencies available are D.C., 0.1, 1, 10, 100 and 1000Hz with duties of 10, 20, 30, 40, 50, 60, 70, 80, and 90%.

5.2.4 Electronics rack

Most of the custom control and interface circuits are housed within the electronics rack which can be seen in **Figure 24**. All circuits were designed and built personally unless otherwise stated.

The panels, from left to right, are as follows.

1. Logic level power supply.

This is a mains input rack mounting power supply with the following outputs. 5V@ 5A, +12V@ 0.6A, -12V@ 0.6A. These are used as the main supply rails for circuits in the rack.

2. Power bus interface

A passive card which connects the outputs from 1 to the correct rails of rack backplane.

3. Instrumentation supplies

This has three isolated D.C.-D.C. converters each with a front panel status indicator. These provide floating 5V supplies for the flow rate, current and voltage panel meters.

4. Current transducer board

This has an isolated 5V-±15V D.C.-D.C. converter to provide the necessary power for the hall effect machining current transducer.

5. Flow sensor board

Provides the conditioning for the flow sensor. Based on the common 2917 frequency to voltage converter, a ten turn potentiometer is provided on the front panel for ease of calibration.

6. Pulse generator

Described in detail above, the front panel has rotary switches for frequency and duty selection and four status indicating LEDs.

7. Blanking plate

8. Glue board

This interfaces the rotary encoder marker pulse to the servo controller and the printer. Used when printing in step-print mode it enables the number of revolutions between steps or prints to be set independently, while ensuring that both operations are not enabled simultaneously. The printer go pulse is ANDed to the operators print-on switch and stretched to ensure reliable triggering.

9. Encoder board

   This panel hides two boards. The Hohner Automation encoder card is described elsewhere. The other card takes the divided encoder output and interfaces it to the printer and servo controller through high speed opto isolators.

5.2.5 Instrumentation

The following machining parameters are measured and displayed on the unit's display panel. In addition the H30/100 power supply has analogue voltage and current meters.

Machining current

This is measured by a hall effect transducer. This has a current range of 0 - 200A and a frequency range of D.C. - 100KHz. The D.C. current is displayed on a 3.5 digit panel meter.

Machining voltage

This is measured by a 3.5 digit voltmeter connected directly across the output terminals. Its range is 0 - 200V.

Pressure

An in line 0-10 Bar pressure gauge is connected to a panel mounted indicator .

Flow rate

A pelton wheel type flow meter giving a pulsed output proportional to the flow rate. This is converted to voltage by a 2917 integrated circuit and displayed on a 3.5 digit voltmeter. Range is 0 - 20 l/min.

Electrode gap

This is measured by a LVDT type transducer (RDP D5 100AGE). It has a range of $\pm$5mm and resolution of 1μm. This is connected to a panel mounted indicator (RDP E309) which also has a 100Hz analogue output for subsequent data logging if required.

5.3 Chapter Summary

This chapter has described the equipment designed for the electro-chemical texturing experiments. It should be emphasised that not all aspects of the design were in existence for all experiments. In common with most experimental apparatus the equipment has evolved through the course of the project to its final form. Those changes have had a significant effect on the research are described at the relevant point in the experimental section, chapter 6.

The section on printing has described many of the significant challenges faced when trying to use an industrial ink jet, designed to print a single line of text, to print a continuous pattern over a roller 300 mm wide. The issues of print registration are core to the success of this project. The effectiveness of the solution proposed here will be described in subsequent chapters.

6 Electro-Chemical Texturing Experiments

This chapter will describe the second stage of the experimental work, the electro-chemical texturing. The results from this work will be discussed fully in chapter 7. Initial experiments were conducted on flat sheets in an attempt to remove some of the variables involved in the roller experiments. These results led to the design of the electrode arrangement used for the rollers. The flat sheet experiments also gave a valuable insight into the breakdown of the ink layer and the factors contributing to it.

The roller experiments section begins with a description of the equipment used specifically for this stage of the work. Primarily this concerns the electrodes and holding mechanisms, the rollers and the lathes used to mount the equipment. The main roller experiments form the basis for the concept evaluation. One of the main challenges of this stage of the research was the isolation and subsequent control of those factors which created the waviness on the textured roller. During these experiments four pairs of rollers were textured for a pilot mill at Hoogovens Stahl in Ijmueden, Holland. This has provided data on roll wear and texture transfer as well as samples of rolled sheet. The rolling trials will be described in the final section of this chapter.

6.1 Flat Sheet Experiments

Having described the equipment used experimental results will now be presented. The previous sections describe the final evolution of the system. Early experiments will not have used all these components.

6.1.1 Introduction

Although the process has been designed for mounting on a lathe or similar machine for the texturing of rollers this had some disadvantages from an experimental viewpoint.

1. The rollers are made from EN31 bearing steel, hardened and ground. They are time consuming to prepare and expense prohibits the production of large numbers of them. This means time is lost while rollers are being reground.
2. The sealing required round the roller to protect the lathe from electrolyte increases the time required to change specimens.
3. The range of low speeds on the lathe is limited to 45 or 60 rpm.

Because of this it was decided to perform the initial experiments on a CNC milling machine using flat steel sheet instead of rollers.

6.1.2 General equipment

A rigid plastic tank was mounted on the bed of a Bridgeport Series 1 CNC mill as shown in **Figure 26**. Within this the steel sheet sample was clamped to a fly cut aluminium false floor. The sample was clamped along both long edges to minimise any form errors due to sheet bending (coil set etc.). These clamps were also used to make the anode connection. Fixed length PVC spacers between the floor and the bed ensured that the sheet was parallel to the mill. This was important to maintain constant stroke height while printing as explained in section 5.1.6. The PVC spacers also provided electrical isolation from the bed of the mill.

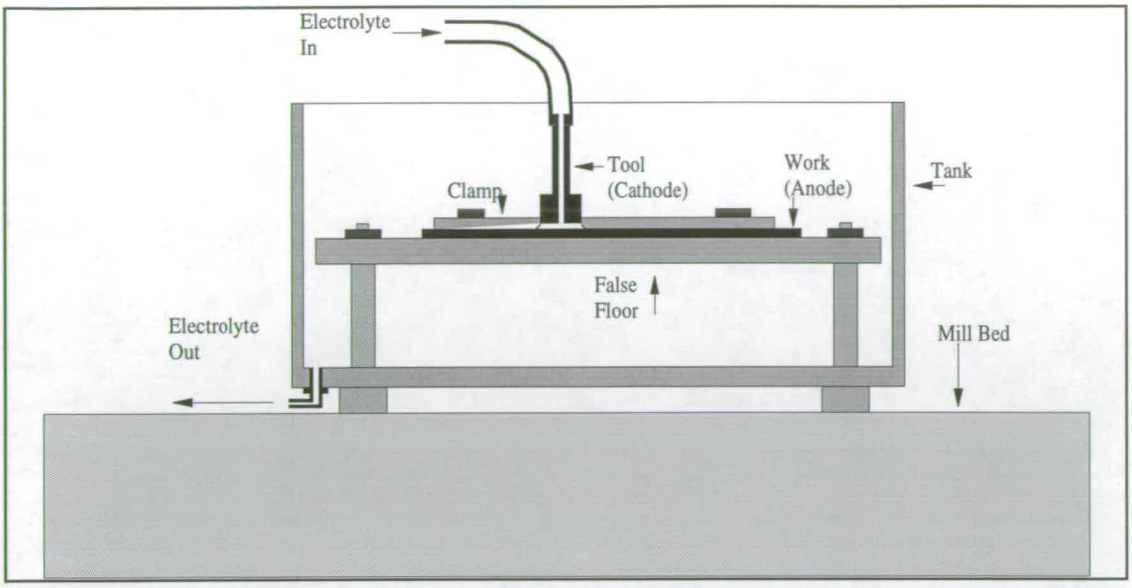


Figure 26 Schematic of machining tank on milling machine

The used electrolyte was free to flow over the surface of the sheet and then drained through the false floor to accumulate in the base of the tank. From there a drain fitting in the base connects the fluid to the return line.

The machine was programmed to traverse a fixed distance in X at a fixed speed. It then returned at rapid speed, incremented in Y and repeated for a predetermined number of cycles. This method was used for both printing and machining.

6.1.2.1 Printing

The printer was connected to the head of the mill and then adjusted to ensure coplanarity between the head and the sample. The print-go signal was generated by the mill bed starting to traverse in X, initially by a micro switch. After the first printing experiments it appeared that the micro switch was not repeatable enough to trigger the printer, resulting in misalignment between strips of up to three strokes. It was unclear why this should be but was possibly caused by deflection of the switch or by speed variations as the bed starts to move. An optical switch and vane system was installed to counter these effects. Being non-contact there would be no mechanical deflection and it was positioned at a point where the mill would be up to speed. This did appear to improve the registration but did not remove the problem. Engineers at Domino could offer no other suggestions so, as this was not fundamental to the flat sheet experiments, it was decided to live with the problem.

Another problem was caused by lack of flatness of the sheet. This was 0.8 mm aluminium killed (AK) steel supplied by British Steel Strip Products (BSSP), cut and ground into coupons before delivery. They seemed to have noticable coil set and, when clamped, a scan using the gap displacement transducers showed flatness errors of up to 1 mm over the central printed section. As mentioned elsewhere this caused errors in the print height.

Due to these problems it was not possible to assess the best attainable print quality. It was still possible to assess the more functional aspects of the masking, those connected to the machining process.

6.1.2.2 Machining

The same arrangement was used for the machining with the feed in Y set to ensure overlapping of adjacent passes. The power supply was switched on during the forward motion and off during the return. In this way it was possible to simulate the machining path of the electrode over the surface of a roller.

The gap sensor was mounted next to the tool to set and monitor the electrode stand off. It was intended to use this during the experiments but abrasion of the ink layer meant that it could only be used for initial setting up of the gap.

The tool was adjusted to be planar with the sheet, but due to the flatness problems this could not be guaranteed.

6.1.2.4 Tool Design

A very simple cathode design was used consisting of a brass tube soldered into a 25mm x 25mm copper chrome head. Electrolyte is pumped through a 3mm diameter hole in the head and escapes between anode and cathode.

A problem with this is that the flow patterns in the gap are difficult to establish. Electrodes were tried with a variety of flow channels machined in the base but these performed less satisfactorily than the plain tool.

6.1.3 Results

Experiments were conducted using 15% sodium chloride solution over a range of flow rates and current densities. All experiments were conducted with constant current supply. The main problem was found to be the adhesion of the ink layer, especially at high flow rates and at high current densities.

A number of observations were made about the adhesion and breakdown of the ink. Thorough degreasing was found to be essential for the ink adhesion - failure to do this inevitably resulted in the ink layer lifting off, irrespective of the machining conditions. High temperatures also seemed to break the ink-substrate bond. This was particularly noticeable when experimenting with sodium nitrate solution where the obtainable current densities were not sufficient to permit machining. The ensuing voltage drop across the electrolyte resulted in boiling in the gap and ink, which had previously been well adhered, was observed to lift off. Sheet flatness prevented gap thicknesses of less than 0.5mm from being used so plans to experiment further with the nitrate solution were postponed.

Microscope examinations of the ink layer showed that the drops were thick on the perimeter but thinned towards the centre. This was caused by the droplet not evaporating on impact but drying from the outside in (see section 5.5). On some experiments breakdown was observed to initiate in the centre of the peak where the mask was thinnest.

The surface shown in **Figure 27** was machined at approximately 4.5 A/cm^2 with a flow rate of 0.5 l/min. A 25 x 25mm electrode made eight passes at 20 mm/sec giving a total machining time of 10 seconds. The filled plot and bearing ratio plot clearly show a uniform surface on the tops of the peaks, indicating a lack of breakdown in the mask.

The same conditions were repeated for a current density of 9 A/cm^2 but with the number of passes reduced to two, giving a machining time of 2.5 seconds. This doubled the current density while reducing the total machining current by a factor of two. The machined surface is shown in **Figure 28**. A recess is appearing in the tops of some of the plateaus indicative of an early stage of mask breakdown. This suggested that current density was a significant contributor to the breakdown effect.

Increasing the machining time at 9 A/cm^2 to ten seconds caused a significant mask breakdown as seen in **Figure 29**. The bearing area plot is now composed of three distinct sections: an initial spike representing the areas where the mask remains intact, a gently angled plateau for the more rounded eroded peaks and an almost level base for the valleys between the peaks. The machining current was increased to 13.5 A/cm^2 at ten seconds and the result is shown in **Figure 30**. By now the mask has been almost completely obliterated with most peaks reduced to gently rounded bumps. The initial spike on the bearing ratio plot has been further reduced and the middle section is barely distinguishable. It can be seen that the exposed peaks are being preferentially machined towards the level of the valleys.

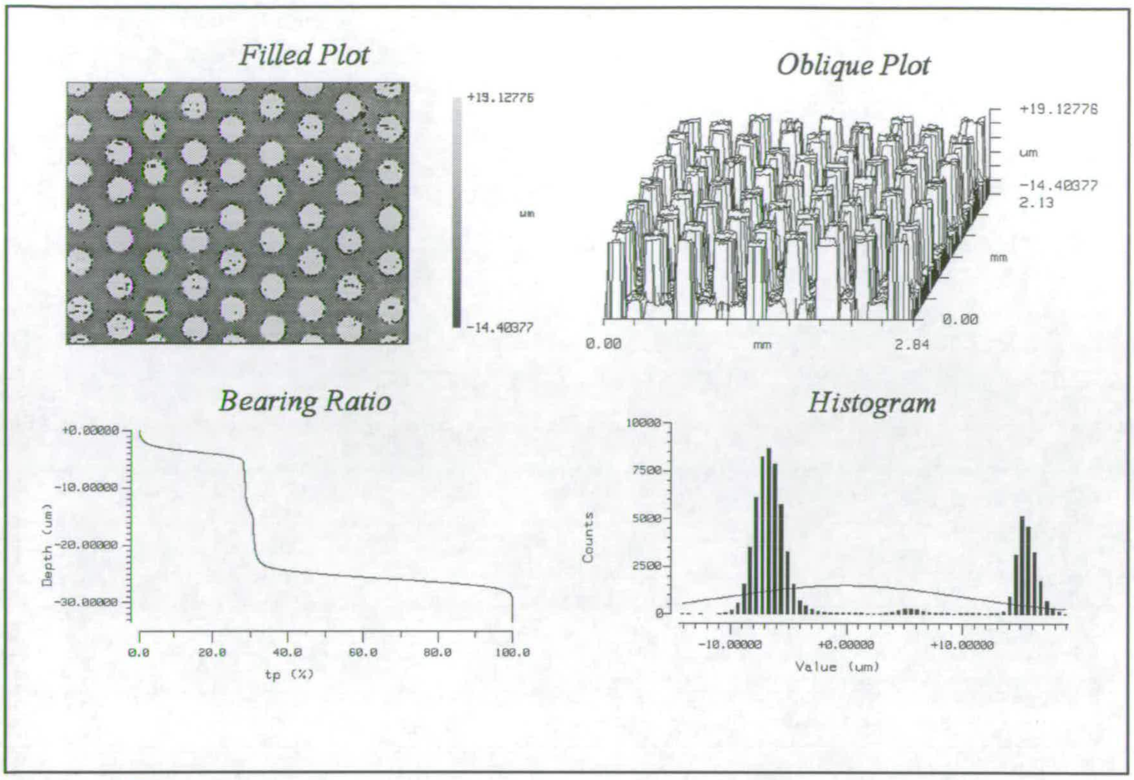


Figure 27 Intact mask

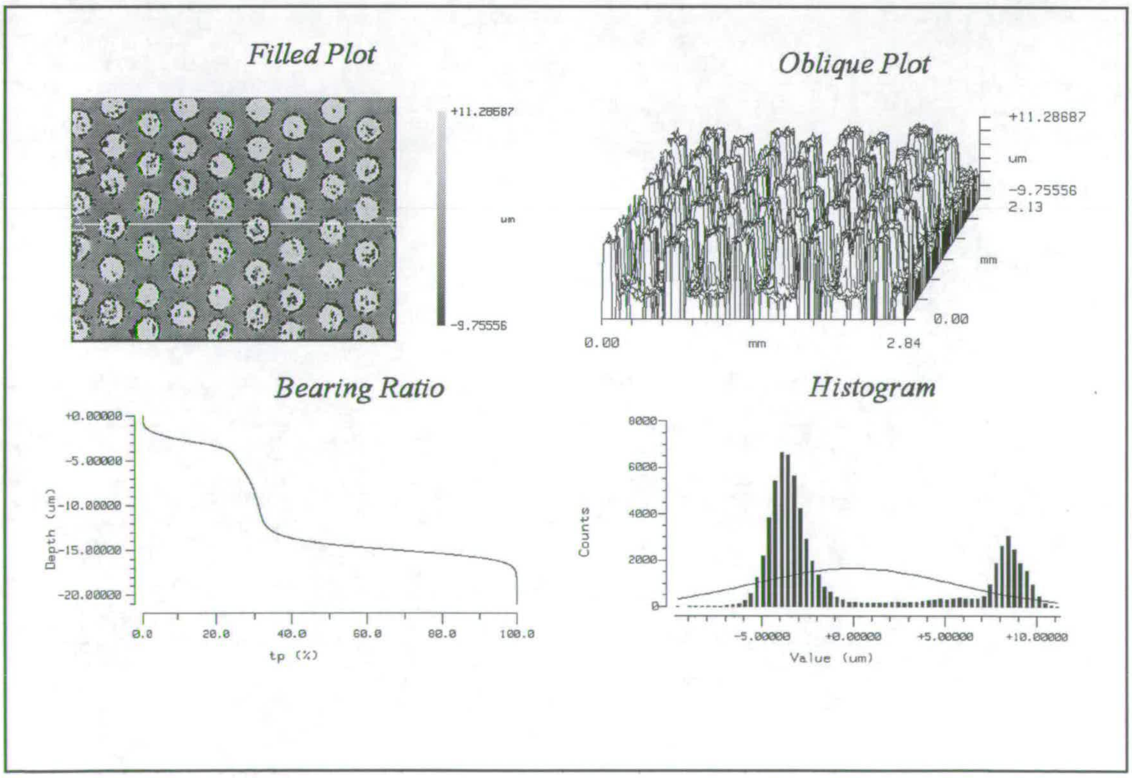


Figure 28 Initial mask breakdown

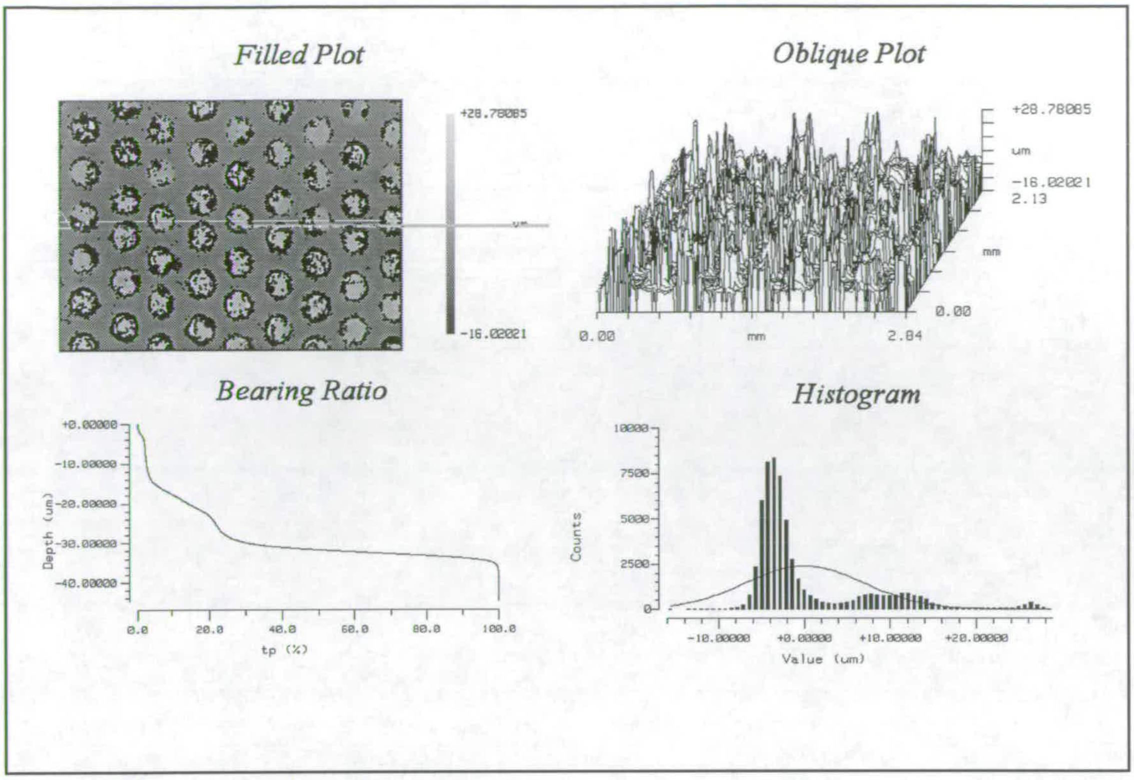


Figure 30 Partial mask breakdown

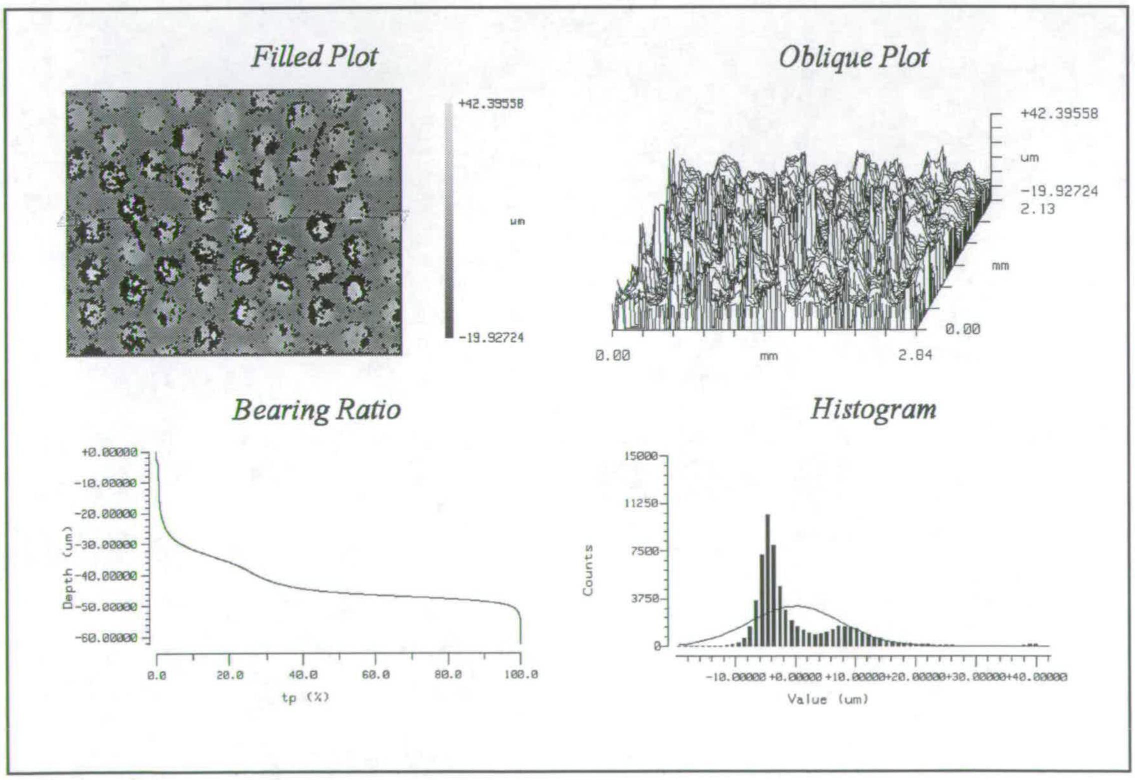


Figure 29 Complete mask breakdown

Numerical parameters for these surfaces are shown in **Table 4**. Parameter definitions are given in the *Notation* section at the start of the thesis .An interesting possibility here would be to take a successfully machined surface like **Figure 27** and post process it by removing the mask and re-machining to provide controlled rounding of the peaks.

	Parameters (all μm)						
Surface	R_a	rms	PV	R3z	Rz	Rtm	H
Figure 27	9.1	10	34	25	27	30	24
Figure 29	4.8	5.4	21	16	16	19	14
Figure 28	5.2	6.9	44	32	34	40	19
Figure 30	5.9	7.7	62	54	55	52	20

Table 4 Roughness results for flat sheet experiments

Figure 27 also shows good uniformity of peak height and valley depth with the maximum variation over the machined floor of approximately 4 μm. This compares favourably to the 8 μm variation observed on the unmachined surfaces of the peaks. It is possible that the base roughness is an artifact of the original surface as high lines, from the original grinding, on the peaks continue as high areas on the base. This suggests that the current efficiency of the solution is constant over the depth variations (around 30 μm) present so high areas are not being machined preferentially. This is not surprising as sodium chloride has a high throwing power and the machined depths are small compared to the original gap width (approximately 500 μm).

Over 30 sheet samples were machined using this apparatus. Problems with printing and planarity of the samples limited the amount of qualitative work which could be done but it did provide a very useful insight to the breakdown mechanisms of the ink layer. It also demonstrated that the masking process could work with electrochemical machining with machining rates, even at low current densities, being considerably higher than with ferric chloride solution. Machined depths of in excess of 30 μm were obtained which is far rougher than any texture required in cold rolling.

6.1.4 Ink heating trials

In an attempt to improve the geometry of the printed drops some experiments were done with heating of the sample. The two issues were thinning in the centre of the drop and ink flow causing merging of drops. The heater was supplied on loan which limited the time available for experimentation. None of the sheets printed were subsequently etched.

Experiments were conducted by locating a small hot air gun on the print head. Samples were printed with hot air at a range of temperatures directed either in front of (pre-heating) or behind (post-heating) the print head. Results were inconclusive but did suggest that heating prior to printing reduced spreading.

This may warrant further investigation but at the time the heater was too large for incorporation with the machining head. In addition some of the objectives may be achieved with a higher viscosity ink.

6.2 Roller experiments

6.2.1 Introduction

After the experiments on flat sheet the texturing equipment was modified to conduct experiments on rollers. The equipment used evolved to the final state described in section 5.2 but with little influence on the machining data. The major change which influenced the machining was a change in ink type.

The original ink supplied with the printer was a black solvent based product called BK0101. This is probably the most common ink used in this type of machine as it gives good adherence to a wide variety of substrates. It is however designed to operate at a low viscosity, presumably to give a faster drying time. The disadvantage of this is that the ink has a tendency to spread on contact with the substrate to form a large spot. When dry the drop is thick round the perimeter but thins in the centre to less than 0.5 microns thick.
This thinning led to premature breakdown in the mask centre in some circumstances while the ink spreading lead to overlarge drops and inconsistency in size and shape across any given stroke.

It was suggested that the ink type be changed to BK0701. This is another MEK based ink, very similar in composition to BK0101 but designed to be run at a higher viscosity. The printed drops tend to be smaller and rounder with less of a tendency to thin in the centre. The most immediate trade off appeared to be a longer drying time, in the region of one second. As the roll surface speeds are quite low this was not thought to be a problem.

This change had a significant effect on the texturing process such that some initial work was repeated with the new ink. As will be described later, the printer was subsequently refurbished with a new head (and longer umbilical) and fresh BK0701 ink. Since that time the ink drops have appeared similar to the earlier BK0101 drops in size and geometry.

6.2.2 General Equipment

The main texturing unit is as described in section 5.3. Although not all facets of the unit were installed for all experiments this has not had a significant effect on the validity of the results except where specifically stated. The main variations are in the rollers, lathes and electrode designs used and these will be described briefly below. All variations were based round an open design where the roller is not enclosed and electrolyte is collected primarily through the electrode design. The only exception to this was the first system which was used briefly prior to the flat sheet experiments and this will be described below.

6.2.2.1 Initial Experiments

Because the solutions to be used were corrosive to exposed sections of the lathe used to drive the rollers, consideration had to be paid to an effective method of electrolyte containment at the point of machining. The initial idea was to enclose as much of the roller as possible and a perspex tank was devised to fit round the barrel of the roll. This is shown in **Figure 31** and has an open top and rubber gaiters at each end to seal around the shafts of the roller. The electrode was mounted vertically above the roller and traversed along its length via the lathe tool post. Electrolyte was pumped through the centre of the electrode and collected in a sump at the base of the tank from where it returned to the texturing unit.

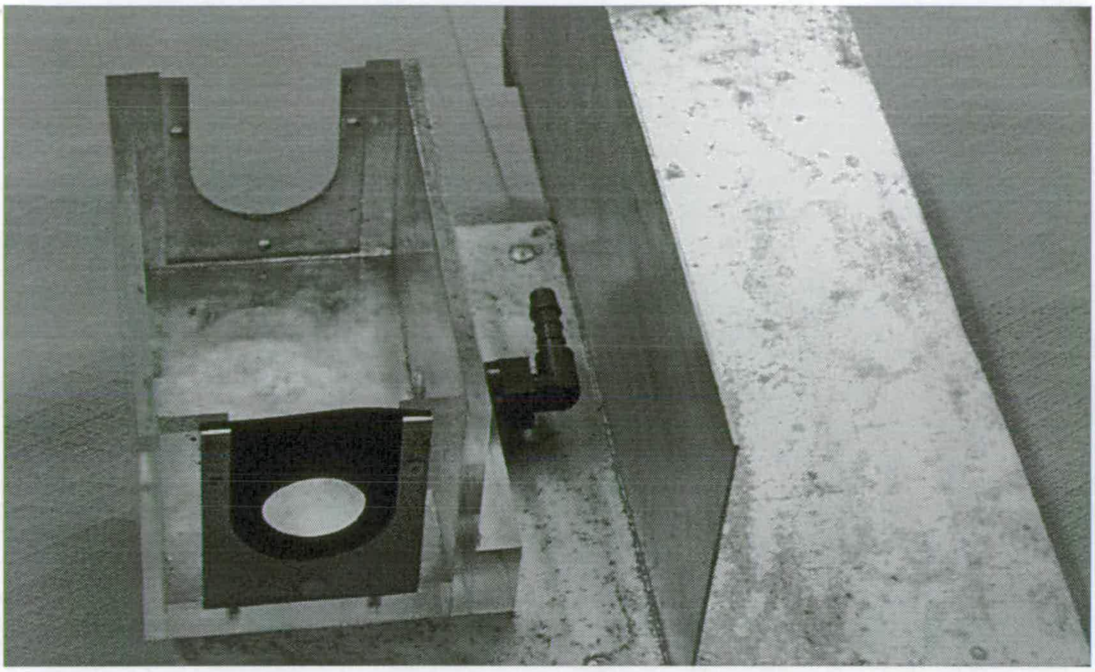


Figure 31 Initial electro-chemical texturing tank

Although the system worked well, with no leakage of electrolyte onto the lathe, it soon proved too inconvenient for general experimental use. For effective protection the walls of the tank extended above the top of the roller and interfered with the print head when used with less than 5 mm print gap. This meant that only the central portion of the roll could be printed under certain circumstances. The enclosed nature of the tank also made it difficult to clean ink off the roll if it needed to be reprinted. After machining it typically took over two minutes to remove the roller from the tank for cleaning during which time the roll surface continued to corrode (it also took a similar time to install the roller prior to texturing but this was less critical). Many of these problem could be reasonably simply overcome but the need to build new tanks to accommodate other sizes of roller proved to be a much greater limitation.

The results of this led to the devising of the flat sheet experiments described in section 6.1 as a way of investigating initial machining conditions and electrode design in a manner which would be cheaper and quicker than that described above but more relevant to the final application than a flow cell study.

6.2.2.2 Main roller experiments

One result of the flat sheet study was to show that an electrode design with a built in return line / scavenge system was a feasible option. All subsequent roller experiments have been conducted with such a scavenging electrode and a small drip tray beneath the roller to collect any fluid which may escape. **Figure 32** shows a scavenging electrode in position against a roller. The upper inlet pipe and the lower outlet pipe are both clearly visible. Next to the electrode is the holder for the print head. This view is shown in close up in **Figure 33**.

The roller can be seen supported on the lathe between chuck and tail stock. With this roller a second smaller chuck has been used as an extension but also to grip more precisely. The anode connection to the texturing unit can be seen clamped to the tail stock. This connection, although primitive, was adequate for all roller experiments (with the exception of those rollers textured in Holland where the connection was made directly onto the roller with a set of spring loaded carbon brushes). The cathode connection can be seen on the aluminium pinch block which holds the electrode tool. Wrapped around the cathode cable is a fine wire gauze and a ferrite bead: these were added to reduce the electro-magnetic radiation when machining with pulsed current.

In this photograph the tool holder is mounted on, but electrically isolated from, a roller slide, which is in turn mounted on the linear actuator. A low rate spring to the rear of the slide ensures that the tool is held in light contact with the roller. Earlier versions had the tool rigidly clamped to small leadscrew dovetail slide. The tool was positioned away from or in contact with the roll surface as required then held in that position for the duration of machining. It was unable to compensate for any mis-alignment or eccentricity or the roller: these usually resulted in uneven machining from the varying electrode gap or mask breakdown where the increased contact force caused the ink to be abraded. A further advantage of the roller slide is the ability to cope with crowned rollers if so required.

Mounted on the linear actuator are the tool holder, the printhead holder and the inlet and outlet valves. The valves have quick release fittings, for fast clean tool changes, and the facility to bypass the head in order to prime the return pump. This helped to ensure effective removal of the electrolyte from the workpiece, but became less important when the scavenge pump was changed from centrifugal type to peristaltic.

The lathe shown in **Figure 24** on page 109 has had the tool post removed and the linear actuator mounted directly to the dovetail of the cross slide. With the actuator locked rigid the tool can then be traversed using the screw cutting mode of the lathe. It also enables quick fitting, removal and alignment of the actuator. When the actuator was initially installed the cross slide was removed and the actuator fixed directly to the bed. This was time consuming, difficult to accurately align, and gave no flexibility of position relative to the central axis of the lathe (to compensate for larger or smaller diameter rollers). Perhaps the biggest advantage of cross slide mounting came when using pulsed machining, as described below.

Electrode Design

The new electrode was designed to minimise the amount of fluid spillage and to dispose of the need to have an enclosed tank around the roller. A selection of electrodes are shown in **Figure 34**. The electrode gap is set by an insulating coating with a clear machining area cut into the middle. The electrolyte is pumped into the gap through a brazed tube at the top of the machining area. A shallow channel cuts across the width of the area at the inlet to encourage flow distribution. The electrolyte return line is linked to a similar tube at the base of the area through which the used fluid is sucked. The electrode block is made of copper chrome and is radiused such that the surface diameter with insulation matches the roller diameter.

The insulating material was a source of many problems. Its main requirements are as follows:

- Soft surface to conform to roll surface for sealing purposes
- Low friction to minimise damage to ink mask
- Closed surface structure to minimise pick up of abrasive particles
- Electrical resistance
- Chemical resistance to electrolytes used
- Temperature resistance
- Abrasion resistance

Interest concentrated at first on self adhesive tapes but these were usually too thin or were open cell foam and suffered rapid surface contamination. A closed cell foam tape was supplied by Sellotape. This was a pu foam, 1.5 mm thick uncompressed, with a silicone rubber adhesive. This promised well but suffered from very poor adhesion when machining. The bond was improved by supplementing the adhesive with a film of epoxy resin but even then the tape would fail after approximately 5 to 10 minutes use.

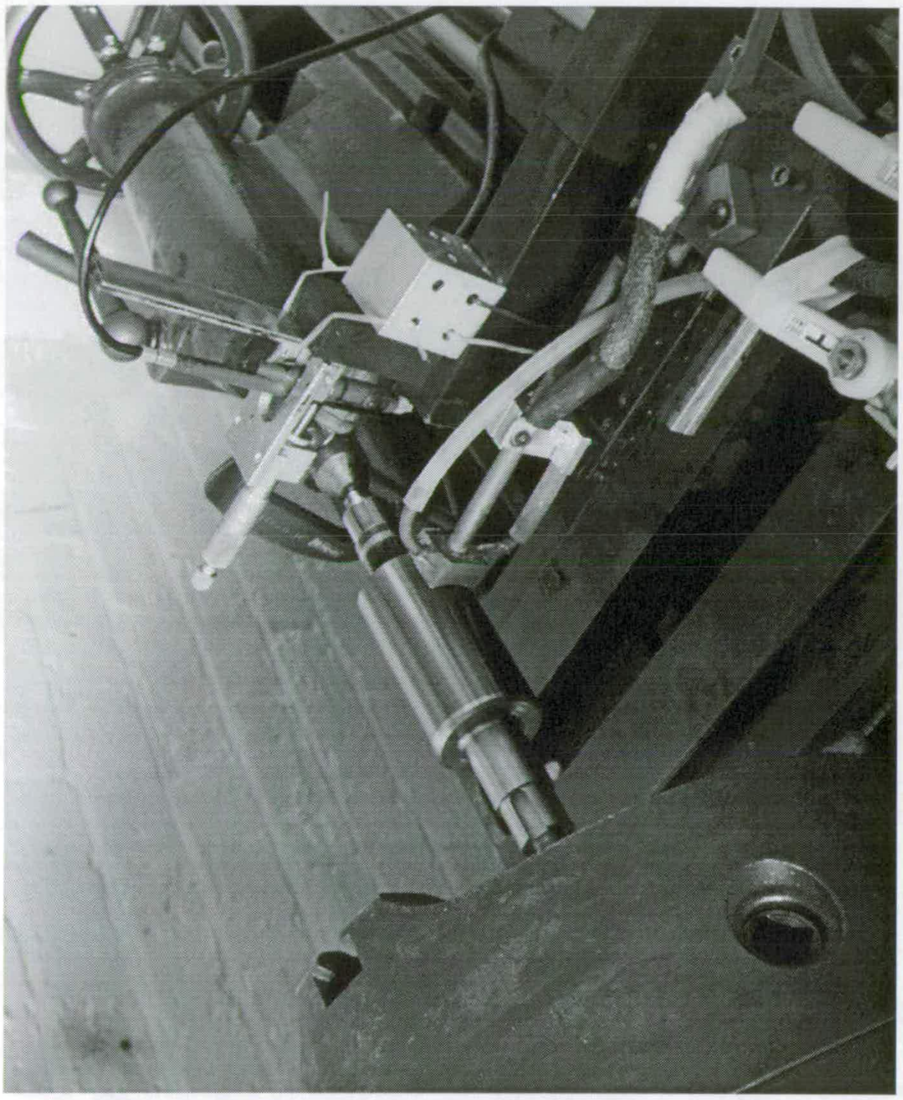


Figure 32 Wide angle view of ECM roller texturing assembly

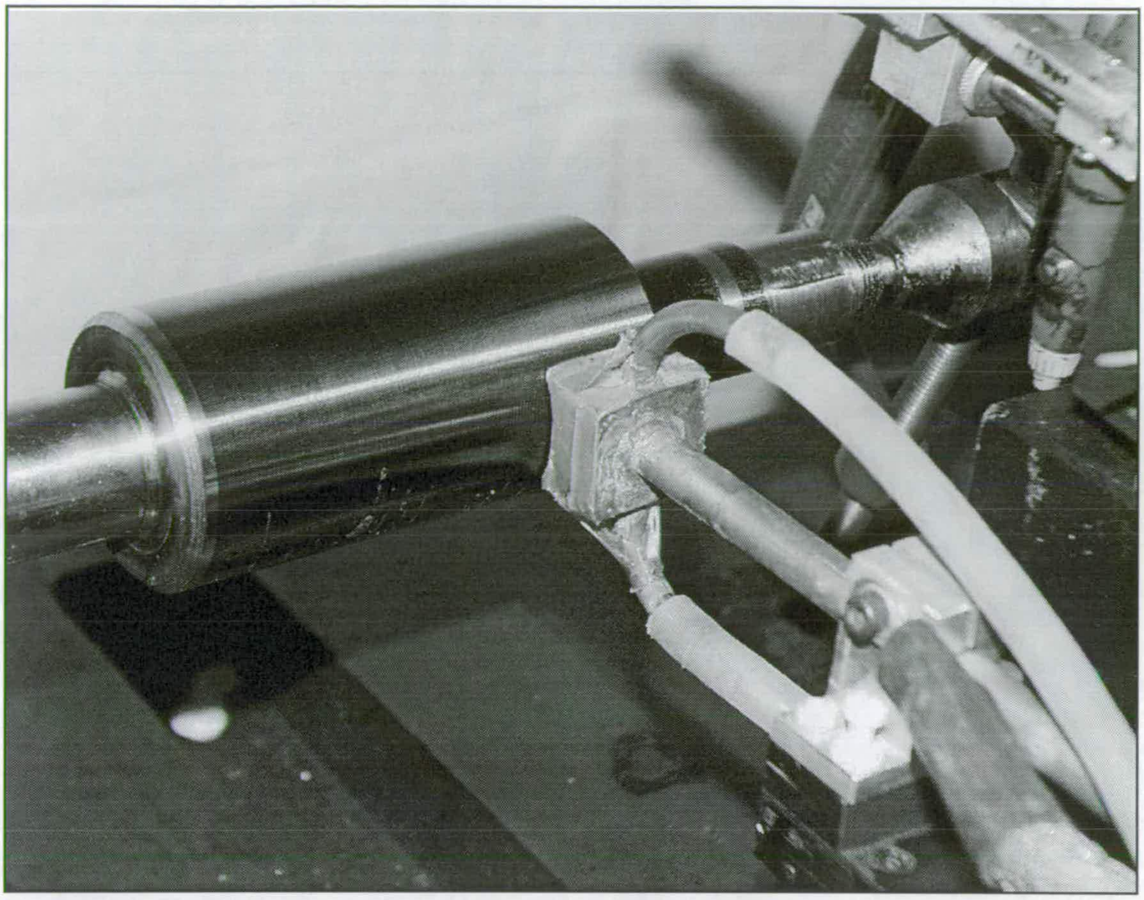


Figure 33 Close up view of electrode tool and roller

A variety of other coatings were tried, some of which can be seen in **Figure 34**. One tool was coated with a layer of non-slumping epoxy resin (Araldite 2014). This was chosen because of its good chemical and temperature resistance. The centre section of the electrode was masked with tape (to prevent adhesion) then the tool head was coated with a thick layer of adhesive. A thin PTFE film was wrapped round the roller to be textured then the tool was positioned such that a layer of adhesive 1.5 mm thick was left between it and the roller. It was then held in position until the coating set. After removing from the roller the central section was trimmed back to reveal the tape which was then removed to expose the machining surface. In use the tool showed no immediate signs of chemical or thermal degradation but had a very poor abrasion resistance. Even with low roll contact forces there was significant wear with under five minutes use. In addition when the coating was removed from the tool (so that the tool could be reused) it came away cleanly and easily from the metal suggesting quite a poor bond strength. This was in spite of the copper chrome being thoroughly prepared prior to bonding (abraded, etched in Ferric Chloride then ultrasonically cleaned).

A selection of conformal coatings were tried but were either too thin, poorly adhered, not abrasion resistant, suffered from creep or frequently a combination of these. PU sheet was tried but again suffered from adhesion problems. After consulting with adhesive manufacturers and suppliers a contact adhesive was recommended (Bostick 2402). This was tried and performed slightly better, lasting almost ten minutes before failure. Almost invariably bond failures occur at the copper chrome interface. Examining failed electrodes show the mask to either peel at the leading edges, presumably due to friction from the roller, or around the central window, suggesting pressure in the gap is finding weakness in the bond, again causing it to fail in peel.

One other method tried was to build up a coating of PU by painting it on in thin layers, allowing the solvent to evaporate between layers. A thick coating was applied with the intention of machining it back to size. The plastic is soluble in MEK and it was intended to soak it in that then abrade it against a rotating roughened roller. Unfortunately this barely even scuffed the surface while attempts to cut it were similarly unsuccessful. The coating did appear to be highly abrasion resistant and very well adhered to the copper chrome but a failure to get it to the correct size meant that its performance while machining could not be assessed. Notwithstanding, this did seem to be the most encouraging of the coating methods but a lack of time meant that it was not possible to pursue it further. Because the foam tape was reasonably quick and easy to apply, with predictable performance, it was decided to continue using that for the remaining experiments.

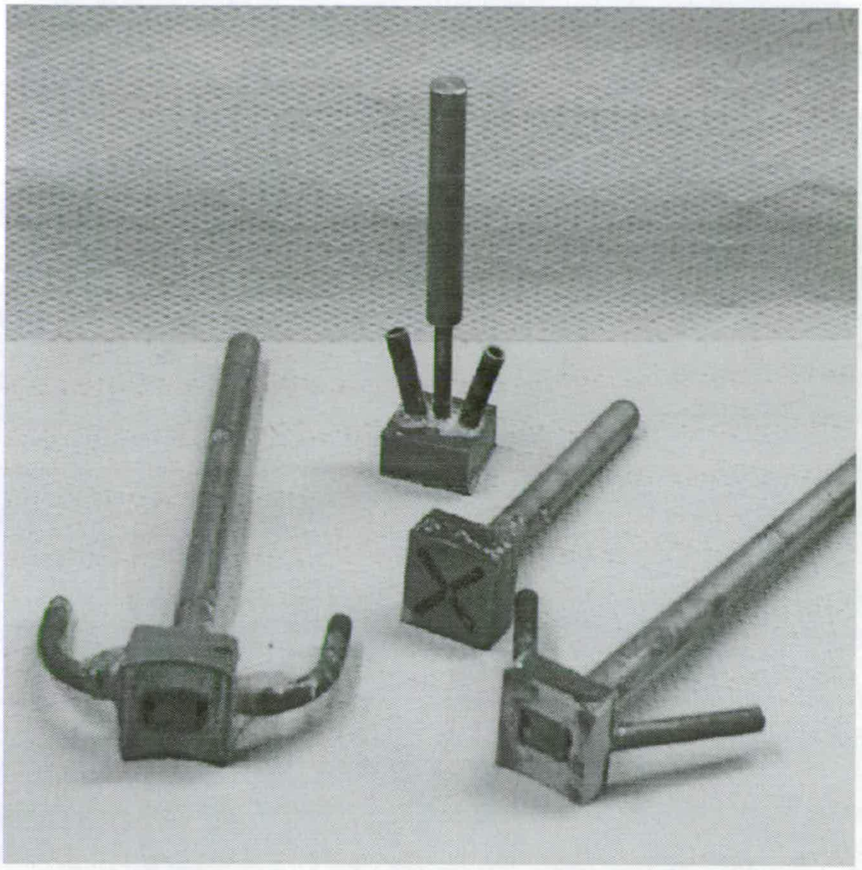


Figure 34 A selection of electrode tools used

Lathes

Three lathes were used for the roller experiments. The initial experiments were performed on a Smart and Browne tool room lathe as described above . The bed length of this was very limited. This added many design constraints due to the need to maintain compactness to get everything to fit. A further problem was the speed of the lathe. The slowest available speed was 45 RPM which lead to difficulties in getting suitable machining rates due to the high surface speeds. Finally a broken gear meant it was only possible to traverse the tool post towards the chuck. While it was always possible to stop the machine before the tool or print head hit the chuck the lack of usable working space meant the risk of damage was unnecessarily high.

The first set of Hoogovens rollers were textured on site in Holland using a tool room lathe. This had a lowest speed of 35 rpm and was just long enough to accommodate the rollers. All other rollers, including subsequent Hoogovens rolls, were textured in Edinburgh using an old (1953) Willson lathe. This was purchased at scrap value as a replacement for the Smart and Browne and was ideally suited to the job. The long bed gave plenty of space to fit experimental equipment and could easily accommodate all rollers used in these experiments. The slowest speed was 28 rpm and with no real capital value any electrolyte spillages would not be a major disaster.

Pulsed Machining

The early attempts to use pulsed current machining met with an unexpected problem. The intention was to bypass the lathe cross slide drive completely by using the linear actuator for both printing and machining, not an unreasonable expectation. When the pulsed machining started the actuator jumped then reported a position error. Further experiments showed that when pulsing the actuator would travel backwards at a rate proportional to the machining frequency. The conclusion from this was that noise from the pulsing was being picked up on the linear encoder signal. The problem was accentuated by two factors. Firstly the drive was a linear motor, as opposed to a rotary motor driving a lead screw. While the latter can get its position information from a well screened encoder at one end of the screw the linear motor relies entirely on an encoder strip running the full length of the slide. This means that the encoder pickup will always be in the immediate vicinity of the machining head. With hind sight it was not a very suitable choice of actuator but at the time of purchase the main criteria were perceived as acceleration, accuracy and compactness. Even so it is possible that it would have still been acceptable but the encoder head was supplied with plain, unshielded, non-twisted pair, ribbon cable. This may have been considered unwise on any high resolution actuator but to supply it on a system ordered for pulsed electrical machining work in an industrial environment seemed to be severely negligent. Unfortunately the suppliers refused to take any action, replacing the cable or otherwise, leaving little else to be done about it. Judicious use of retrofitted screening and ferrite beads helped to improve the problem but not to the extent that it could be used for pulsed machining.

The result was that it was decided to concentrate on dc machining as this seemed to work reasonably well. Unfortunately all the early trials on the system used small rollers and short machining times. The first time the actuator was used for machining times longer than a minute was in Holland when texturing the first Hoogovens roll. In the course of five minutes the servo controller reset twice, the first time resulting in a deeply machined groove in the centre of the roller. To avoid this happening on the second roller as well it was decided to bypass the linear motor by locking the actuator and using the lathe cross slide drive instead. This was easily accomplished as the linear motor had been mounted directly onto the cross slide. The second roller was then machined without incident.

On return to Edinburgh the actuator mounting was modified such that it would also fit onto the cross slide of the Willson lathe. The lathe drive was then used for all subsequent machining. The result of this was that pulsing could be used on the latter experiments.

Rollers

Three main rollers were used for these experiments. These were the rollers from the jeweller's mill (as used for the chemical etching experiments), ground steel bar stock and the rollers from the Hoogovens pilot mill. The main details of these are given in **Table 5**. The small disc rollers used for the chemical experiments did not prove so useful as a certain amount of lead in and lead out is required for the electrode. With half an inch run in and the same run out this left none of the inch wide roller surface for the experiment.

	Nominal barrel diameter	Barrel length	Material
Jeweller's roller	52.5 mm	100 mm	EN31 water quench hardened
Practice roll	52.5 mm	500 mm	EN 8
Hoogovens roller	140.0 mm	360 mm	Forged tool steel

Table 5 Data for rollers used in electro-chemical texturing experiments

The laboratory mill rollers were used initially but these are time consuming to make and only allow short machining runs. This meant that any long term effects would not be noticed until a larger roll, such as the ones for the Hoogovens pilot mill, was attempted. Because of this two half metre lengths of EN 8 were adopted for general experimentation. These were cheap, required minimal machining and enabled experiments to be conducted over an extended period. In a non-hardened state these did not grind as well as the hardened EN31 rolls, something which was not immediately noticed.

The final set of rollers used were referred to as the Hoogovens, or large, rolls. These were for a fully instrumented pilot mill at Hoogovens Stahl technical laboratory in Ijmeuden, Holland. Different rollers exist for operation as either two or four high; it was the latter which were used in this project. These were textured as part of an ECSC project investigating zinc coating adhesion and provided a valuable opportunity to texture commercial rollers and to receive some representatively rolled sheet samples.

Although the jeweller's mill is capable of rolling sheet metal it has no control over rolling loads and does not give representative conditions for assessing texture transfer and other factors. The possibility of obtaining a small mill was investigated but the cheapest reconditioned mills were over £14 k while one of the standard of the Hoogovens mill would be more than £1.5 m.

6.2.3 Preliminary Experiments

These were primarily concerned with testing the various components of the new scavenge electrode setup installed on the Willson lathe. Due to late delivery of the linear actuator there was very little time for experimentation with the system before it was shipped to Holland for the texturing of the first set of Hoogovens rollers.

During this period the problems with pulsing and the linear actuator were discovered. This led to the decision to concentrate on d.c. machining. Problems with the printer also accounted for much of the time. This was mainly due to the jet "wandering" such that in time it would start to leave the nozzle at an angle and clip the gutter. The problem was eventually sorted in Holland when a reservoir of fresh ink was fitted.

Hoogovens Rollers I

The first pair of large rollers were textured on site at the steel mill in Holland. The texturing equipment was transported out in a large estate car and installed onto a lathe in one of the tool rooms ready for use. Difficulties were encountered in printing the first roller (for reasons mentioned above) but these were sorted by changing the ink. The roller was printed as a sequence of bands with good positional accuracy but poor synchronisation between strokes.

The linear actuator was used for both printing and machining of the first roller. Midway through machining the servo controller reset leaving the tool stationary.

By the time this was noticed a deep band had been machined around the center of the roller. The actuator was restarted but again reset just before the finish of machining. It was thought that this was caused by either noise or, more likely, a floating ground line causing the servo power to reset. The servo controller was reconfigured using a second, separate, power supply but tests without machining showed that a reset still occurred approximately one pass in three. The decision was therefore taken to machine the second roller using the slide feed of the lathe to drive the tool. This worked well and has been used for machining in all subsequent experiments.

The electrolyte was 15% NaCl and fresh solution was made for each roller. Mask adhesion was good on both rollers except for the over machined band in the centre of roller 1 which showed some signs of breakdown. **Figure 35** shows the R_a values for the top and bottom rolls taken as an average of 2D stylus measurements made by Hoogovens directly onto the roll surface. Replicas of the top and bottom rollers after rolling (**Figure 36**) were measured on the Zygo interferometer and showed mean roughness values of $R_a = 1.05\ \mu m$, $H = 3.23\ \mu m$ and $R_a = 1.61\ \mu m$, $H = 4.50\ \mu m$ respectively.

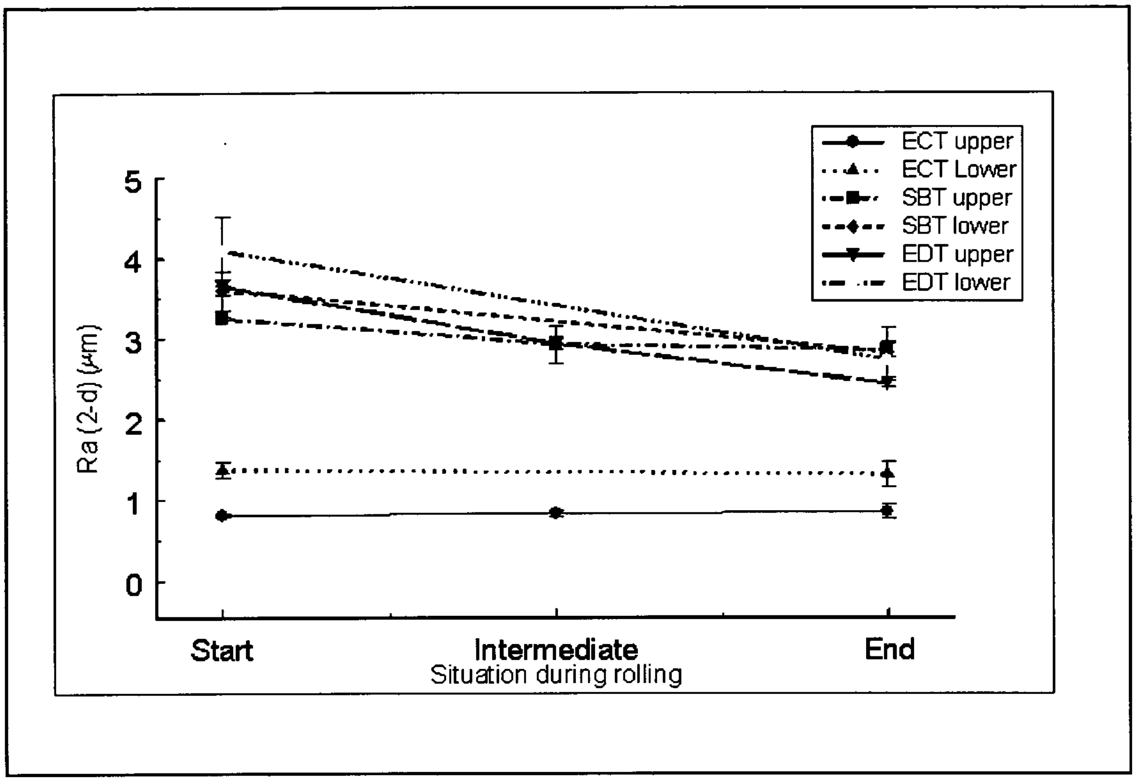


Figure 35 2D R_a measurements from rollers before, during and after rolling.

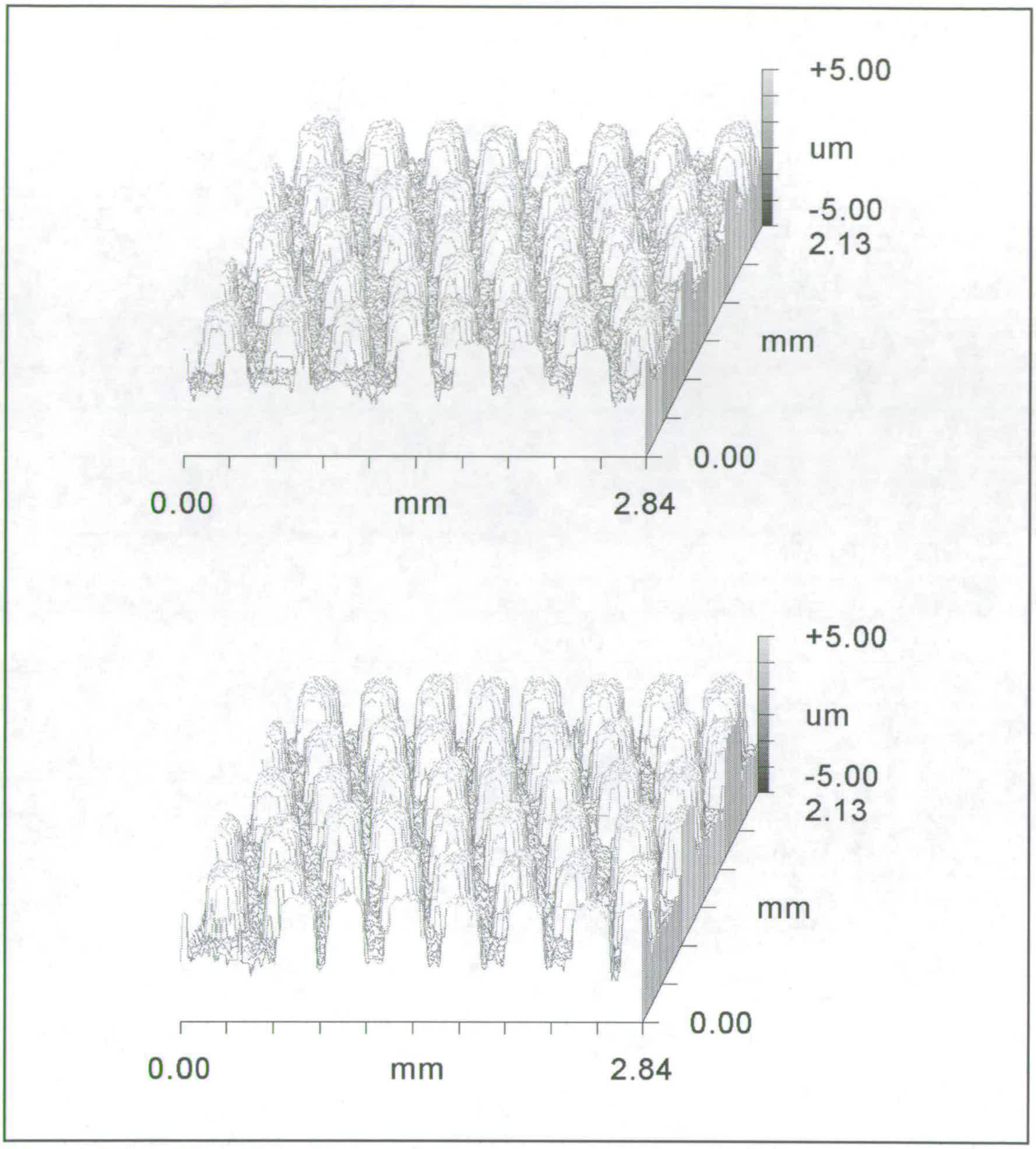


Figure 36 Replicas of top and bottom rollers after rolling.

6.2.4 Main Roller Experiments

After the Hoogovens visit a more systematic study was conducted using the practice rollers to try and understand the effects of some of the process variables and to improve the general quality of the texture. These led also to a further three sets of rollers being textured for the Hoogovens mill. After the successful texturing of the first pair it was decided to process subsequent large rollers in Edinburgh as a cheaper and easier option.

The nature of the experiments are as follows. All experiments up to roller 12 were done with pulsing at 30V and 15% NaCl solution. From roller 13 onwards machining was constant current. Rollers 1 and 2 had very high surface R_a after grinding (0.7 micron +). Unfortunately this was not picked up on until after texturing. This means that there is a limited amount of information that can be drawn from this. From roller 3 onwards a new protocol was established for grinding the rollers. This included slowly dressing the wheel before starting and finishing with a series of four dwell passes. The effect was to at least halve the R_a of subsequent ground rollers. **Figure 37** gives a comparison between the ground finishes of roller 1 and roller 3.

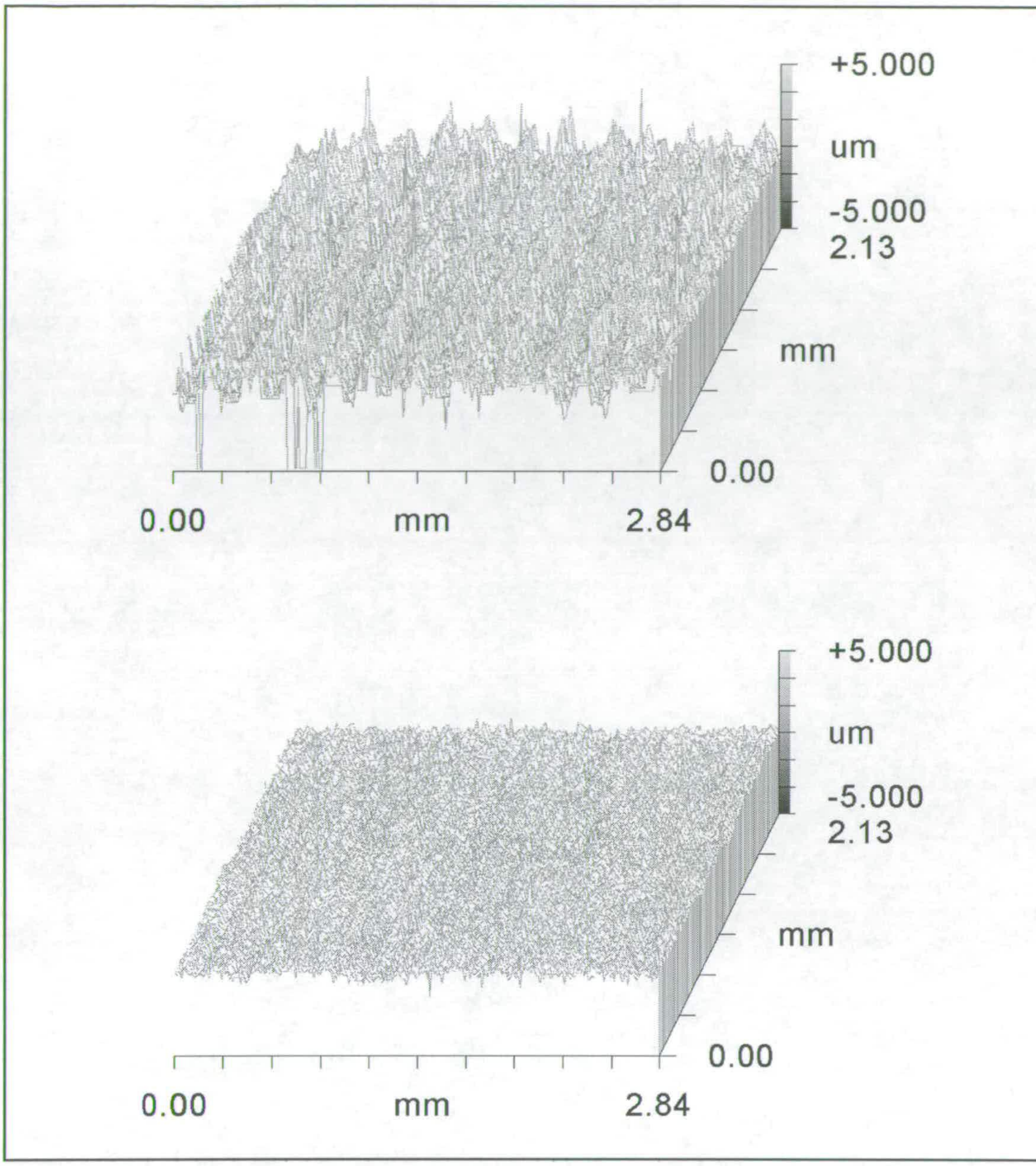


Figure 37 Comparison of roller 1 and roller 3 ground surfaces

Roller 1 frequency f=100Hz duty ratio d=varied speed=varied pitch=14tpi

	R_a (μm)	H (μm)
D=60%, 45 rpm	2.04	6.47
D=60%, 65 rpm	1.51	4.94
D=70%, 65 rpm	1.79	5.55
Ground	0.72	2.58

Table 6 Roller 1 roughness results

This experiment was based around a pulse frequence of 100 Hz and a tool feed rate of 14 tpi. The duty cycle and roll speed were varied at different parts of the roller. Results in **Table 6** show roughness increasing with duty cycle but falling with roll speed.

Roller 2 f=1 KHz d=varied 65 rpm 28 tpi

This experiment looked at the effect of varying the pulsed current duty cycle. Many of the replicas were bubbled and as the original roller was very rough it did not seem worth making more. Results for the good replicas are included here for completeness in **Table 7**.

	Ra (μm)	H (μm)
Ground	0.71	2.53
Duty = 20%	1.96	6.33
Duty = 70%	3.05	8.98
Duty = 90%	3.24	9.36

Table 7 Surface roughness values for roller 2

Roller 3 f=100Hz d=60% 65 rpm 28 tpi

This roller was treated with constant machining conditions for the whole roller. The intention was to see whether machining would vary significantly with time. Unfortunately the tool mask started to break down about 90 mm into the pass causing scoring of the ink mask. This will have an effect on the roughness values from that point on, as can be seen in **Figure 38**. This shows the R_a decreasing as the mask starts to be removed before gradually increasing again. This suggests that the mask damage has stabilised and that the effect of electrolyte heating was becoming dominant.

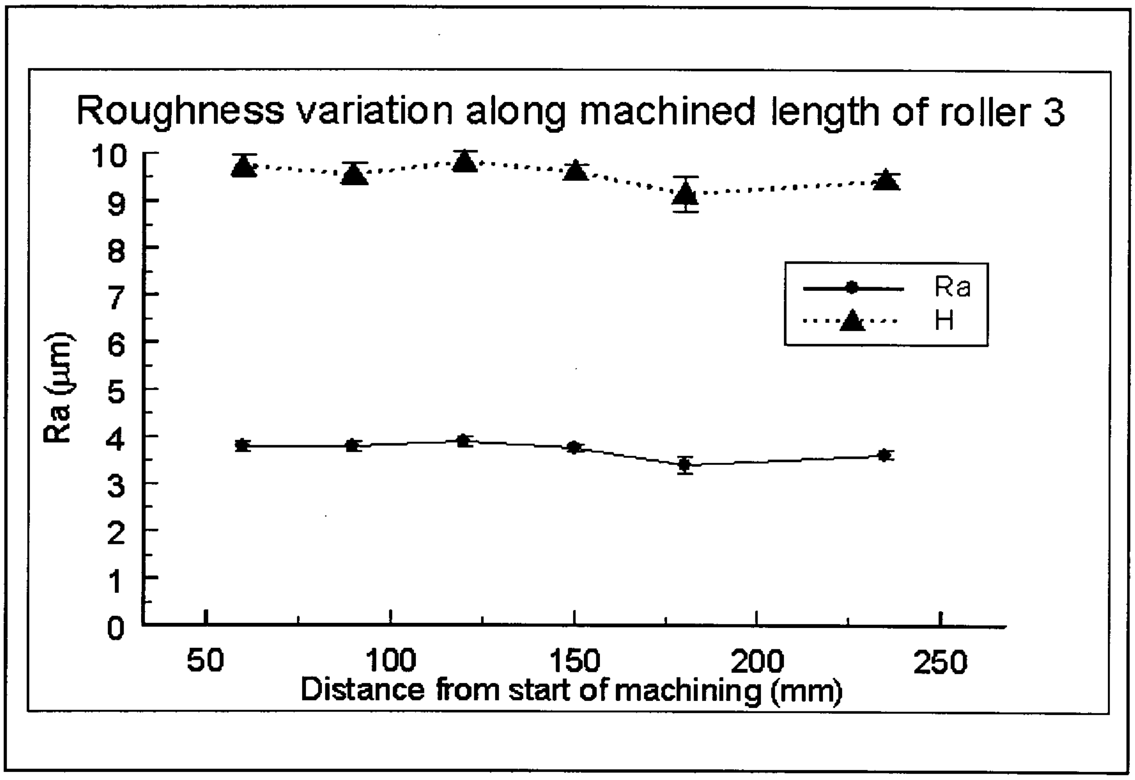


Figure 38 Graph of R_a versus machining distance for roller 3

Measurements were also taken directly around the centre of the roller at 90^0 intervals and show a mean R_a of 4.2 μm and H of 10.17 μm.

Roller 4 f=1KHz d=30% 65 rpm 28 tpi flow=0.2 L/m

This roller was also processed with constant machining conditions along its length. The pulsing frequency this time was 1 Khz. Pulsing at 100 Hz was producing a pattern of horizontal lines on the machined surface of the roller which, while difficult to detect by surface measurement, were obvious to the naked eye. It was felt that this may be introducing a waviness of about 1.5 mm wavelength into the texture and so the decision was taken to concentrate on the higher frequency.

Figure 39 shows a high initial R_a value which drops initially and then gradually increases as the electrolyte warms up. The roughness starts to plateau then drops off slightly as mask breakdown starts. The reason for this initial drop is not clear but it could be due to the build up of contamination in the electrolyte reducing conductivity or due to a film forming on the cathode causing an potential drop.

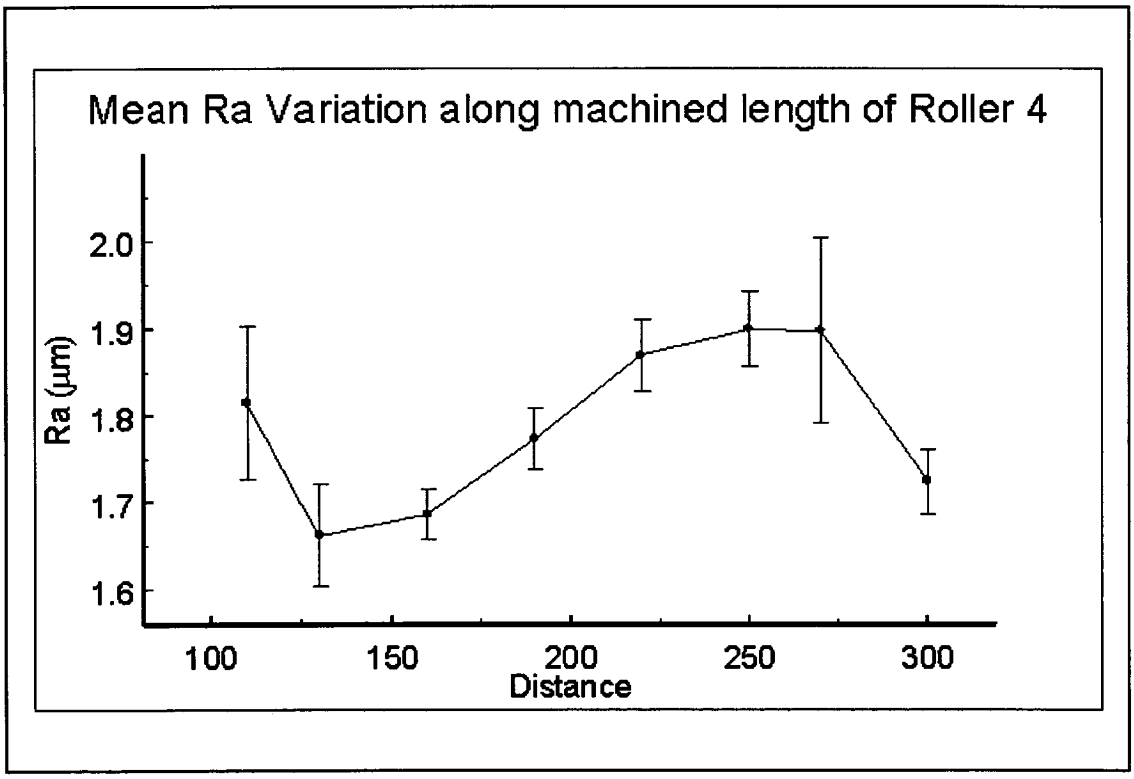


Figure 39 R_a versus machining distance for roller 4

Direct measurements taken around centre of roll show mean R_a of 1.8 μm and H of 4.62 μm.

Roller 5 f=1KHz d=50% 65 rpm 28 tpi flow=0.2 L/m

Rollers 5 and 6 were intended to test the variability from roll to roll and determine the optimum duty ratio for machining the large Hoogovens roller to an R_a of 2.5 μm.

Measurements taken directly on the central section of the roll showed a mean R_a of 2.34 μm and H of 5.7 μm.

Roller 6 f=1KHz d=50% 65 rpm 28 tpi flow=0.2 L/m

A repeat of roller 5. Measurements taken on the centre of the roll showed a mean R_a of 2.29 μm and H of 5.6 μm.

Roller 7 f=1KHz d=70% 65 rpm 28 tpi flow=0.2 L/min

The previous experiments gave an R_a of approximately 2.3 μm. This was still too low to give the desired roughness on the large rolls. It was decided to increase the duty to 70% with the following results. Again the roll was measured directly in the central section and showed a mean R_a of 2.45 μm and H of 6.26 μm.

On the basis of this it was decided to try the large rolls at a duty of 80%.

Hoogovens 2A f=1KHz d=80% 28 rpm 28 tpi fl=0.2 L/min

Print quality was poor with very bad spreading of drops combined with drop non-uniformity in size and ovallity as seen in **Figure 40**. This was attributed to contaminated ink and, as a replacement reservoir was not available, it was decided to etch the roller anyway. Since the purpose of the roller was for high reduction tandem rolling prior to galvanising it was felt that the texture appearance was not critical.

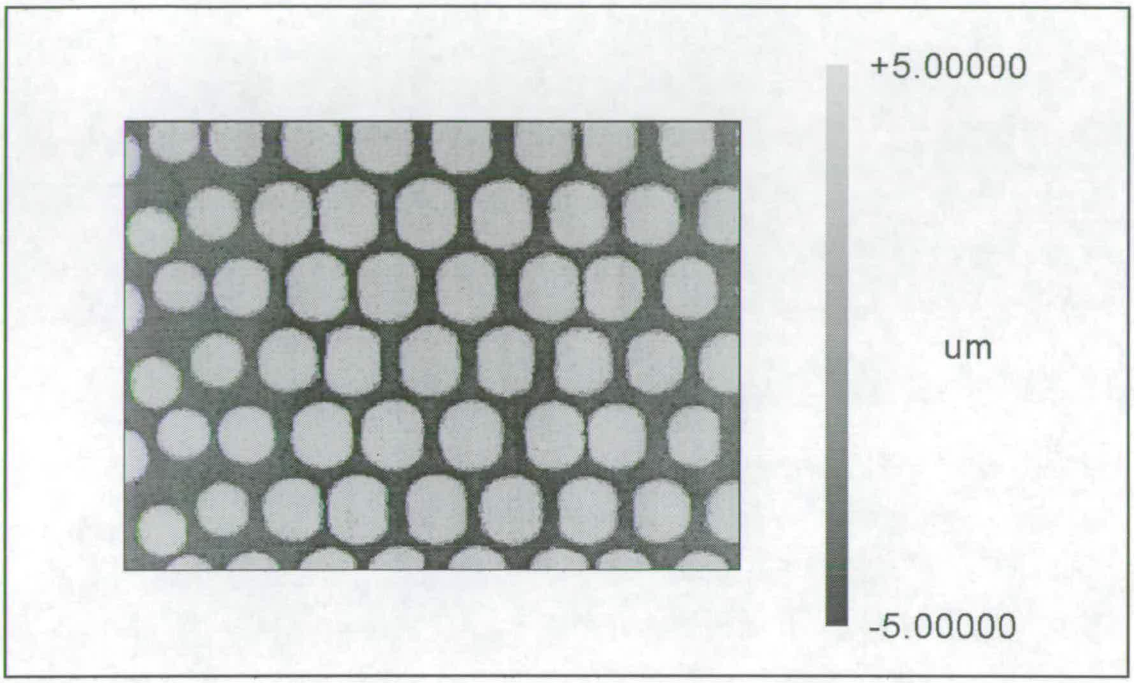


Figure 40 Replica of Hoogovens roller 2A showing oval peaks from poor drop formation

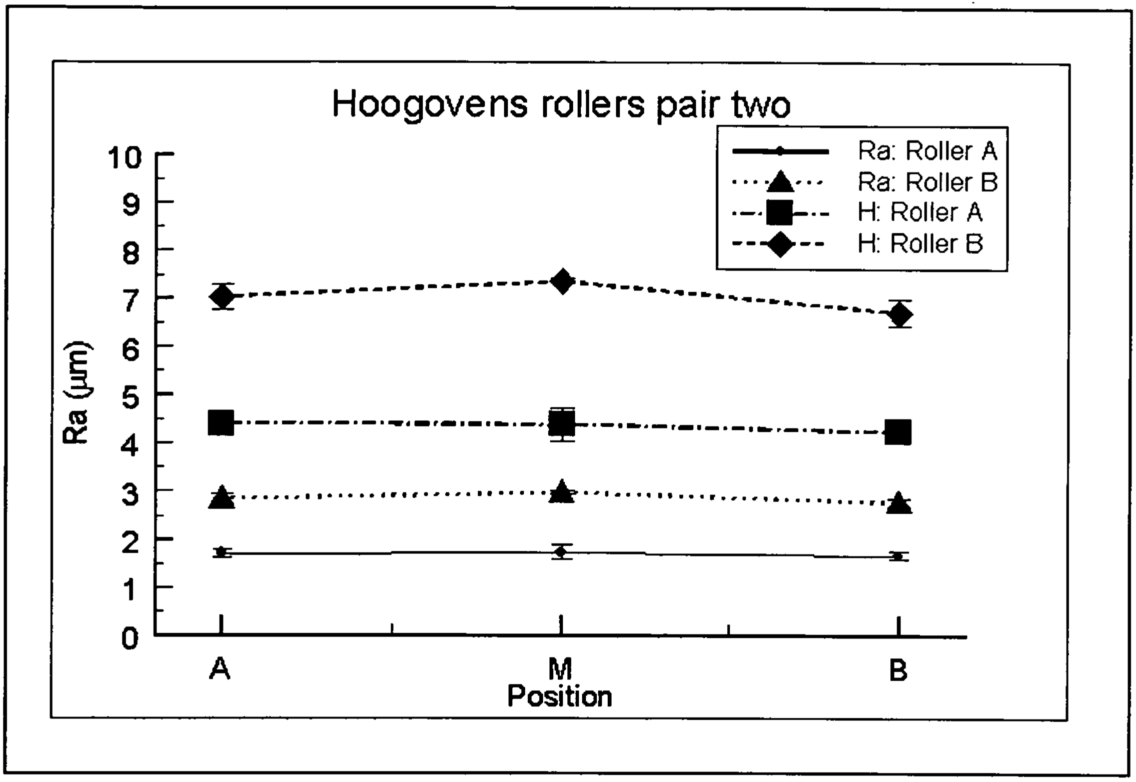


Figure 41 Roughness measurements for Hoogovens rollers pair 2

The roller was machined less than an hour after printing and suffered from significant mask breakdown. As a result the roughness was lower than had been predicted. Replicas were taken from the beginning, middle and end of the roller (sites A, M and B) and the roughnesses of both rollers are shown in **Figure 41**.

The mean roughness from the replica measurements of roller 2A is an R_a of 1.7 μm and H of 4.4 μm.

Hoogovens 2B f=1KHz d=80% 28 rpm 28 tpi fl=0.2 L/min

This time the roller was left overnight before machining. The ink adhesion was satisfactory but the ink spreading was worse leading to larger drops. This in turn reduced the machinable area and therefore increased the final R_a to an average 2.9 μm. A slight drop was noted on the last replica. This was due to the tool being withdrawn slightly to reduce abrasion which appeared to be causing the ink mask to break down.

Roughness variation across the roller is shown in **Figure 41** while the mean values are an R_a of 2.9 μm and an H of 7.1 μm.

After these rollers had been textured Hoogovens decided that they would also like to use them for skin passing and would therefore require a higher quality of pattern. After consultation Domino kindly agreed to supply a new reservoir of BK0701 ink to see if this improved the drop geometry. The ink change resulted in a reduction in dot size of approximately 35 % between R6 and R10, the first to be printed with the new ink. This can be clearly seen in **Figure 42**.

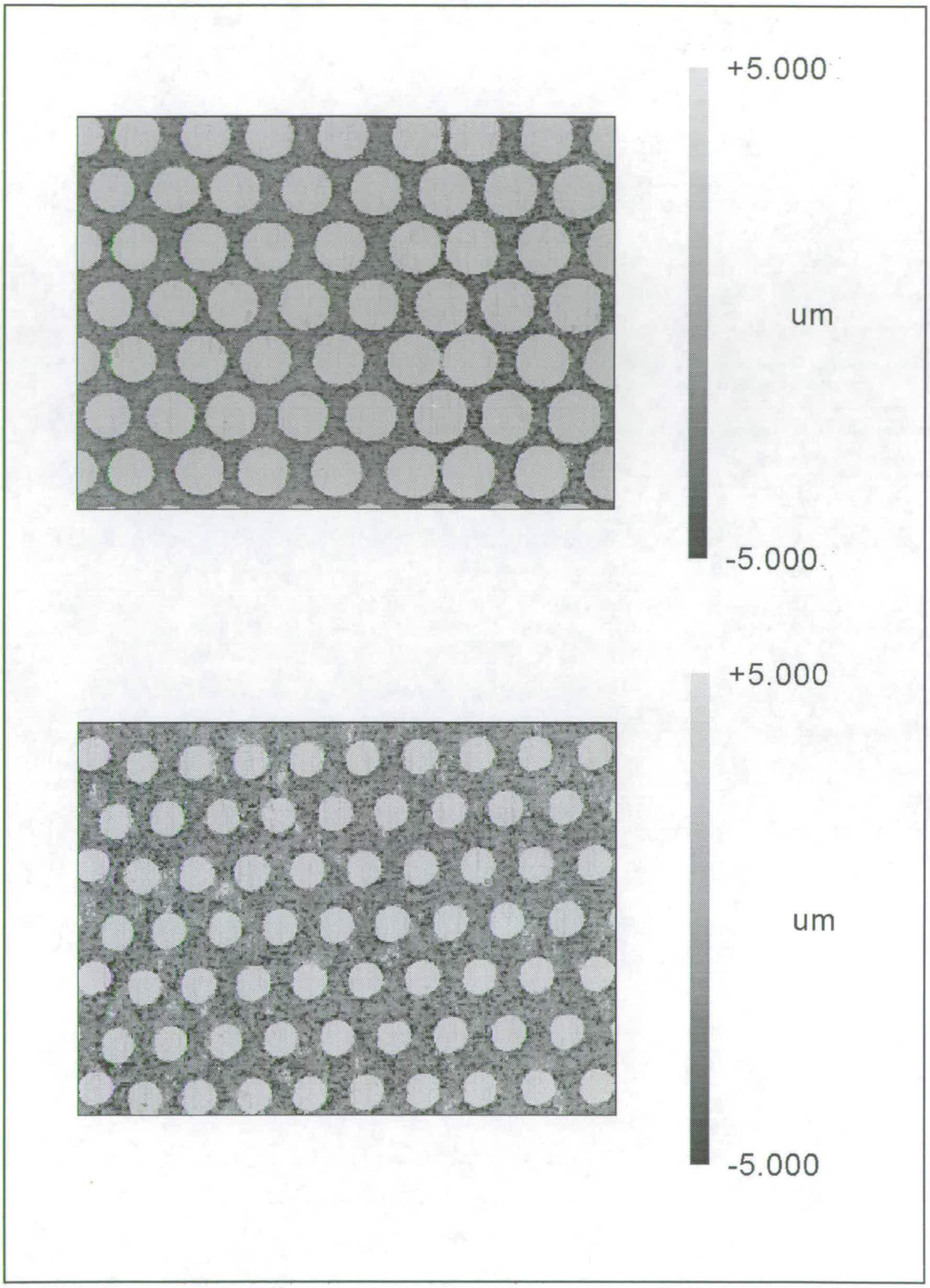


Figure 42 Comparison of dot size for different ink types, BK0101 (R6) and 0701 (R10)

Roller 10 f=1KHz d=70% 65 rpm 28 tpi fl=0.2 L/min

This was printed with the same drop spacings as the previous rollers. As with roller 3 clutch slippage meant that the roller was initially rotating slowly. This was noted and corrected about 200 mm in from the start of machining. The R_a was lower than before due to the increased surface area to be machined.

Measurements taken around centre of roll show mean R_a of 2.3 μm and H of 6.9 μm.

Roller 11 f=1KHz d=70% 65 rpm 28 tpi fl= varied

The increased machining area for the 0701 made achieving the 2.5 μm R_a in the Hoogovens rolls more difficult. In an attempt to increase the machining rate this experiment looked at the effect of increasing both the peak count and the flow rate. The roller was printed in six bands, alternating between high peak counts (encoder divide 25 x) and low peak count (40 x divide as before). These are shown in **Figure 43**.

The results of this experiment are shown in **Figure 44**. This shows that increasing

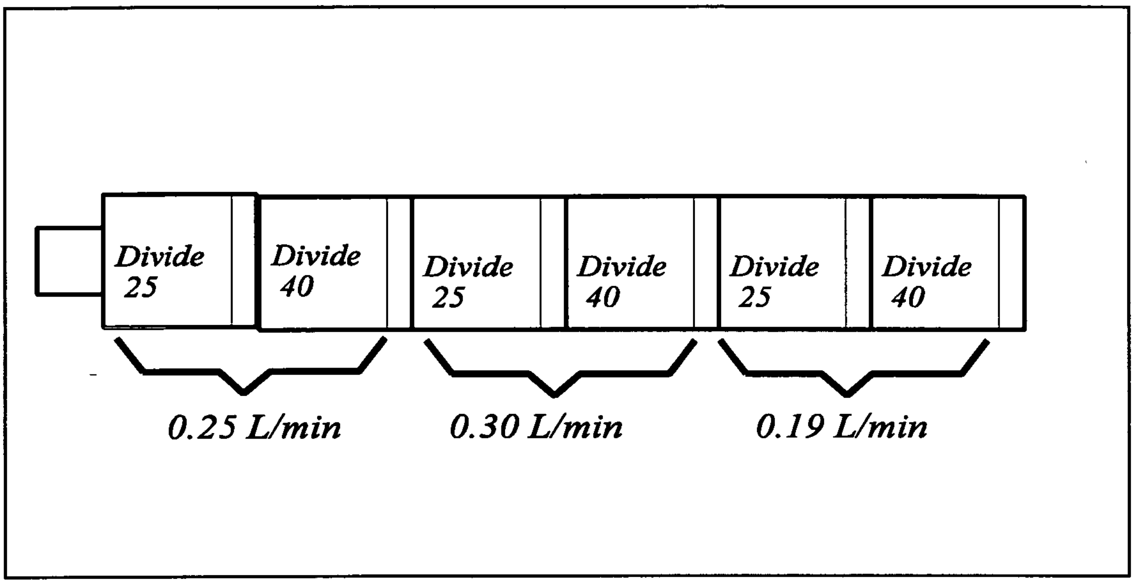


Figure 43 Location of machined areas on roller 11

flow rate and increasing peak density both increased the R_a. It also showed that the Hoogovens rollers could be printed at a higher peak density and that the required roughness was attainable.

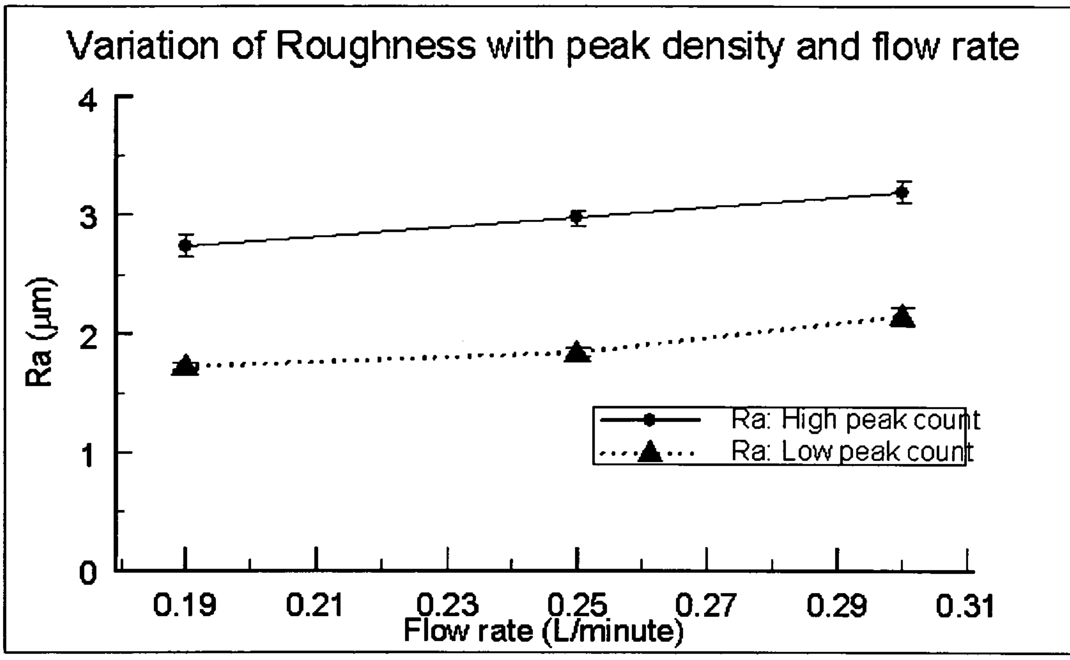


Figure 44 Roughness variation with peak count and flow rate

The radiused tool was masked by 0.9 mm thick low density polyurethane sheet for this experiment. Adhesion appeared to be good and slight discolouration and scuffing seemed to be the only signs of wear. It was therefore decided to use this material for the Hoogovens rollers.

Hoogovens 3A f=IKHz d=80% 28 rpm 28 tpi fl=0.2 L/m

The third set of large rollers to be textured were printed with BK0701 ink with an encoder divide of 10 and a stroke height of 3.0 mm. A number of problems were encountered with the printing. Marker pulsed were occasionally missed resulting in either double printed or missed bands depending on whether a print go or a move command had been due. Also the print spacing was observed to vary around the circumference. This was not noticed on the smaller rollers, even at equivalent stroke rates, and may be due to lathe speed variations or vibrations, accentuated by the greater diameter. Because of this perfect butting of strips could not be ensured even where they had started in phase. Printing was tried at speeds of 24 and 31 rpm with the faster speed being worse.

Spreading was also worse than on the small rollers with some drop merging initially observed at 10 divide. To minimise this the printhead gap was increased to 8 mm.

Again replicas were taken at beginning (A), middle (M) and end (B) of machining with 11 measurements per site. The electrode mask started to break down about a quarter of the way into the machining. Leakage was observed at the leading edge of the tool and got slightly worse with time. The mask remained attached at the top and bottom faces but upon examination after use it was observed to have separated almost completely on the machining face. This failure occured exclusively on the copper chrome suggesting that a more specific etchant may be required prior to bonding.

Figure 45 shows the roughness variation for both rollers of set 3. The mean roughness values for roller 3A were $R_a = 2.50\ \mu m$ and $H = 6.10\ \mu m$.

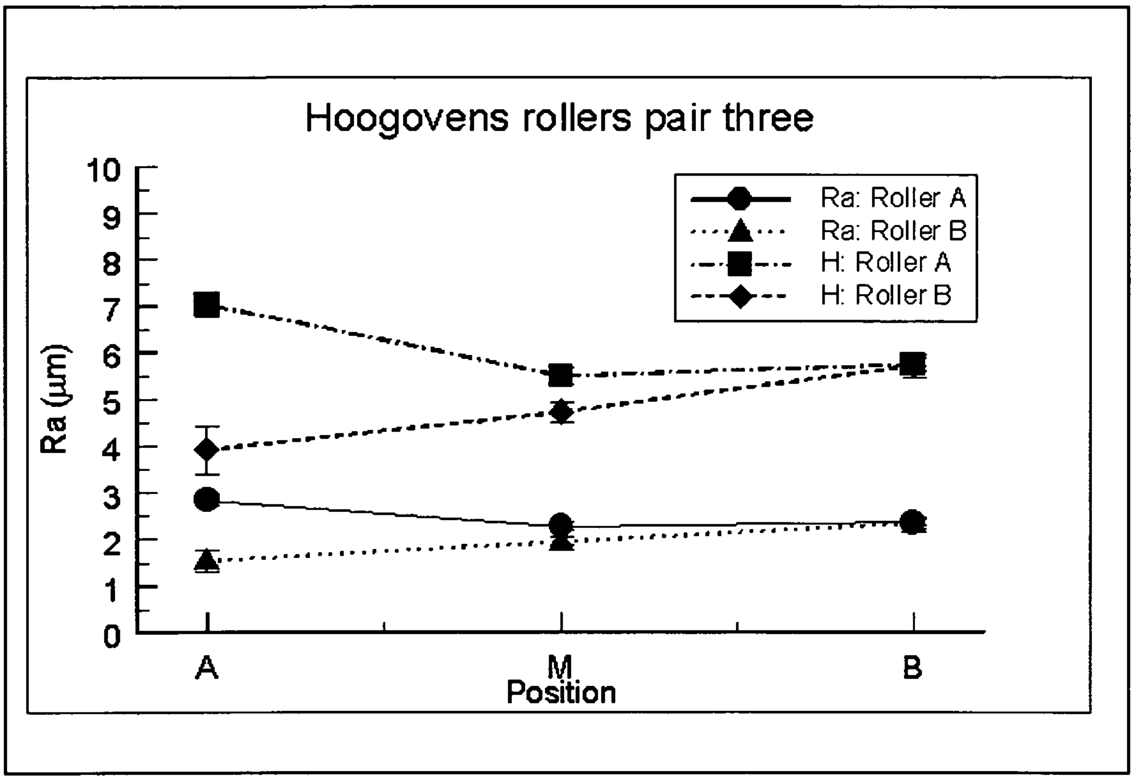


Figure 45 Roughness variation for Hoogovens rollers set 3

Hoogovens 3B f=lKHz d=70% 24 rpm 28 tpi fl=0.25 L/min

Printing was the same as roller 3A but the printer was run for some time without the makeup cartridge in an attempt to raise the viscosity of the ink. This was partially successful with less tendency for drop merging observed.

Machining conditions were similar to 3A but with the pu mask replaced by the foam tape and epoxy adhesive. The adhesion of this was good throughout the machining but poor tool alignment meant the electrode gap was large initially. Realignment during machining led to a more uniform current density. The peristaltic scavenge pump was used with little leakage being observed. The surface of the roller remained wet after machining but there were no signs of premature corrosion before texturing was completed.

The mean roughness values were R_a = 1.95 μm and H = 4.79 μm.

Printer refit

After these rollers were textured the equipment was adapted to enable ECT to be applied to other types of objects. These are beyond the scope of this thesis but included injection mould dies where accurate drop placements were essential. At this point the printer was modified to use 16 drop raster with a noticeable improvement in print quality. Unfortunately the printer needed a major service and it was suggested that a new head be fitted to bring it into line with the most recent versions of the machine. This was agreed and the new head was installed, this time with an increased umbilical length of 5 m - the standard is four metres - for added range.

Unfortunately after this the printer has been unable to achieve the small dot sizes that characterised the 0701 ink. A new reservoir of the ink had been installed but Domino were adamant that there had been no changes to the formulation which would account for this effect. The change in drop size appears to be a result of the head change but again it is difficult to see how this would change the drop size. Three main possibilities were felt to exist.

The nozzle diameter could be larger leading to larger drops. This is unlikely as they are precision bored to high tolerence. The 0701 ink has a tendency to coat the inside of the nozzle with time but this is unlikely to be the cause as a new nozzle plate was fitted before the head was replaced and the drop resolution was similar to before.

The gunbody heater (which maintains the temperature of the ink in the head) could be at a different set point. If the ink was warmer it would be less viscous and therefore spread more. The gunbody temperature was verified to be correct but this does not necessarily mean that the ink temperature was correct.

The final, and seemingly most likely cause for the change is in the increased umbilical length. Why this should be is not clear but it may be due to an increased pressure drop between pump and nozzle. This would lead to a lower jet pressure so a slower ink flow rate. This would result in a slower passage through the gunbody and therefore a higher temperature on exit.

While the reason for the change in dot size remains unclear it does seem to be a result of the change of print head. Further investigations are beyond the scope of this work but with the correct conditions the small dot sizes should be attainable again in the future and the subject will warrant little further consideration here.

The final stage of development was to enable the printing of the roller as a continuous helix to avoid the problems with band to band registration. This was done by using a proprietary parallel interface card for the printer and controlling it directly with an embedded micro-controller. This system worked and was used for the remaining experiments.

Roller 12 f=1KHz d=50% 65 rpm 28 tpi fl=0.2 L/min

This was intended to be printed on a 2.8 mm helix to give a peak count of 2.86 peaks per mm. This proved very difficult to achieve as the stroke could not be reduced to this height without clipping of the ink return gutter. Eventually the roller was printed on this pitch but with a one drop overlap to give an effective pc of 2.5 ppmm. Pattern matching seemed good so it was decided to machine it anyway. Air was blown in to the print gap giving much better uniformity of drop diameter.

The roller was machined at constant potential using the same tool and mask as used for roller 11. This was still intact except for some peeling around the internal edges which were sealed with cyanoacrylate adhesive. The scavenge pump did not work (this was later traced to a blocked return valve) so electrolyte leaked into the collection tray. Adhesion of both ink and tool masks was found to be good throughout.

Current was 10 A initially rising to 11 A by the end of machining. Two bands were machined into an unmasked section at the end of the roller. First the duty was increased to 80% with no increase in current. The second was machined at d.c. and the current dropped to 7 - 8 A.

Measurements in the centre of the roll show a mean R_a of 2.40 μm and H of 6.0 μm. These measurements were repeated 90^0 round the circumference to give R_a = 2.46 μm and H = 6.0 μm. **Figure 46** shows the variation of roughness with machined length. Again it shows an initial drop followed by a gradual increase.

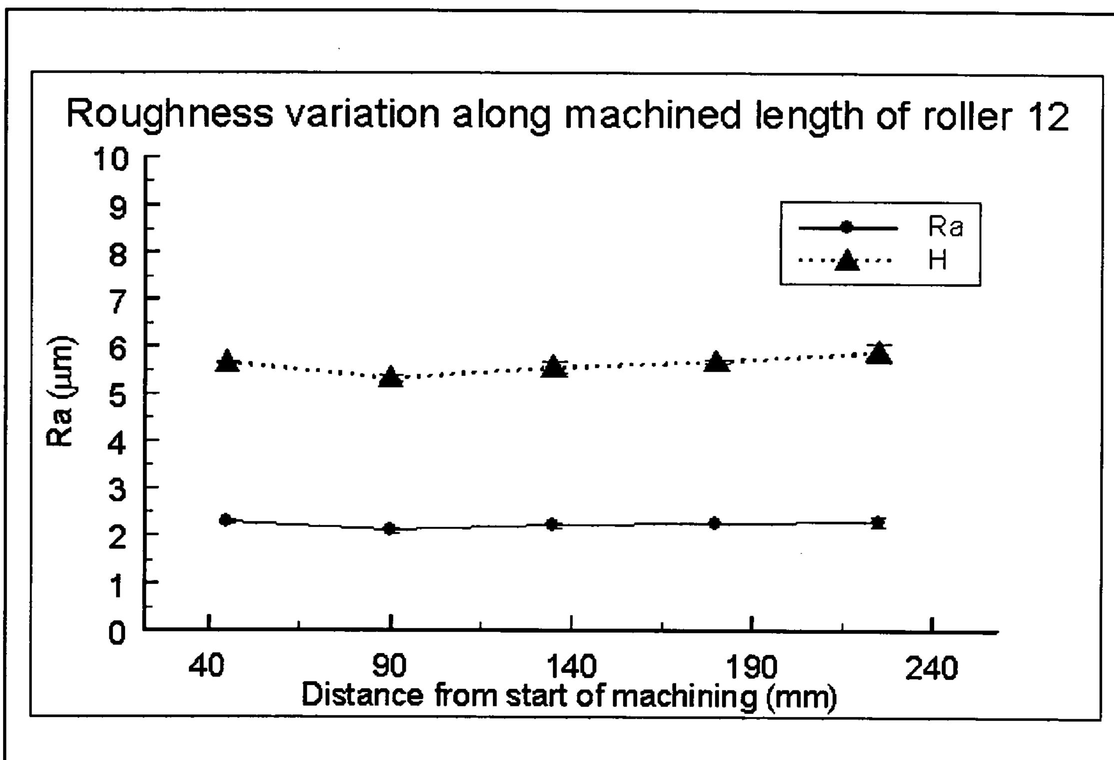


Figure 46 Variation of R_a versus machining length for roller 12

An 8 mm by 4 mm scan of this area is shown in **Figure 47**. A fourth order polynomial has been applied to remove the curvature of the roller but the residuals can still be seen. None the less it does show uniformity of texture and machining depth with little sign of waviness.

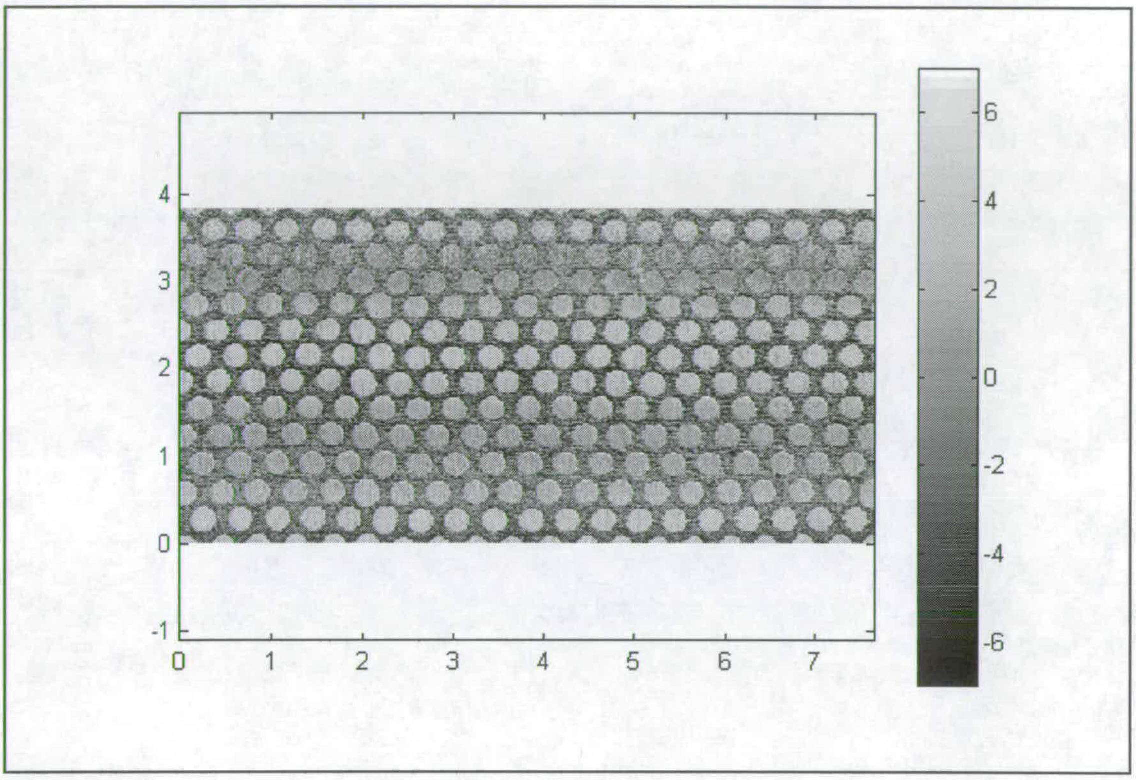


Figure 47 Large area scan of roller 12

Roller 13 f=1KHz d=50% 65 rpm 28 tpi fl=0.25 L/min

The printer was readjusted so that the jet was positioned very close to the edge of the gutter. This enabled the full eight drops to be printed within a 2.8 mm pitch. The pattern printed well but went from a slight overlap at the start of printing to a slight gap at the end. This suggests that the print head was slightly out of true from the roller.

It was intended to attempt to machine this roller at a constant current of 10 A using the current limit of the power supply. Some ink scoring occured at the start so the head was angled slightly to reduce rubbing. The flow was initially 0.2 L/min but the current was limiting at 8 A so flow was increased to 0.26 L/min. The current then fluctuated between 9 and 10 A. The scavenging worked well on this occasion with no appreciable leakage and a dry roller surface after machining.

As with roller 12 two sets of measurements were made at 90^0 round the centre of the roll. These gave mean roughnesses of R_a = 2.27 μm, H = 5.63 μm and R_a = 2.15 μm, H = 5.4 μm respectively. The mean wavinesses for these areas were 0.115 μm and 0.120 μm respectively. Roughness variation from replica measurements is shown in **Figure 48**.

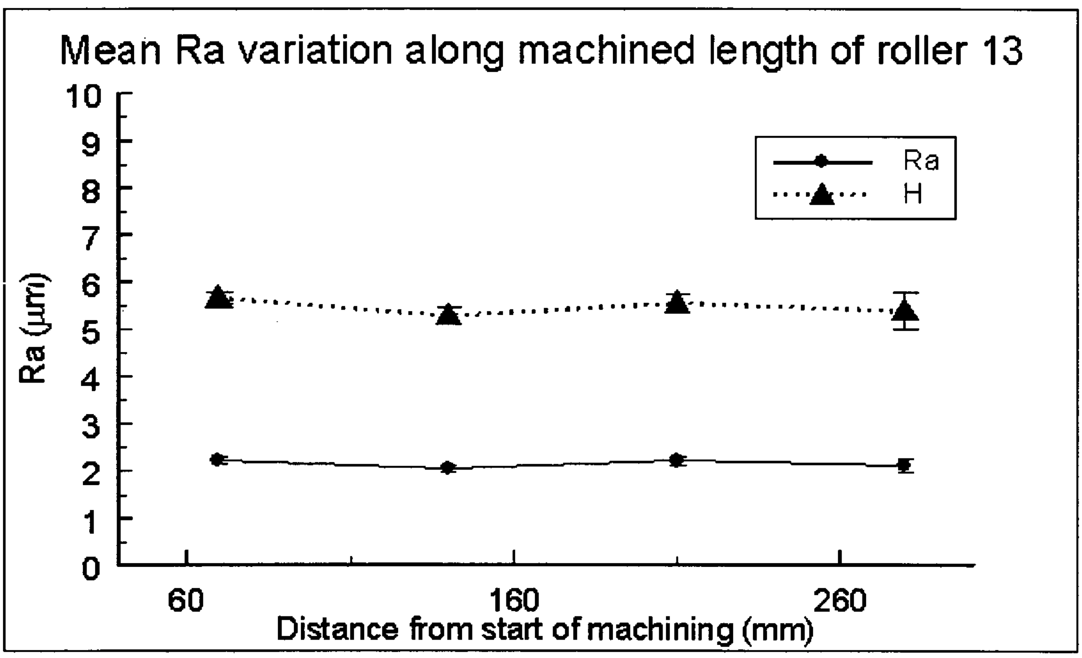


Figure 48 Roughness variation with machined length for roller 13

Roller 14 f=1KHz d=50% 65 rpm 28 tpi fl=0.26 L/m

This was printed under the same conditions as roller 13 but machined ten days later. Machining conditions were as previously with no mask breakdown apparent on while machining. Surface measurements after machining showed that some damage had occurred in the form of chipping on the leading edges of some dots although there were no signs of scoring or drop removal. **Figure 48** shows a plot of rms slope (brighter is steeper) which clearly shows the result of mask chipping.

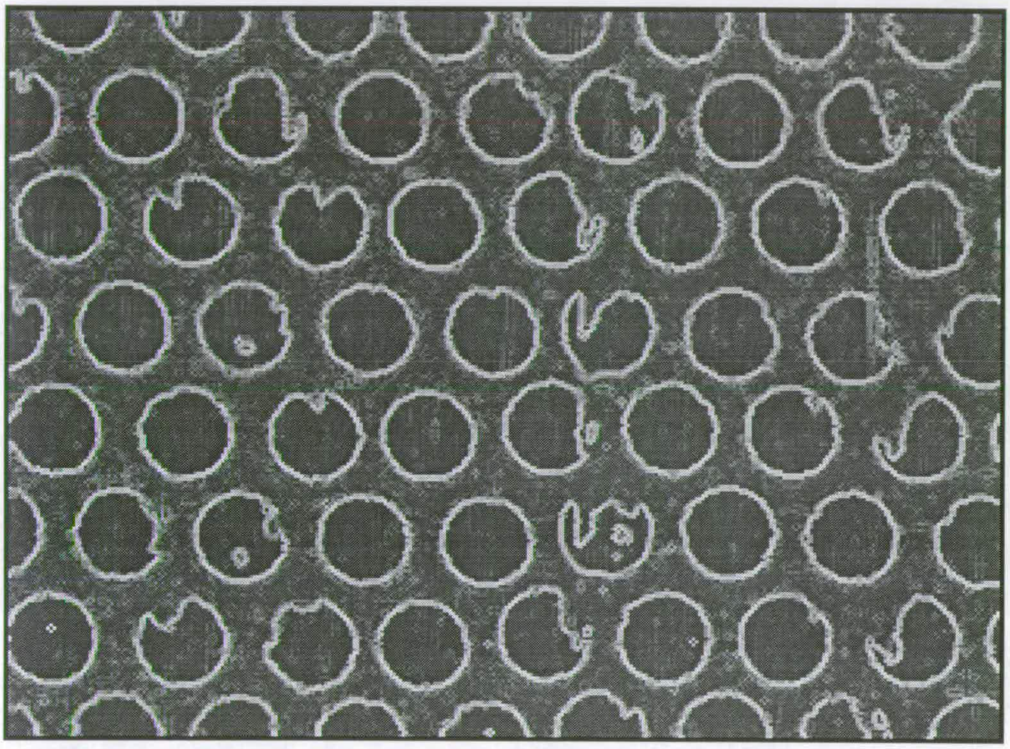


Figure 49 Slope map showing effects of damaged ink mask

As with roller 12 two sets of measurements were made at 90^0 round the centre of the roll. These gave mean roughnesses of $R_a = 2.01\ \mu m$, $H = 4.9\ \mu m$ and $R_a = 1.92\ \mu m$, $H = 4.7\ \mu m$.

These values are lower than roller 13 but this can be attributed to the greater exposed area caused by the chipped ink.

Hoogovens 4A f=lKHz d=50% 24 rpm 28 tpi fl=0.25L/min

This, the final set of large rollers, was textured for skin passing before and after galvanealling. Because of this it was decided to aim for an R_a of 2.0 μm as a compromise between the two requirements (high R_a before plating but low R_a after). Volumetric calculations based on the data from rollers 13 and 14 suggested that this would be achievable with a machining current of approximately 11 A.

The roller was printed with a pitch of 2.8 mm and an encoder divide of 16. The localised variation of stroke spacing, observed with Hoogovens roller 2, was still present. This meant that perfect registration of the pattern was not possible, although it was still an improvement on previous large rollers. The stroke errors seem to be caused by small variations in the machine speed. Vibration of the print head is also possible but this was stiffened with little significant effect.

The tool used the same mask as was used over a year previously for Hoogovens roll 3B but showed no signs of leakage. Flow rate was steady at 0.25 L/minute. The machining current remained very steady at 11 A for the duration of the processing. Three replicas were taken at 60 mm from each end and in the middle. Four measurement were taken from each of these.

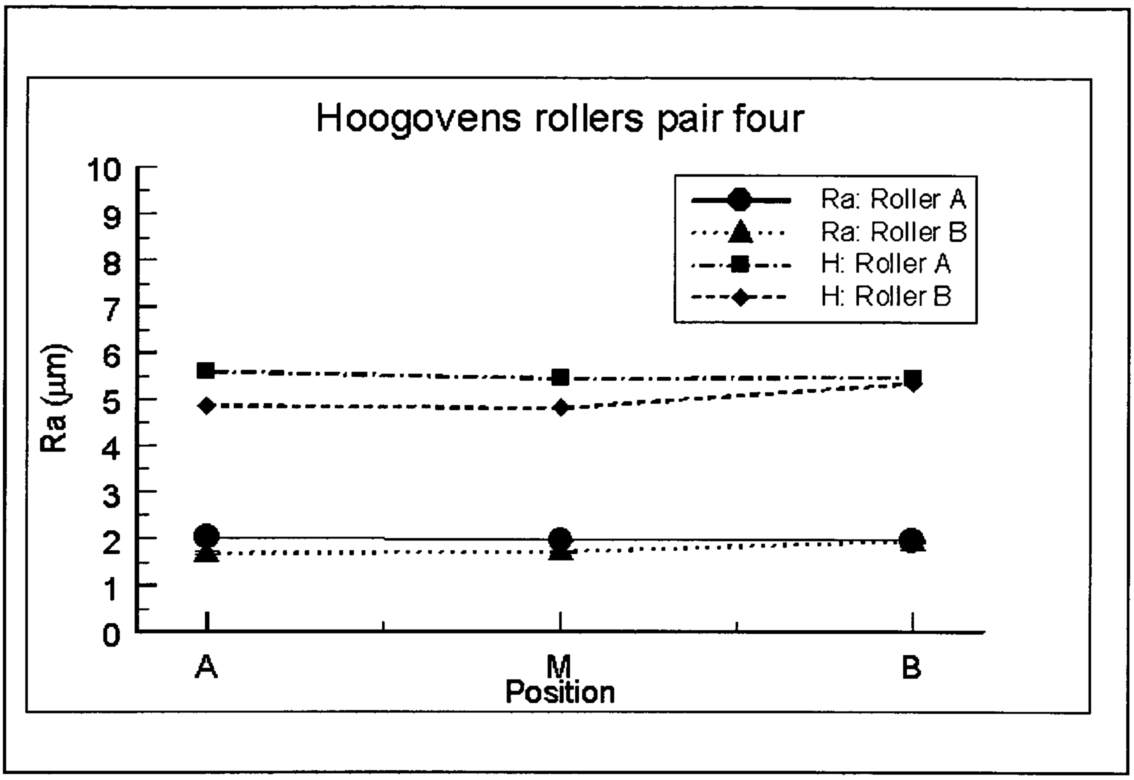


Figure 50 R_a variation for Hoogovens rollers set 4

The mean roughness gave R_a = 1.99 μm and H = 5.5 μm. **Figure 50** shows the uniformity of the roughness with a standard deviation across the three replicas of less than 0.1 μm. Unfortunately the standard of grinding of the roll as supplied from Holland was poor. The quoted R_a was 0.31 μm (compared to 0.1 -0.2 μm for previous rollers) but measurements taken from the tops of machined peaks suggest that it may have been more than 0.5 μm. This will not affect the ECT process significantly but it may be detrimental to the rolled sheet. An example of the texture is shown in **Figure 50** with an example of Hoogovens roller 3B. This gives a comparison of the BK0701 drop size before and after the printer refit.

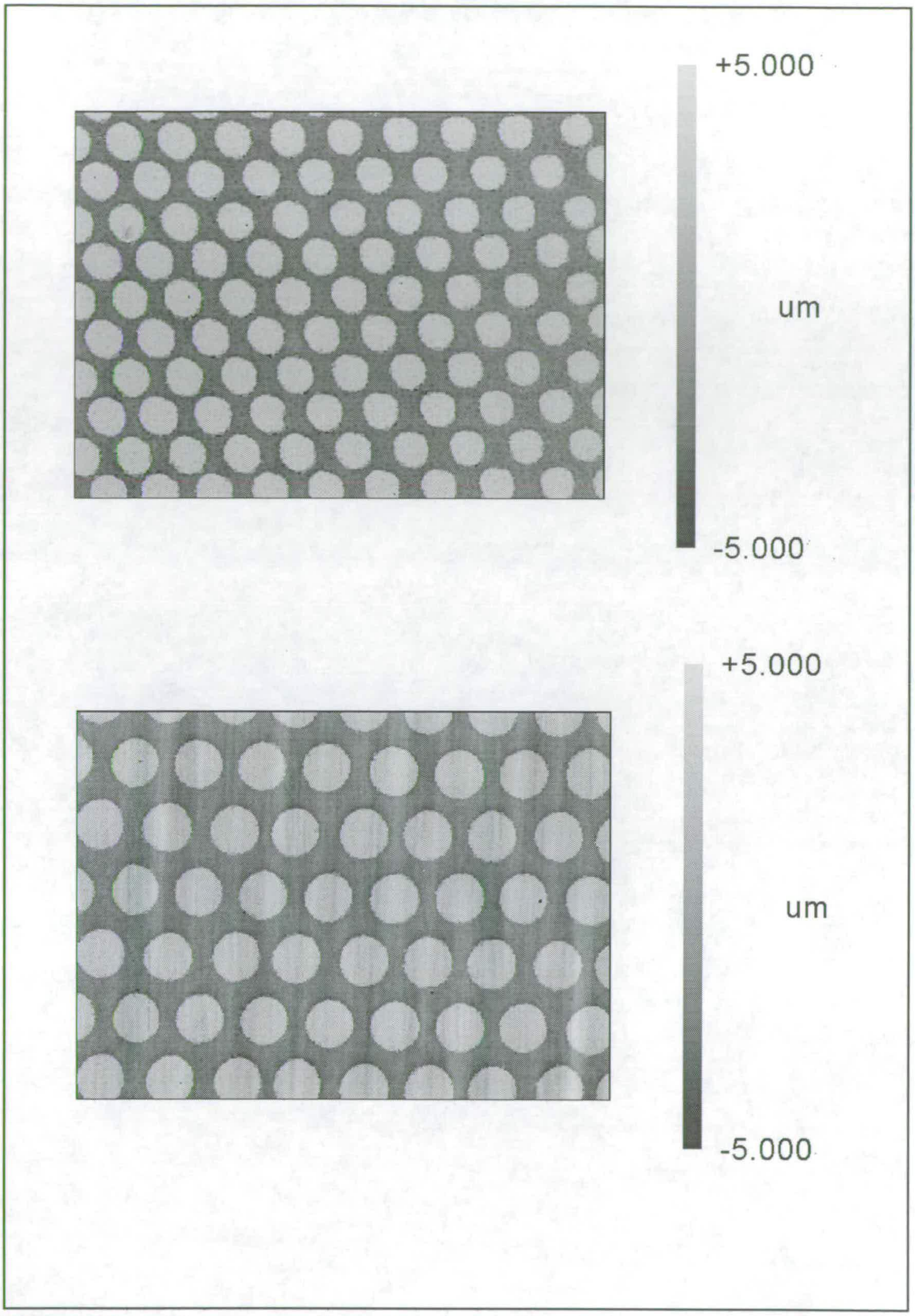


Figure 51 Hoogovens rollers printed with 0701 before (roller 3B) and after (roller 4A) the printer refit

Hoogovens 4B f=1KHz d=50% 24 rpm 28 tpi fl=0.24 L/min

This was printed and machined under the same conditions as the previous roller. The only slight variation was in the flow rate which started slightly lower at 0.24 and gradually increased to 0.26 L/min towards the end of machining. Replicas were taken at the three sites, A, M and B, as before.

Mean roughnesses were $R_a = 1.79\ \mu m$ and $H = 5.0\ \mu m$. Again roughnesses are plotted in **Figure 50**. This shows that while the roughness variation is very low, there is a rising trend towards the end of the roller.

6.3 Rolling Trials

6.3.1 Introduction

Although the main aim of this thesis is to investigate the texturing process, it must always be remembered that roller texturing is only a means to an end and that it is the rolled strip which is of most general interest. While the issues of rolling and texture functionality are out with the remit of this work some basic consideration may be of benefit.

One problem is the difficulty in generating rolled strip under realistic conditions within the laboratory. A small jeweller's rolling mill was purchased but is capable of demonstrating little more than that the textures are transferable from roll to sheet. More useful was the collaboration with British Steel and Hoogovens which enabled the generation of some data on roll wear and texture transfer on the latters pilot mill.

6.3.2 Roll Wear

Two sets of data have been collected for roll wear. From the first set of

Hoogovens rollers the wear over an extended period can be seen. This is based on 2D profilometry data provided by Hoogovens taken before, mid way through and after rolling on the upper rollers, and before and after on the lower ones. It is particularly useful as it also provides data for shot blast and electro-discharge textured rollers. These were commercially processed and used on identical rollers under the same operating conditions as the ECT rolls. In this way a direct comparison can be made between the wear of the three texture types in these conditions.

The R_a figures are shown in **Figure 35** on page 144. This shows no significant decrease in R_a over this period for the ECT rolls but drops of 21% and 33% for SBT and EDT respectively. The surface plots of the after rolling replicas in **Figure 36** on page 145 show a distinct rounding of the peaks but no signs of other damage such as broken or chipped tops.

The other wear data comes from the second pair of rollers. These had replicas taken before rolling and after a small amount of sheet (40 0.3 m plates, about 12 metres) was rolled. **Figure 52** shows the R_a of roller 2 before and after rolling. No reduction in R_a can be observed - if anything there is a slight increase but this is not seen as significant. **Figure 53** shows replicas of the same area of roller 1 before and after rolling. This clearly shows the effect of the ink mask damage during texturing resulting in the formation of small raised areas. These are the features which may be most vulnerable to chipping or breaking. The figures show no discernable wear from one to the other.

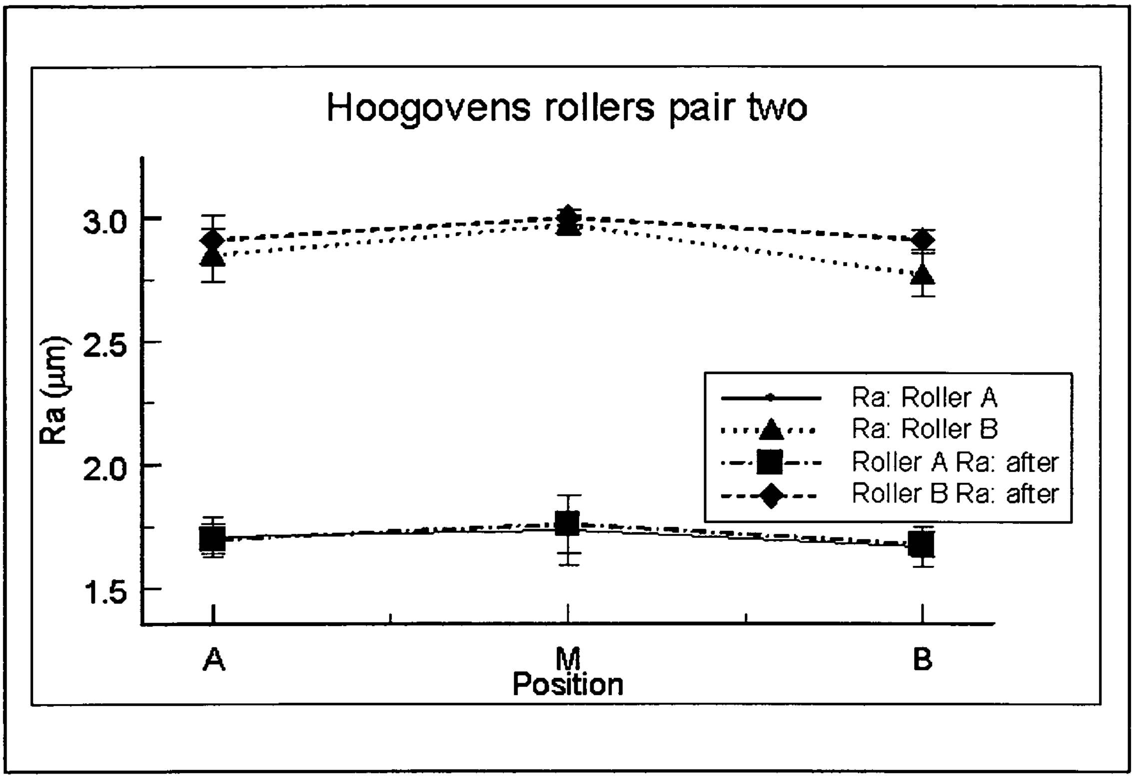


Figure 52 Variation in R_a for Hoogovens roller 2 before and after initial wear

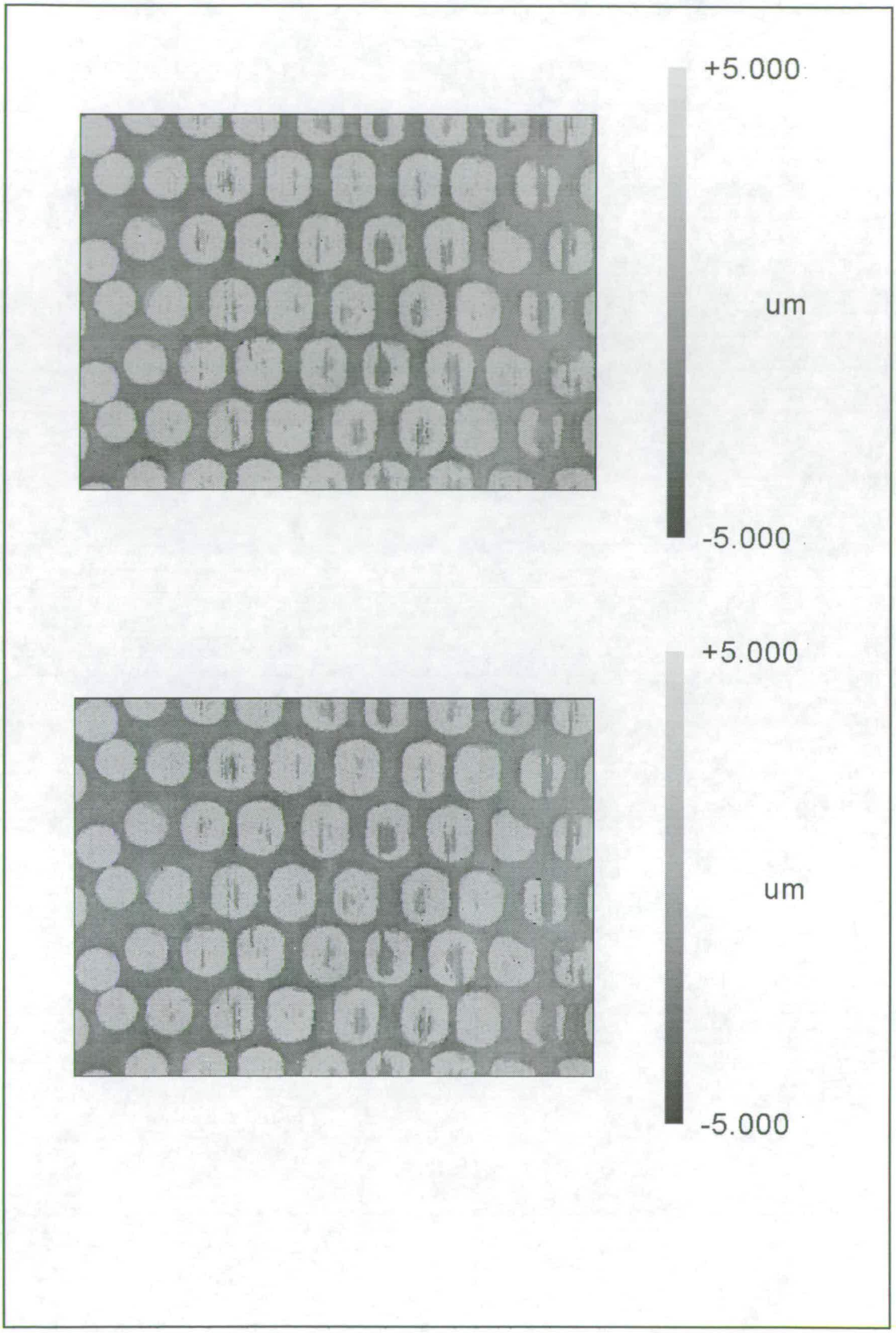


Figure 53 Area of roller 1 before and after rolling

Although a very small amount of material (equivalent to approximately one tonne at full scale) was rolled it should be sufficient to show any immediate wear such as has been seen with other processes.

6.3.3 Texture Transfer

Texture transfer is a difficult thing to assess in any circumstances. Should it be a straight ratio of roll to strip R_a, or peak count, or should it include other factors such as the original strip R_a as well. In this instance the ECT makes peak count transfer unsuitable (peaks are uniform height so transfer should be close to 100% or zero) while a lack of data precludes any attempt at sophisticated analysis.

6.3.3.1 Tandem roll transfer

By considering tandem rolled sheet the calculation becomes easier. The primary texture is *mill finish* imparted by the ground rollers used for the main reduction passes. The R_a of the primary texture is low, typically 0.1 - 0.2 μm, and can be neglected in a first approximation. A collection of histograms were supplied which give R_a values versus number of measurements for the three texture types (ECT, EDT and SBT) on two substrates at a variety of rolling loads. These have been used together with the R_a data from the first Hoogovens rollings (as given in **Figure 35** on page 144) to give a rough estimate of R_a transfer. This is shown in **Figure 54**, and while the numbers cannot be assumed to be exact they do represent general trends.

Rolling was done on the Hoogovens pilot mill in four high configuration and without lubricant. Two different interstitial-free steel substrates were used. Strip was fed through as individual panels although the option of rolling coils does exist on this machine. The actual roll R_a at the time of rolling is not known but values have been assumed between start and finish roughnesses. The assumed roll values are 3.0 μm for SBT and EDT, 1.35 μm for ECT top roll and 0.83 μm for ECT bottom roll.

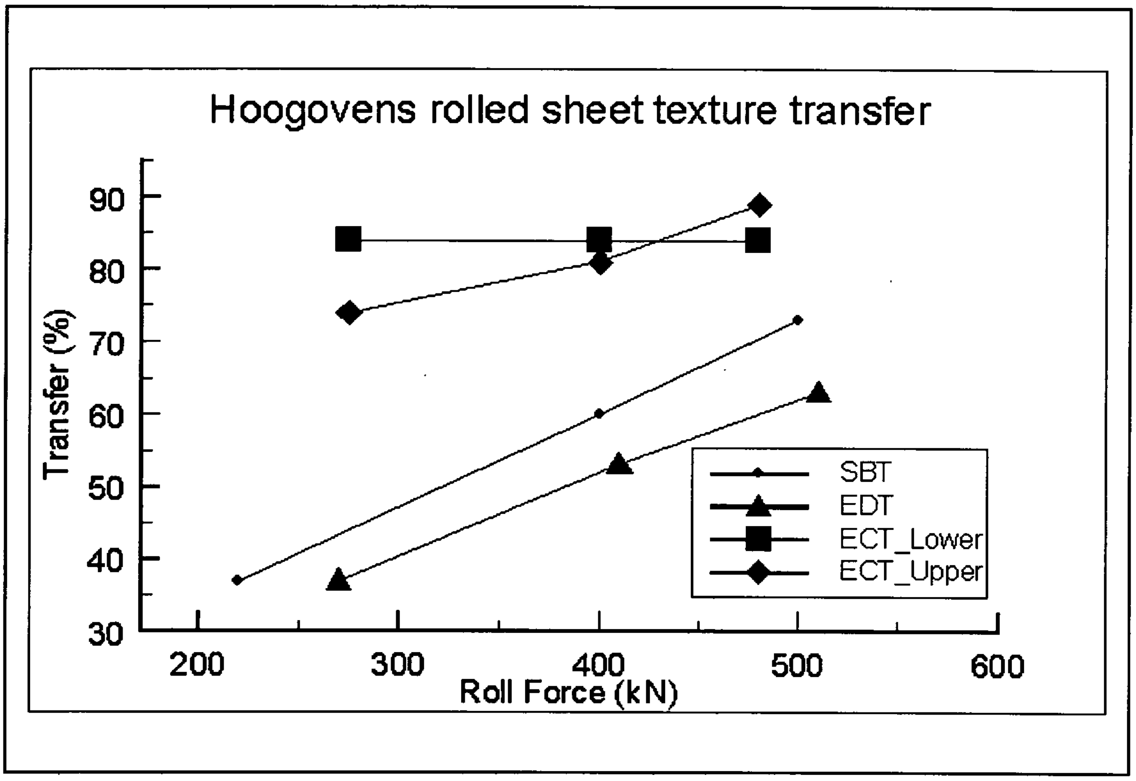


Figure 54 Texture transfer (2D R_a) for first Hoogovens rolling

Transfer for the ECT rolls seems to be significantly different to the other two, for both substrates. Firstly it is higher but secondly, and more significantly, it does not show the same linear relationship to roll force that the other two do. ECT transfer seems almost independent of roll force. This is supported by observations made during rolling that the texture would either transfer or would not. In other words once the elastic limit of the strip was reached transfer went from almost nil to full very quickly. This is in contrast to the other processes where it increases gradually with increasing load.

This difference can also be seen on the rolled sheet at regions where there is some variation in the spacing between peaks. Texture transfer can be seen to vary across these regions, the effect being particularly pronounced in areas where there is significant variation in dot diameter along the stroke. **Figure 55** shows an 8 mm square of sample H15 measured on the Scantron machine. This was produced using the third pair of Hoogovens rollers with a texture transfer, i.e. insufficient to cause the sheet to be deformed to the base of the roller. This shows a very pronounced waviness with a period equal to the height of the printed stroke. It can be seen that where the drops are further apart, through either diameter or stroke spacing variations, the sheet is rolled further into the texture to give a higher surface (assuming a uniform peak height). This can also be seen in the small area scan of **Figure 56**. Here the length of the measured area closely corresponds to the stroke height of the texture. The variation of peak to valley height along the stroke can be clearly seen, although it should be noted that the base of the craters should be planar with the variation on the top surface. The opposite can be seen here but this is due to the least squares plane extracted from the data to normalise it.

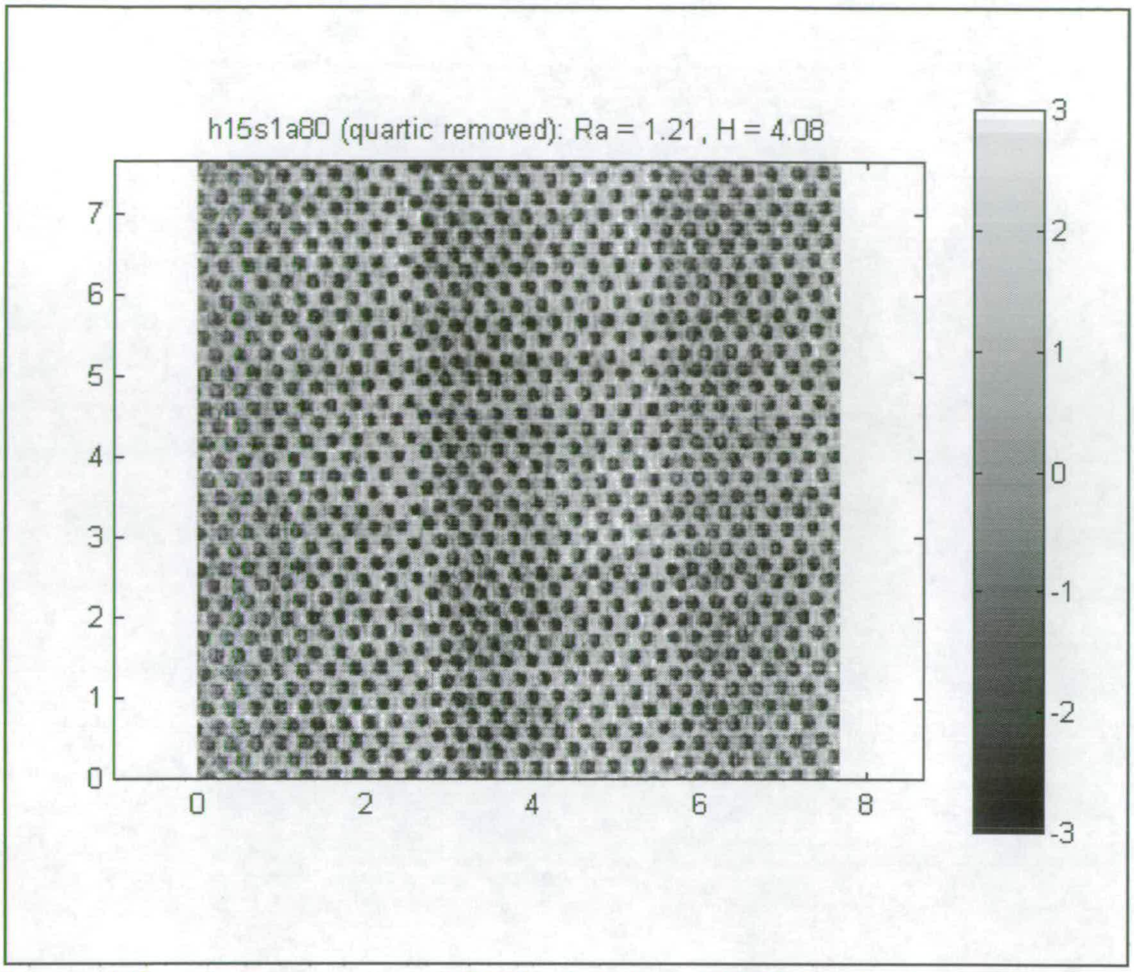


Figure 55 Large area scan of ECT rolled sheet (H15) showing incomplete texture transfer

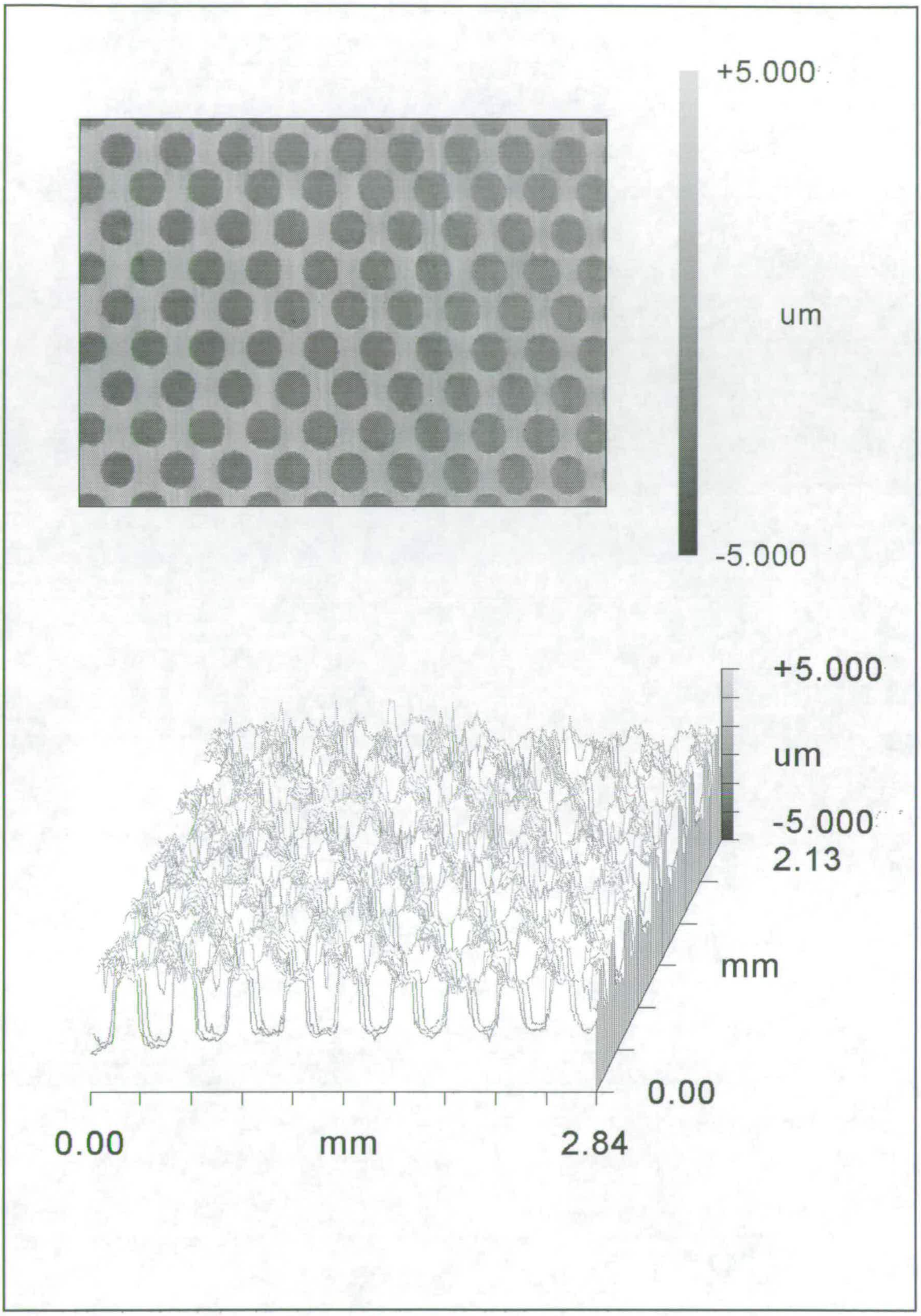


Figure 56 Small area scan of H15 ECT sheet showing peak height variation along stroke

The same rollers were used to produce sample BS20 which is shown in **Figure 57**. This time the reduction was higher resulting in almost complete transfer of texture to the sheet. A slight waviness can be seen but this time the high area correspond to where the spacing between peaks is at a minimum. These regions correspond to those areas of the roller which had the highest current densities (due to field concentrations) and therefore greater machined depths.

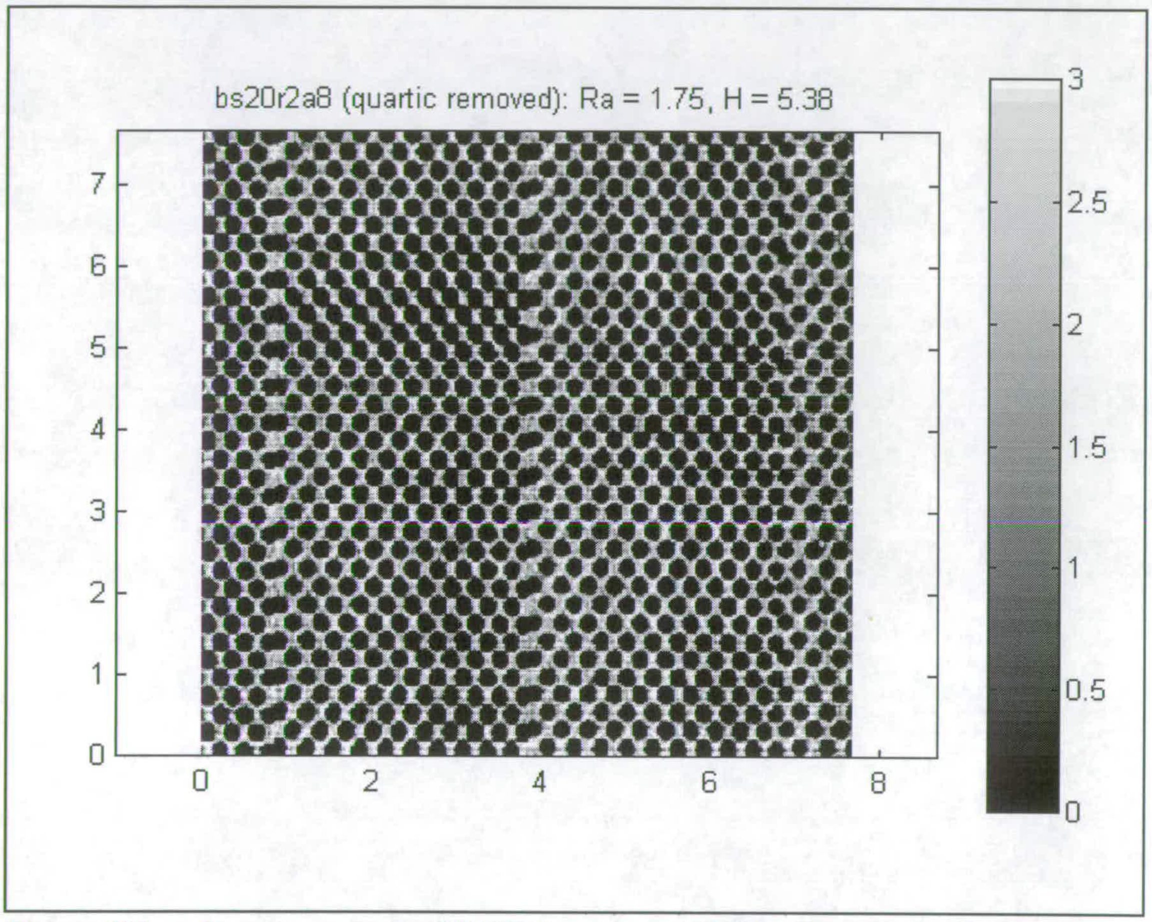


Figure 57 Large area scan of ECT sheet sample BS20 showing high texture transfer

6.3.3.2 Temper Rolling Texture Transfer

Calculation of transfer during temper rolling is more complicated. The primary texture is the result of the tandem rolling and may have significant roughness. This will result in the final texture being a composite of both the tandem and temper rolling such that identifying the transfer of the latter can be very difficult. Sheet samples were obtained which had been temper rolled on the Hoogovens mill at 0%, 1%, 2.5% and 4.5% reductions. The primary texture was EDT while the temper rolling was done with the fourth (and final) pair of ECT rollers. The 0% reduction represents the original tandem rolled EDT surface while 1% is perhaps most representative of normal temper rolling reductions. Unfortunately the higher reductions were obtained by passing the sheet through the mill twice. This has resulted in two sets of craters overlayed giving a non-uniform final texture. **Figure 58** shows R_a, H and Wa plotted against percentage reduction. Each point of the Zygo data was an average of nine measurements. The Scantron data uses only one measurement per point but this is compensated for by the larger area of the scan.

Figure 59 shows large and small area scans of the original EDT texture. Note that the vertical scale of the Zygo scan has been increased to accommodate the greater peak heights. The sheet with one percent reduction is shown in **Figure 60**. The original texture can still be seen but the ECT structure is clearly superimposed on top. Both plateau and craters show good height uniformity with a significant reduction in R_a, H and Wa. The high spots of the tandem texture have been effectively flattened although many of the valleys remain.

The higher reductions of 2.5 and 4.5%, shown in **Figure 61** and **Figure 62** respectively, demonstrate a further reduction of the original texture. Residual EDT craters can be seen but these become smaller and fewer as the reduction increases, to the point where they no longer represent a structure of interconnecting valleys. Also evident are the craters from the first pass of the ECT rolling, creating a mid level surface between plateau and valley bottoms. Both sheets show a good uniformity of plateau height and primary (from the first ECT pass) and secondary (from the second ECT pass) valley depth.

Also of concern is the waviness of the rolled sheet as this will influence the paint performance. The ECT rolling from 1% on shows a reduction in average waviness of approximately 40% from the original EDT sheet. While this is obviously a significant improvement, the magnitude of the ECT (Wa≈0.2 μm) was still higher than expected. **Figure 63** shows waviness plots for the temper rolled sheet at 0, 1, and 2.5% reductions. Waviness of the original sheet (top) shows the random structure associated with EDT but increasing reduction shows this evolving into a regular form of parallel groves on a pitch of approximately 0.65 mm. This form can be traced back to the original grinding of the fourth set of rolls by consideration of the roller replica plots in **Figure 64**. The waviness plot shows the same structure and pitch as the temper rolled sheet while the unfiltered data shows this to pass through both masked and unmasked areas. In this way it can be seen that the waviness is not a function of the ECT process.

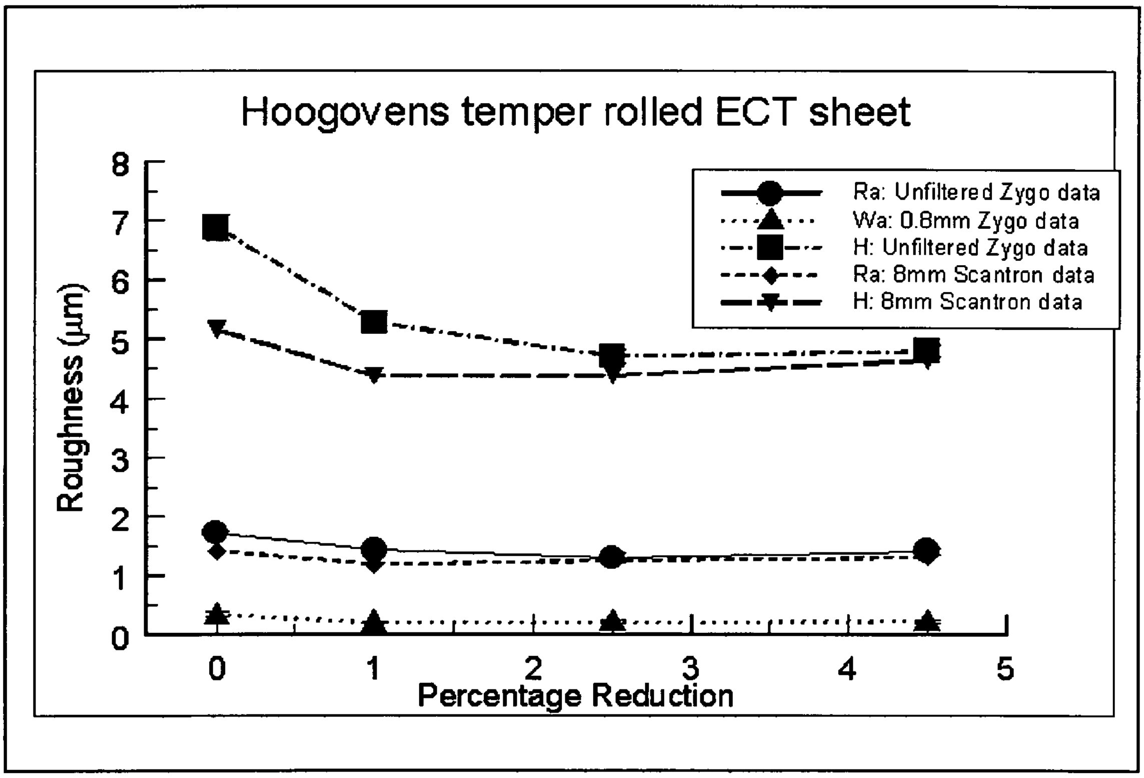
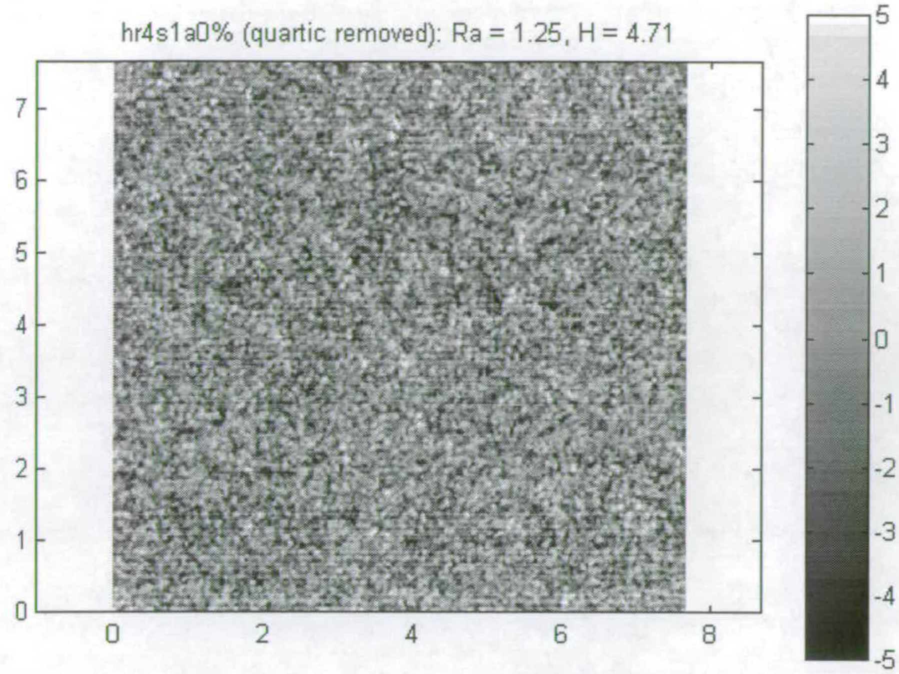


Figure 58 Roughness / waviness values for temper rolled ECT strip



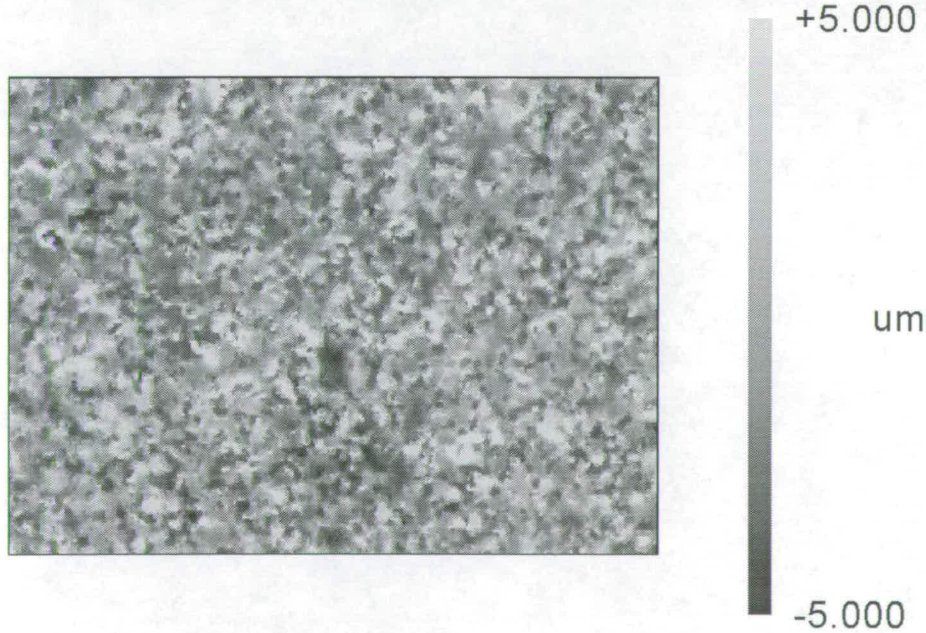


Figure 59 Surface plots of 0% reduction temper sheet (EDT tandem)

Lower measurement area 2.84 x 2.13 mm

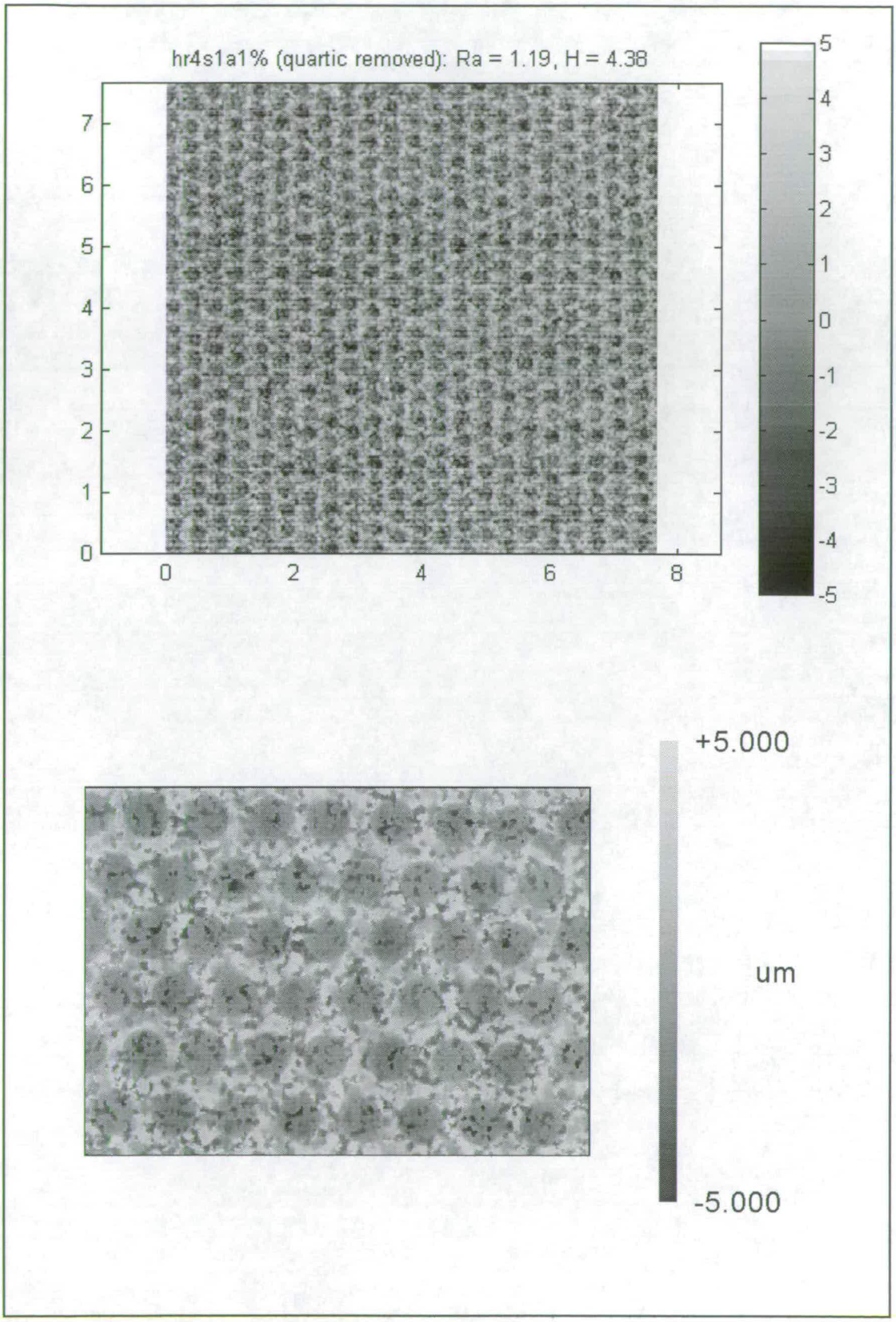


Figure 60 ECT temper rolled sheet, EDT tandem, 1% reduction

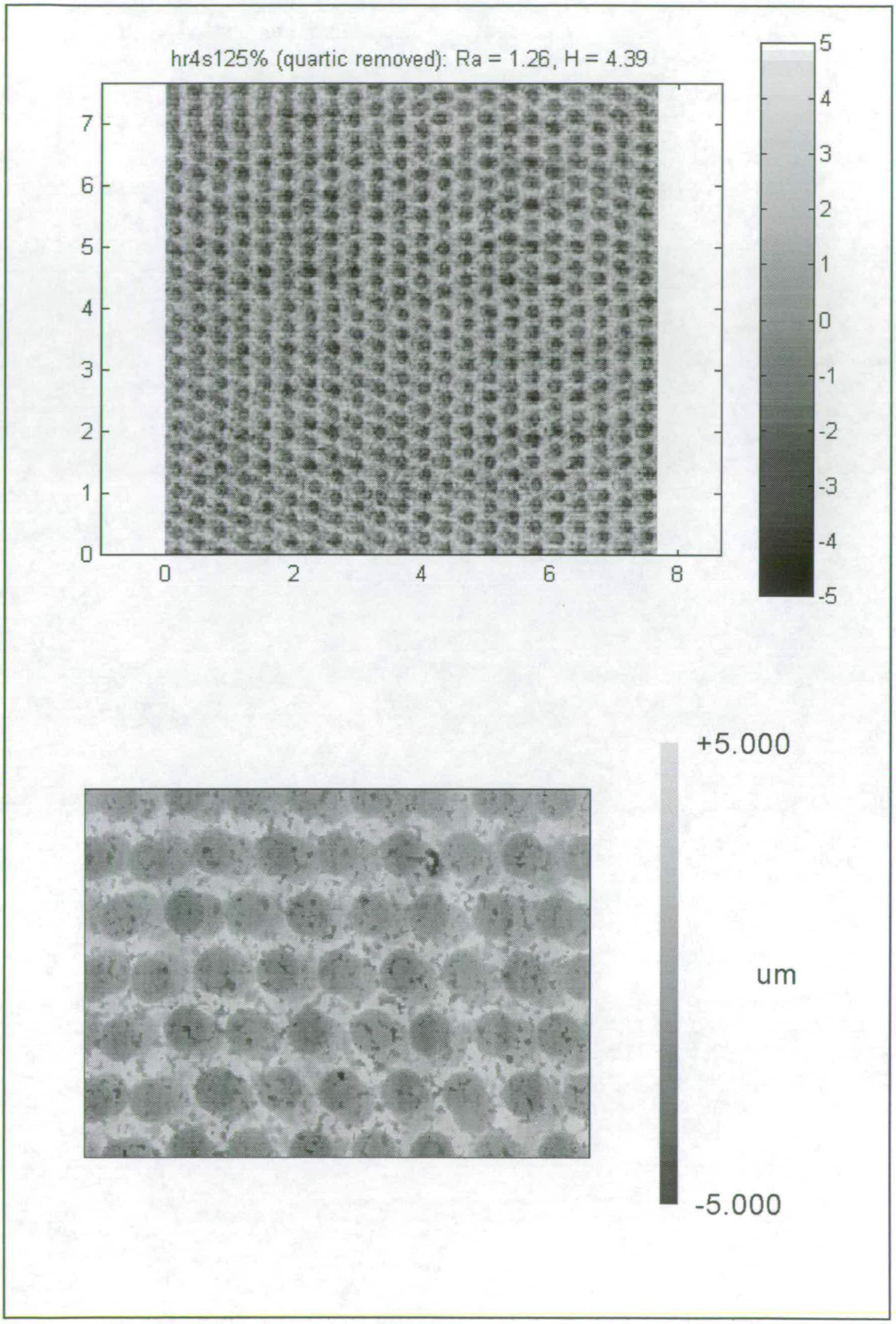
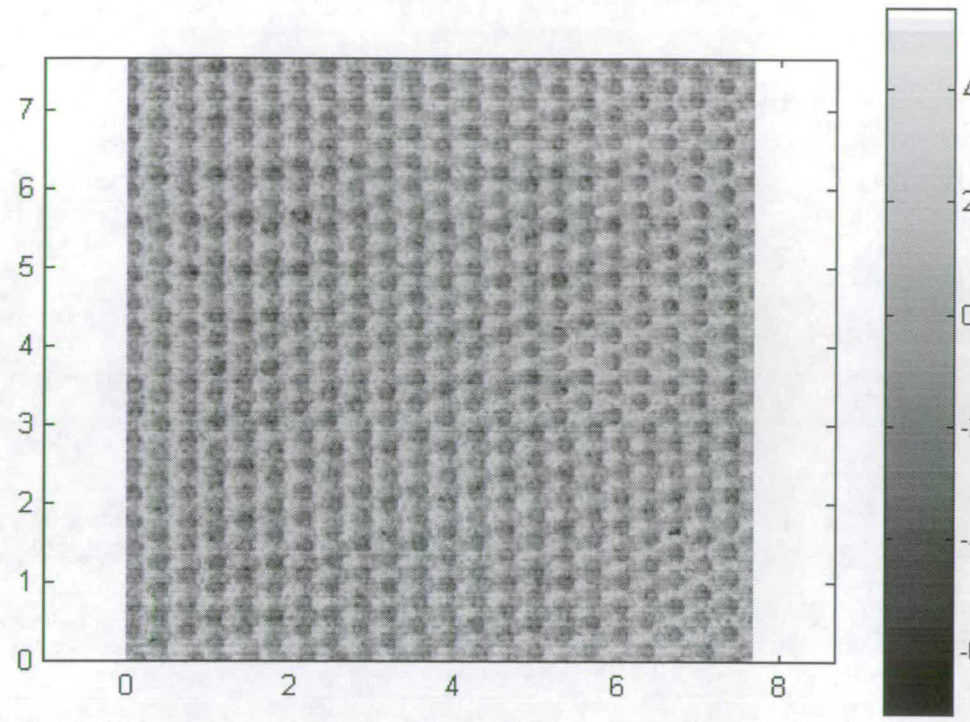


Figure 61 ECT temper rolled sheet, EDT tandem, 2.5% reduction



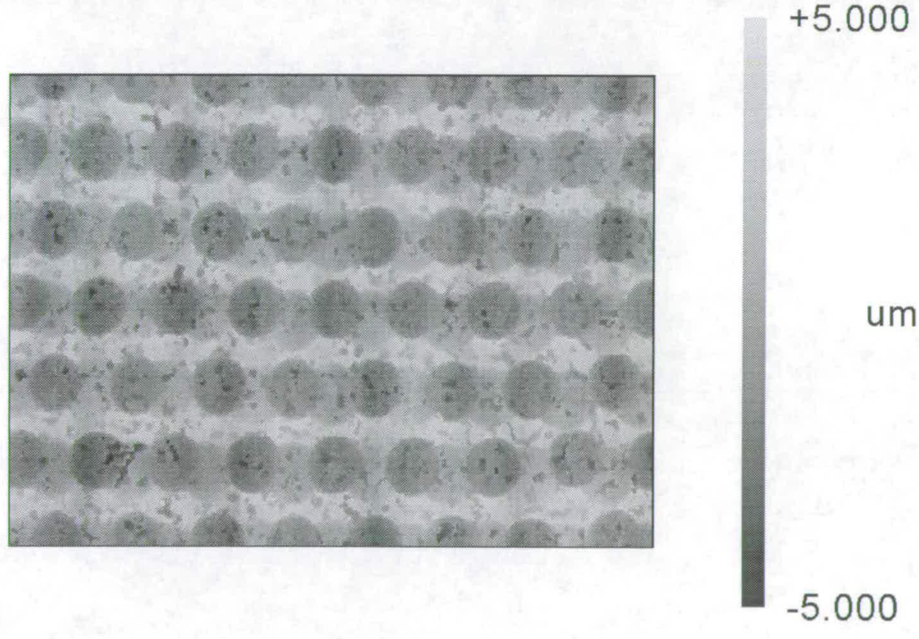


Figure 62 ECT temper rolled sheet, EDT tandem, 4.5% reduction

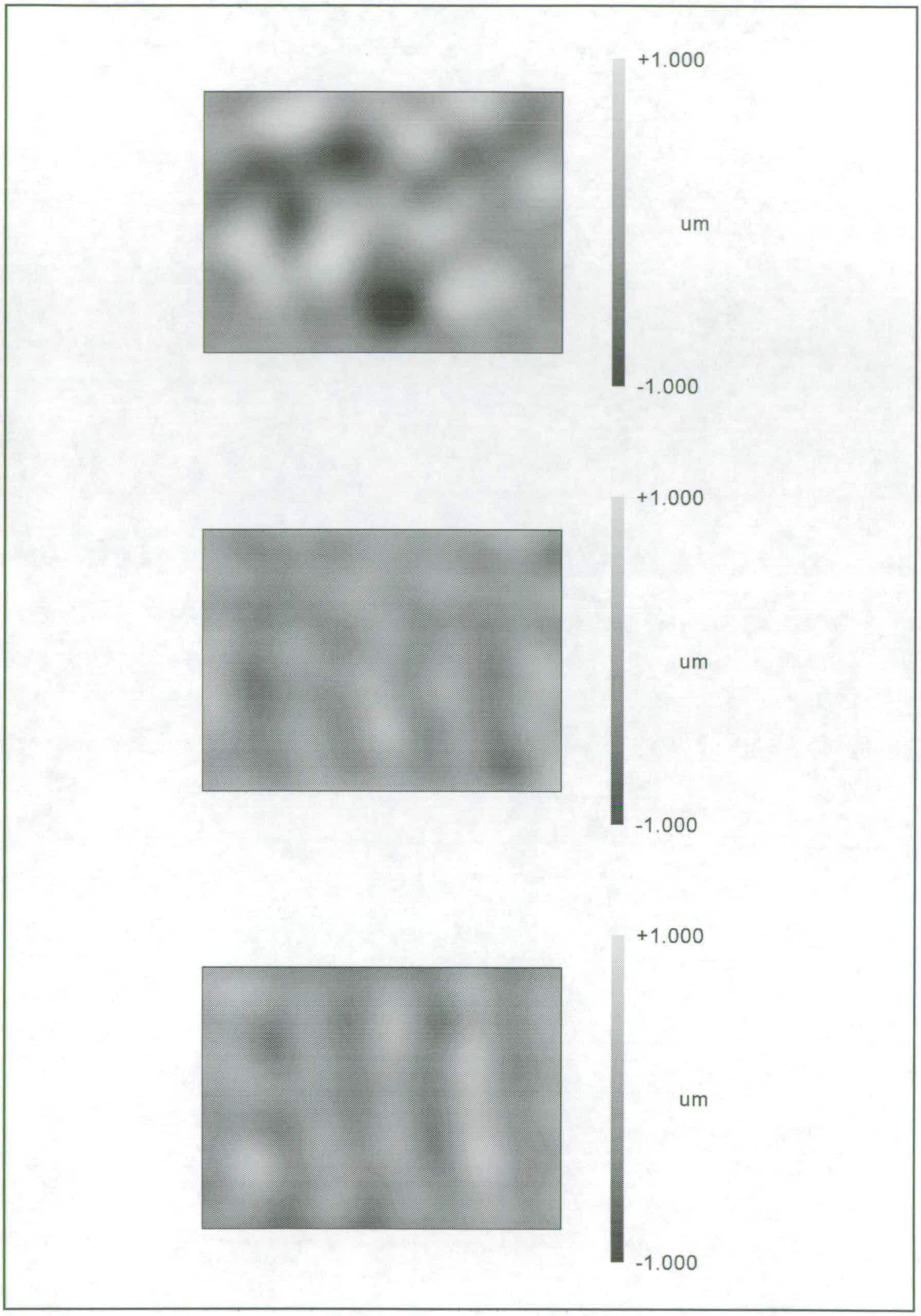


Figure 63 Waviness data for ECT temper rolled sheet: 0% top, 1% middle and 2.5% bottom

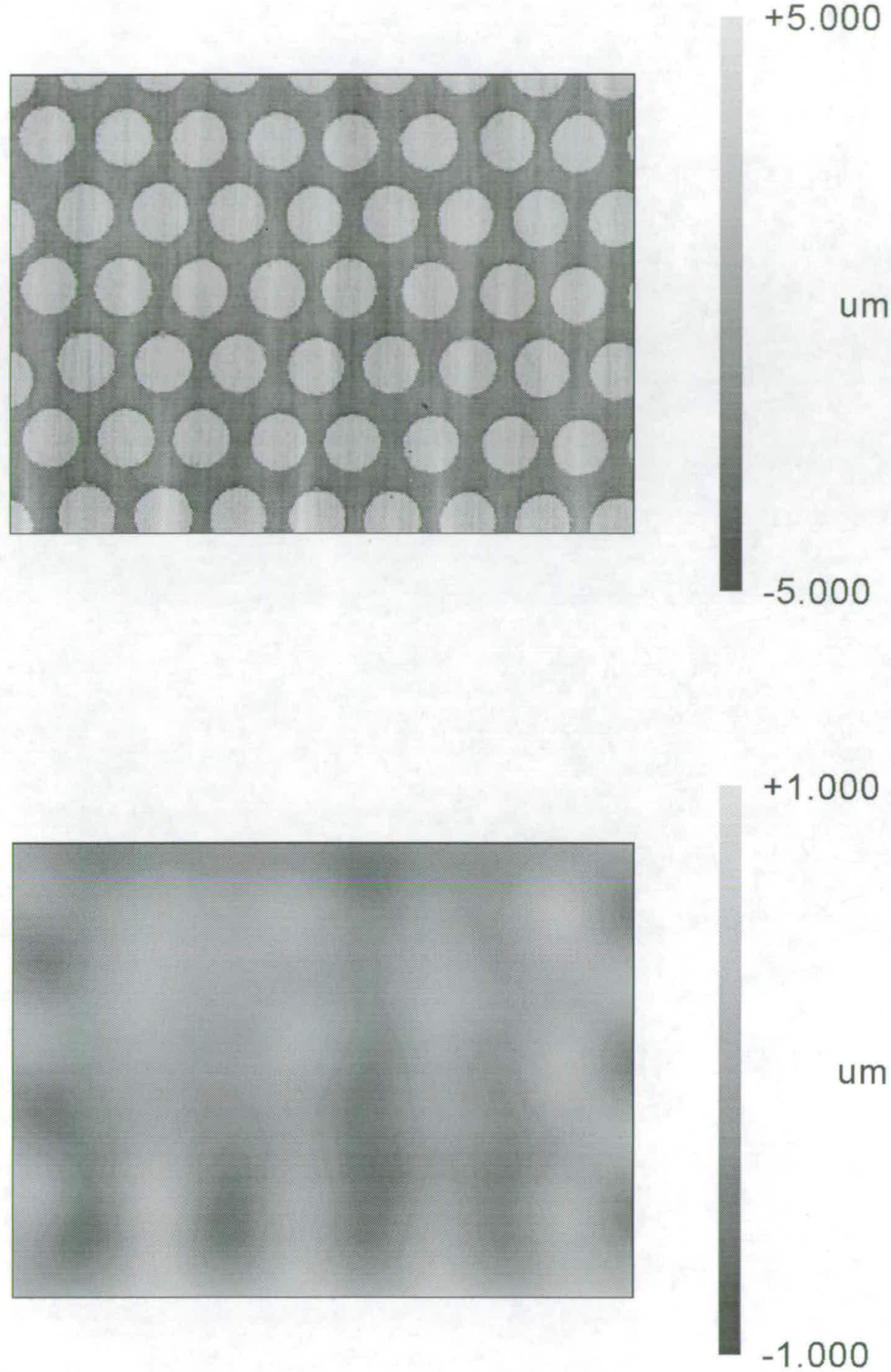


Figure 64 Unfiltered and waviness plots from middle of Hoogovens pair 4 roller 1

6.3.4 Rolled Sheet

Although various samples of commercial rolled sheet have been obtained and analysed, this section will concentrate on those produced by tandem rolling in the Hoogovens trial. This will give the most realistic comparison between ECT and the other processes, SBT and EDT. Lasertex and EBT are not included as all samples have been temper rolled, that is to say they have been textured at least twice. This means that the measured texture will be a composite of different textures, possibly from different processes. The samples included here allow comparison based on a single pass.

The measurements are taken from four sheets rolled on the Hoogovens mill. All were reduced from 1.8 mm to 0.8 mm by successive passes through the mill with the textured rollers being used at the final pass. One panel each of EDT and SBT are studied with two of ECT representing medium and high reductions. Surface plots of the ECT sheets are given in **Figure 56**, **Figure 55** and **Figure 57**, on pages 179, 177 and 179, where they form part of the consideration of texture transfer. A selection of parameters for the different substrates are given in **Figure 65**. These represent the mean of 15 Zygo measurements from one side of each panel. Parameters with a *W* prefix are waviness filtered (0.8 mm), with an *I* are unfiltered (input) and all others are roughness filtered (0.8 mm high pass).

As well as the mean parameter values, distribution of R_a, Wa and H over the panels was examined to see if any trends could be identified. The plots of R_a variation are shown in **Figure 66** while Wa and H are given in **Figure 67** and **Figure 68** respectively.

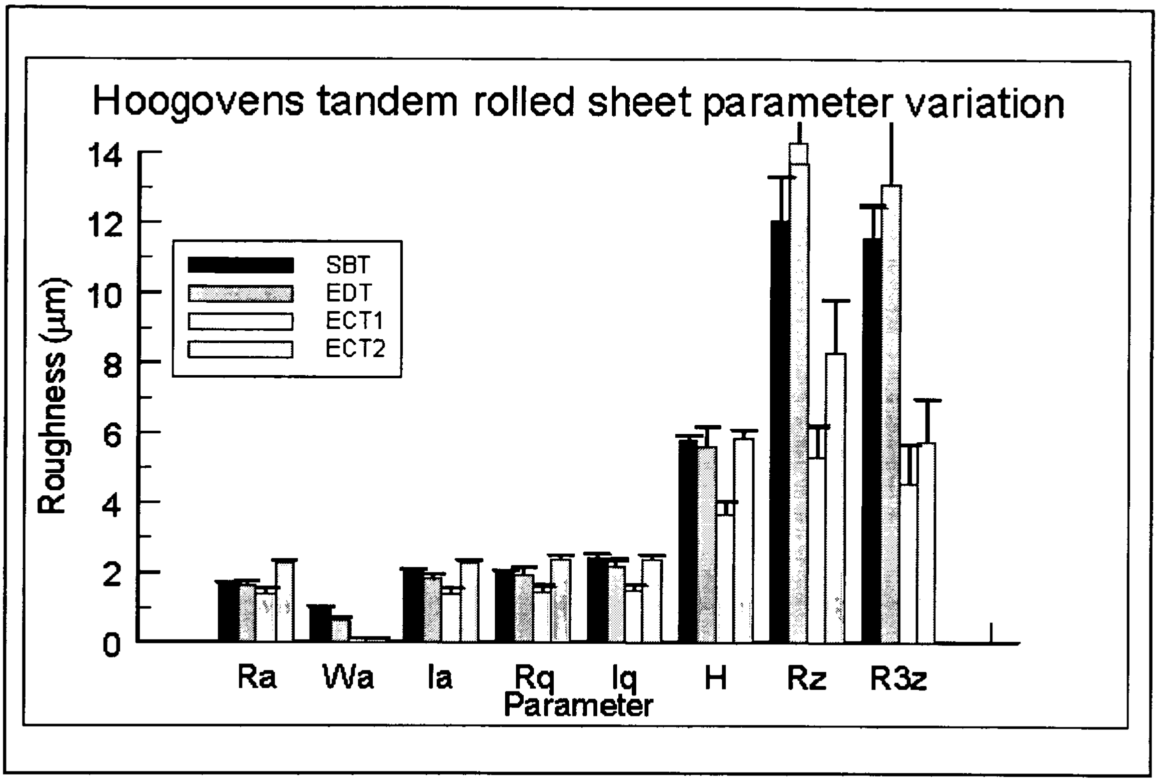


Figure 65 Selected parameters for tandem rolled sheet comparison

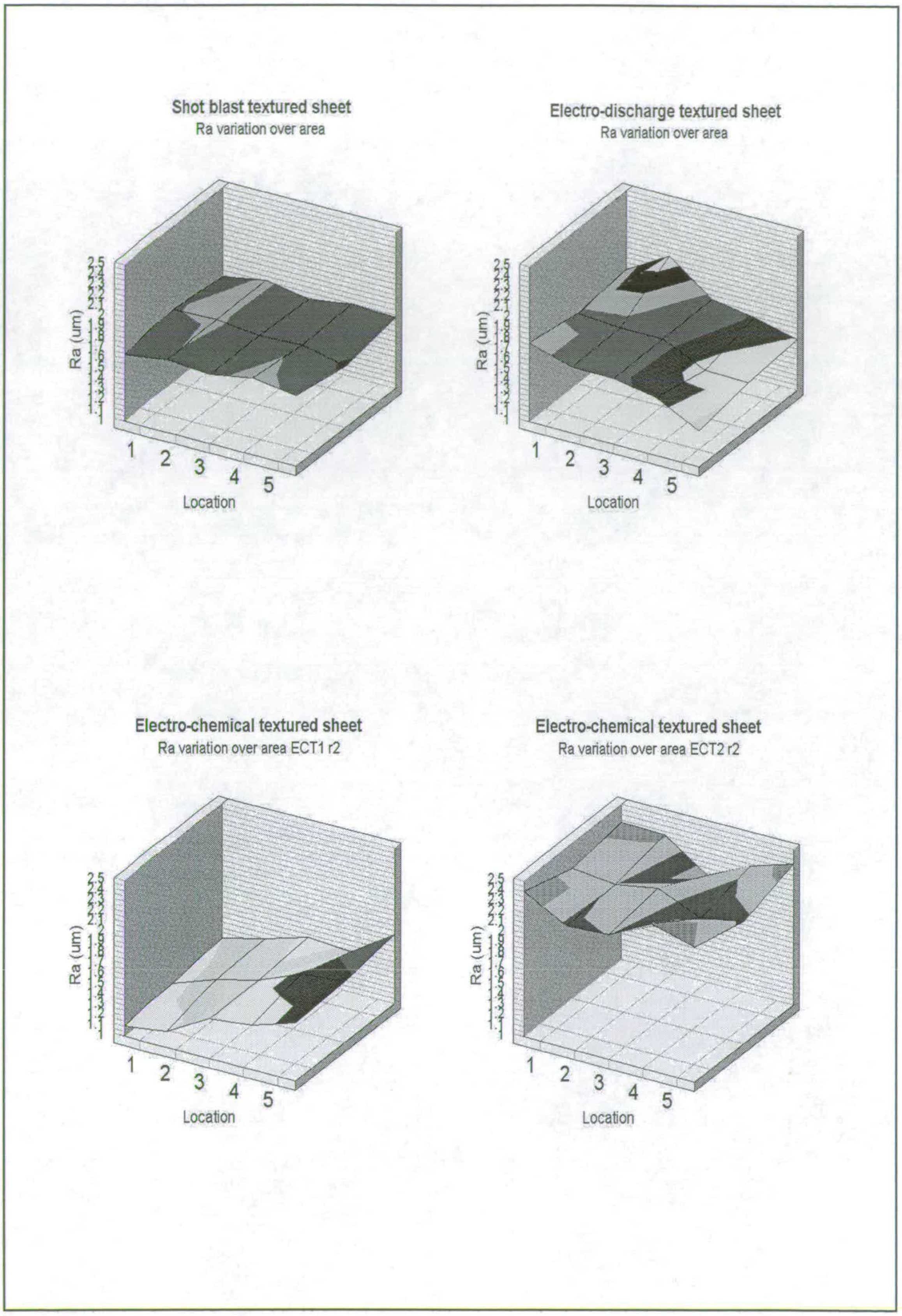


Figure 66 R_a variation over tandem rolled sheet

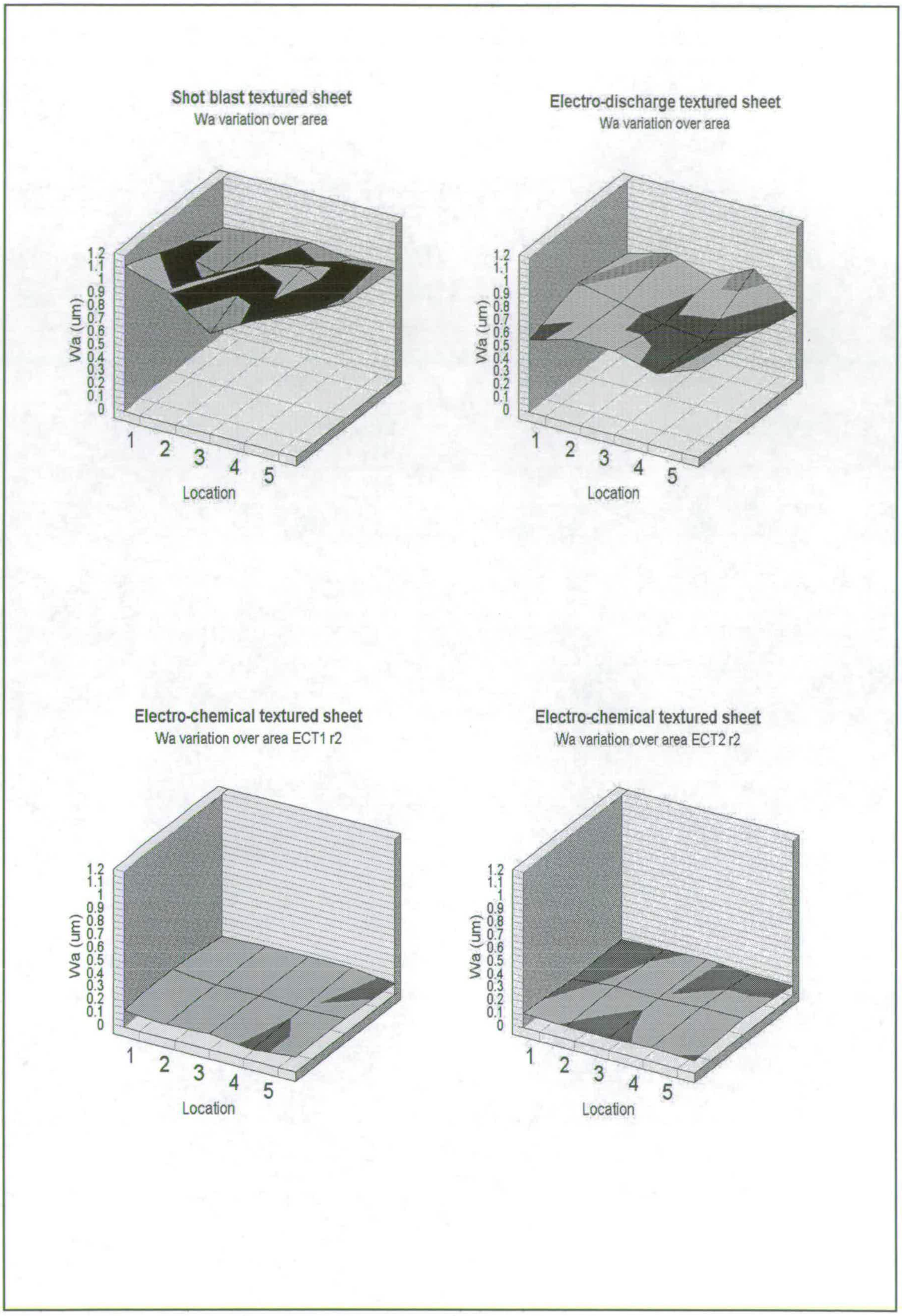


Figure 67 Waviness variation over tandem rolled sheet

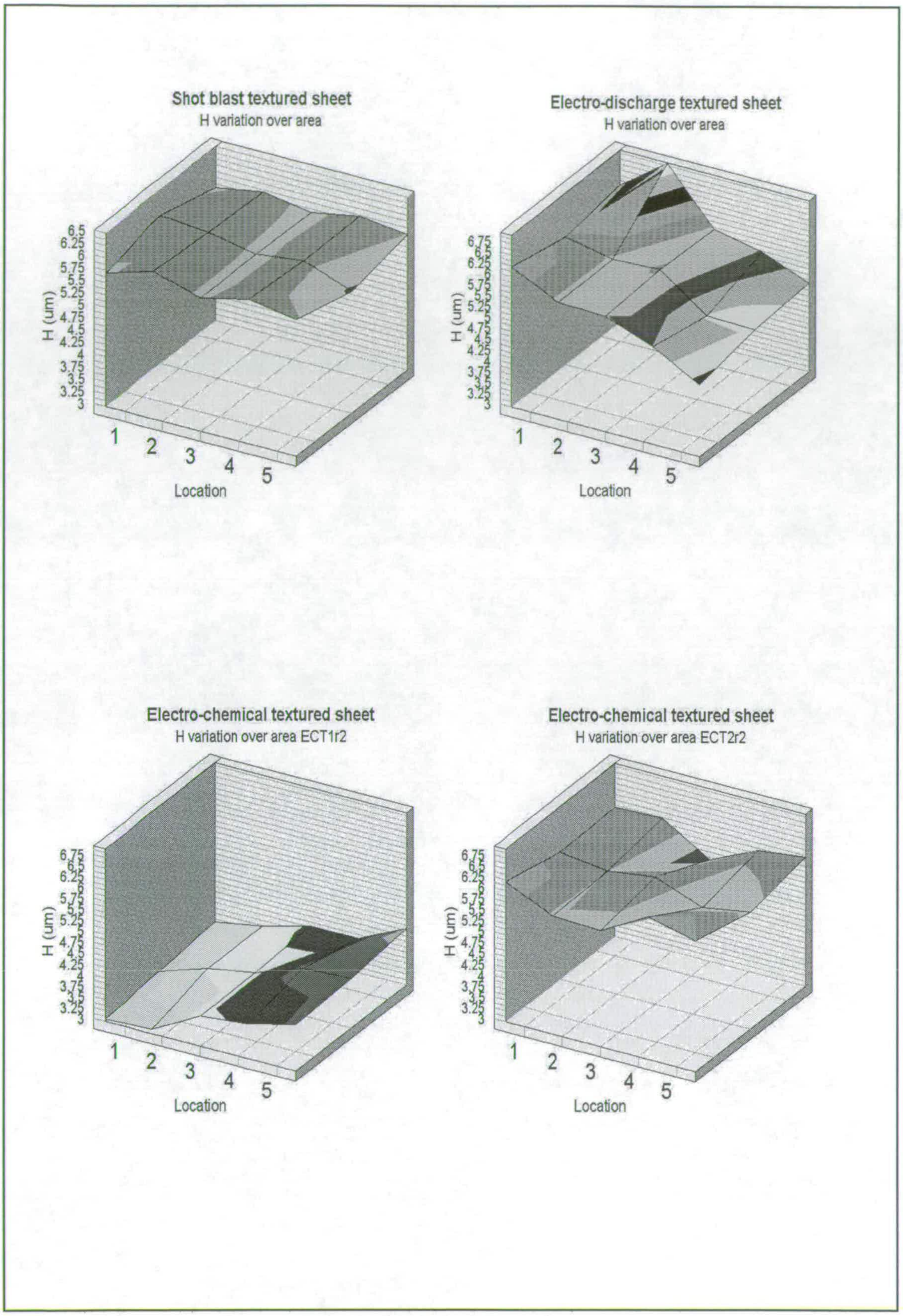


Figure 68 Variation of H over tandem rolled sheet

7 Discussion

The purpose of this chapter is to examine the different aspects of roll texturing and how they are dealt with by the ECT process. It will draw together the results of many experiments in an attempt to assess the potential of Ink Jet Texturing as a commercial method of texturing rollers for sheet steel production. Where appropriate, comparisons will be made with available data for existing commercial processes. One problem here is that much of this information is viewed as sensitive by manufacturers and steel producers. This has meant that while people have been generally supportive and willing to provide information they have not been happy to be directly referenced. It has been decided, rightly or wrongly, that this information should be included here where no other - published - source is available.

A further difficulty has been in obtaining samples of rolled product. The rolling mill at Hoogovens is capable of producing representative strip samples but it has been difficult to gain access to them. A large number of samples have been rolled but these have mainly been used in the ECSC project on Galvaneal adhesion. The few examples that have been obtained are 'rejects' from the ECSC project in that their roughness is out of specification. An exception to this are the temper rolled panels which were rolled specifically for this thesis. While they do not present much data they have been used in the absence of anything else.

The chapter is divided into a number of sections. The technical aspects of the process will be discussed in *Roll Texturing*. This will focus on those aspects which define the limits of the process within the laboratory. *Commercial Considerations* will look at factors which may not be so significant experimentally but may affect the commercial viability of the process. The end product, the rolled strip, will be considered in *Rolled Sheet*. These sections are based on the findings of the later work which used electro-chemical machining as the removal mechanism. A final section, *Machining Comparison*, will give a brief discussion of the relative merits of chemical verses electro-chemical machining.

7.1 Roller Texturing

7.1.1 Roughness texture

This section will discuss the primary texture, i.e. that which has been intentionally created through the mask deposition and material removal process. It will be termed the roughness as it typically has a wavelength of less than 0.8 mm. The waviness of the surface is also created by the texturing process (although some waviness will be inherited from the original surface) but is not deliberately created - it is in effect an unwanted by-product and will be described as *waviness texture*.

Can an appropriate surface roughness, or range of roughnesses, be created using ECT? A number of factors need to be considered here: can the right texture patterns be obtained and is the texture fully deterministic?

7.1.1.1 Texture Patterns

For most applications of deterministic texturing the pattern selected on the roller is one of distinct isolated peaks orientated as a face centred hexagonal. This ensures that any peak is equally spaced from its nearest neighbours. When rolled this gives a structure of isolated craters with maximum crater density for a given area. These craters act as lubricant pockets during press forming so both volume and spacing is important.

Circumferential stroke spacing

That ECT can create such textures can be clearly seen although obtaining equal spacing between craters is often compromised by the available equipment. The circumferential stroke spacing is set by the encoder on the lathe spindle and the hardware divide. Because the pattern must match from band to band the encoder resolution divided by the hardware divide and the texture repeat, must result in an integer. This means that as the roller diameter, and therefore the number of strokes per revolution, increases, then the range of possible stroke spaces reduces. With the Hoogovens rollers and the 20,000 pulse per revolution encoder this gave just two feasible stroke spacings, one too close and the other two widely spaced. This could be resolved by using a higher resolution encoder (potentially very expensive) or more practically a gearbox on the existing encoder. Backlash is perhaps the main concern when using a gearbox in such an application but, since the roller is rotating continuously in one direction, it should not be a problem here. A third option would be to use an encoder which gives a sinusoidal rather than binary output waveform. This could then be sampled by a high resolution analogue to digital converter to give the required stroke spacing. This would be a nice solution as it may remove the need for a digital divide stage.

One problem noticed with the fourth set of Hoogovens rollers was a localised variation in stroke spacing, manifesting itself as a beating type pattern over the roller. It could be caused by vibrations of the print head or, more likely, localised variation in the surface velocity of the roller. In theory the latter would be compensated for by the encoder which is directly linked to the spindle of the lathe but this is not necessarily the case. The roller is not directly coupled to the chuck but is turned between centres using an 8mm diameter bar to drive it. This arrangement was felt to be adequate in that there was little load being applied to the roller but significant rotational inertia of the roller would tend to smooth any speed variations giving a velocity error between encoder and surface speed.

The problem of localised variation is not apparent with the smaller roller, even when printing at equivalent surface speeds, but gets worse with the large rollers as the lathe speed is increased. Both these observations tend to support the theory that it is a problem of relative motion between roller and lathe.

Radial drop positioning

It can be seen that with the correct equipment the circumferential positioning can be accurately maintained from stroke to stroke. The radial position within a stroke should also be easily determined. It would be nice to assume that the position of a printed drop is a linear relationship of the print height and its position in the stroke (i.e. drop 8 would be positioned at half the total stroke height, for a 16 drop matrix). Unfortunately it is not quite so simple. The drop position is not purely fixed by the charge applied to it and the deflection voltage. One other factor is the printhead to roller gap. This is discussed else where in so much as the print height increases with increasing printhead gap, but if the head is not perpendicular to the roller drops at one end of the stroke may be closer together than those at the other. In practice this does not seem to be a problem: the effect is small and easily compensated for by correct alignment of the head. More significant is the effect of the *raster voltage*.

The raster voltages represent the charging voltage applied to each drop in the stroke. These vary depending on the type of software installed and are supplied by the manufacturer on pre-programmed EPROM chips. Because the drops in flight are effectively charged particles their trajectory - and therefore their printed position - will be affected by the presence or absence of other charged particles. The deflection of a give drop if it was in, say, the main stroke of an upper case *I* would be different than if it represented the dot of a lower case *i*. In the former it would be surrounded by charged particles while in the latter there would be none either side of it. Because of this effect the raster voltages are programmed to give the best overall print quality for the installed character set. As the stroke patterns used in texturing are unlike anything found in international character sets the uniformity of the printed strokes inevitably suffered. The best solution would be to have a new set of raster voltages programmed for this application and this would be feasible for a commercial ECT unit. In practice a set of voltages were eventually supplied which had been programmed for printing *Snowflake* 2D bar codes. These are made up of symmetrical patterns of isolated dots and depend on accurate drop placement for machine readability. They were also found to give acceptable uniformity of drop placement for texturing.

Drop Uniformity

With the drop placement sorted problems remained with the uniformity of drop size, across the stroke and from stroke to stroke. **Figure 69** shows a texture where the drops are increasing in diameter across the stroke. The dot diameter depends on the rate of spread of the ink before it becomes too thick to further wet the surface. As this will be a function of its initial viscosity on contact with the roller and of its evaporation rate thereafter then it may be thought that the first dots would be larger. The increased flight time of the later drops should allow more solvent to be evaporated, thus increasing the contact viscosity and therefore reducing the final drop diameter.

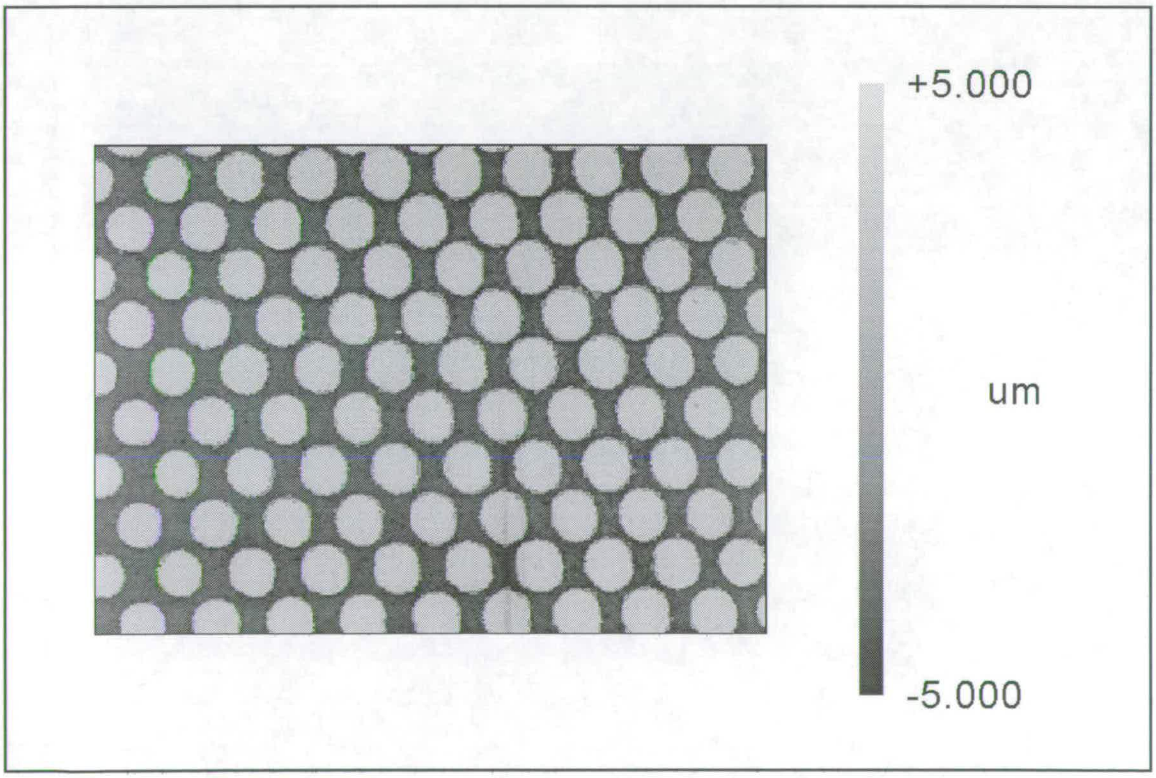


Figure 69 Hoogovens roller replica (0701 ink) showing drop diameter variation

Unfortunately the opposite is observed: the first drops are small and the last are large. The only apparent explanation for this is that evaporation in flight of the later drops is inhibited by the presence of solvent vapour from previous ones. It was latterly observed that the drops in the first few strokes of a block of print were noticeably smaller than those that followed. The only apparent reason for this was a build up of solvent vapour within the boundary layer, inhibiting further solvent evaporation. This was tested by spraying air gently into the gap while printing. The results of this are shown in **Figure 70** and it can be seen that stroke to stroke uniformity was improved significantly, as was uniformity within strokes.

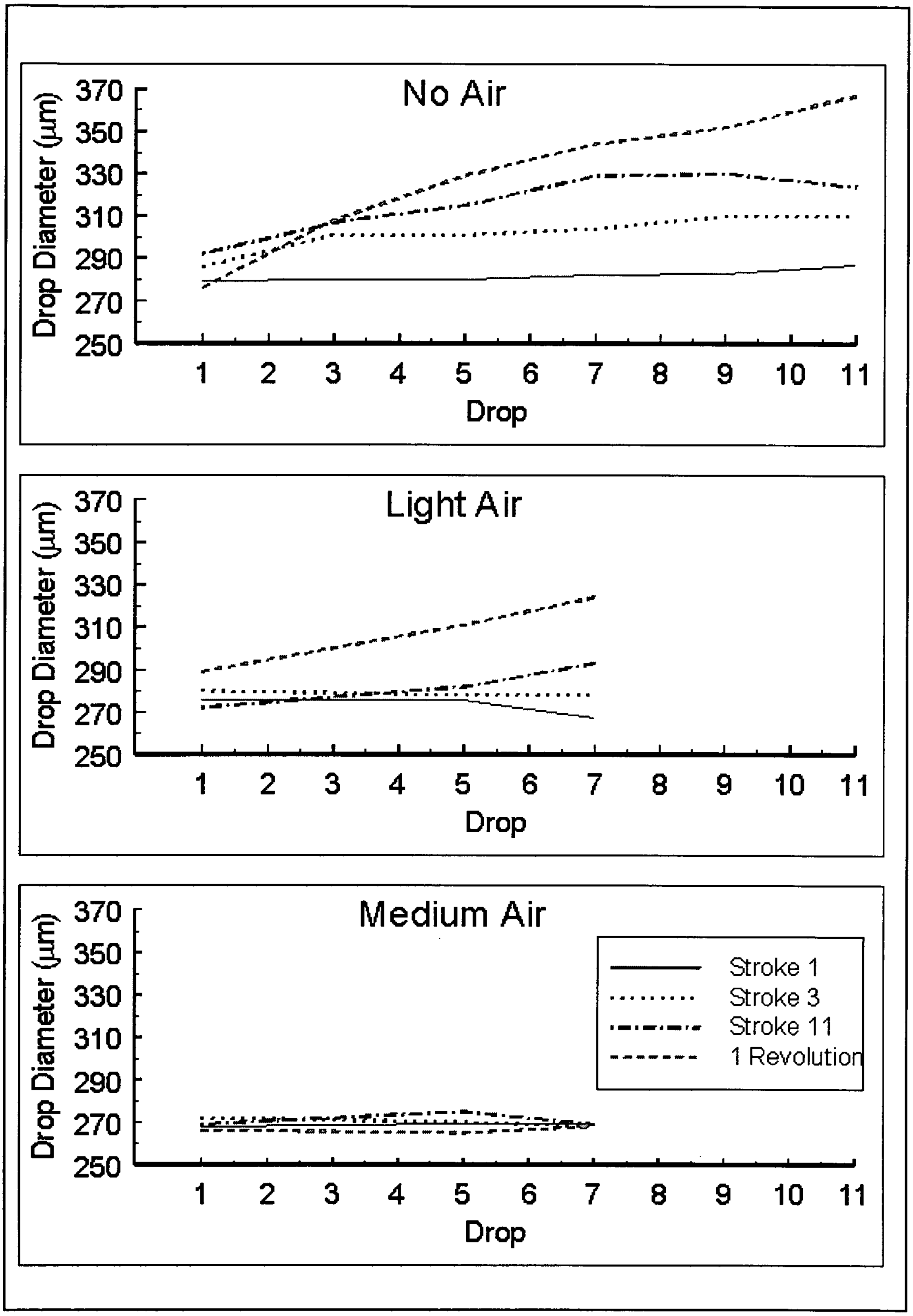


Figure 70 Variation of drop diameter with no (top), light (middle) and medium (bottom) air flow into gap

Although dot diameter will vary, the parameters controlling this are largely outside the operators control. Typically it may be desired to reduce the diameter which is done through increasing the viscosity. This can be done through increasing the reservoir viscosity or the flight time. The former can be achieved by removing the *make-up* cartridge and waiting for the ink to thicken, but if too thick print quality deteriorates significantly. Flight time can be increased by a variety of methods, but these also have limitations. Increasing the printhead gap increases the flightpath but also increases sensitivity to drop disturbance through external sources. Reducing ink pressure reduces ink velocity, thus increasing flight time and reducing drop volume, but is also sensitive to disturbance.

These methods may allow small adjustments to be made to the relative drop size but do not permit the operator to select drops of specific dimensions. It may be possible to create an expert system which would take as inputs the ink, head, air and surface temperatures, ink type, viscosity, pressure and run time, and possible surface data such as speed and roughness. The user would then be given an estimate of the printed dot size. The number of variables involved would make this a major piece of research in its own right, and certainly outwith the scope of this thesis.

It is questionable whether these dot variations would directly affect the performance of the rolled sheet. If the dominant wavelength stayed constant then paint performance should not be significantly affected and if the crater volume was sufficient then these variations may not unduly impair the press performance. These questions could only be answered through the generation and testing of sufficient quantities of production rolled sheet (i.e. level enough for testing). This would require a significant commitment of time and finances and would not be feasible without full industrial support. The main concern over variations is perhaps connected to the secondary effects.

Dot diameter is directly linked to current density in that is it increases the masked area increases and the machined area reduces. If current remains constant then the current density will increase, as will the machining rate. Therefore, under otherwise identical conditions as dot diameter increases so will the machined depth. If there are localised diameter variations then there will also be depth variations. This effect can be clearly seen in **Figure 69**. It can also be transferred to rolled sheet (if high enough reductions are used) giving a series of ridges parallel to the rolling direction with a pitch of the stroke height, as shown in **Figure 57**. The pitch would typically be between 2.5 and 3.5 mm, well within the critical waviness band. Conversely, where partial transfer occurs it can be seen that the localised transfer increases with decreasing dot diameter, as can be seen clearly in **Figure 56** and **Figure 55** on pages 179 and 177 respectively. This again introduces a waviness into the sheet of period corresponding to stroke height. The effect is dependent on the localised ratio of high to low area as can be seen by **Figure 60** on page 183. The rollers used here (Hoogovens pair 4) were printed with good uniformity of dot size and spacing and as such show an even transfer, even at low (1%) reduction.

It is likely that it would be these secondary effects of drop variation that would have most effect on the functional performance of the rolled product. It seems that stroke wise drop variation has been largely removed by spraying air into the print gap but further rolling trials would be beneficial to confirm or deny this.

Band to band alignment

Good uniformity of drop placement within a printed band is important but for the texture to be truly deterministic the drops must be accurately aligned from band to band. When the printed roller is examined it should display a uniform dullness with no evidence of the printed strips. This was a major problem when printing the roller as a series of individual bands (the step-print configuration). Strokes could be accurately aligned between strips but with the pattern out of phase, as shown in **Figure 71**. This is caused by variation in the time the printer takes to respond to the print-go signal from the encoder marker pulse and results in an error of zero or one stroke (note that with a pattern repeat of two strokes, any error of greater than one will still look like zero or one). In some earlier work an error of between zero and one can be seen as shown in **Figure 72**. This is caused by an alignment error of the print head and was corrected by introducing a variable tilt platform for the head in later work.

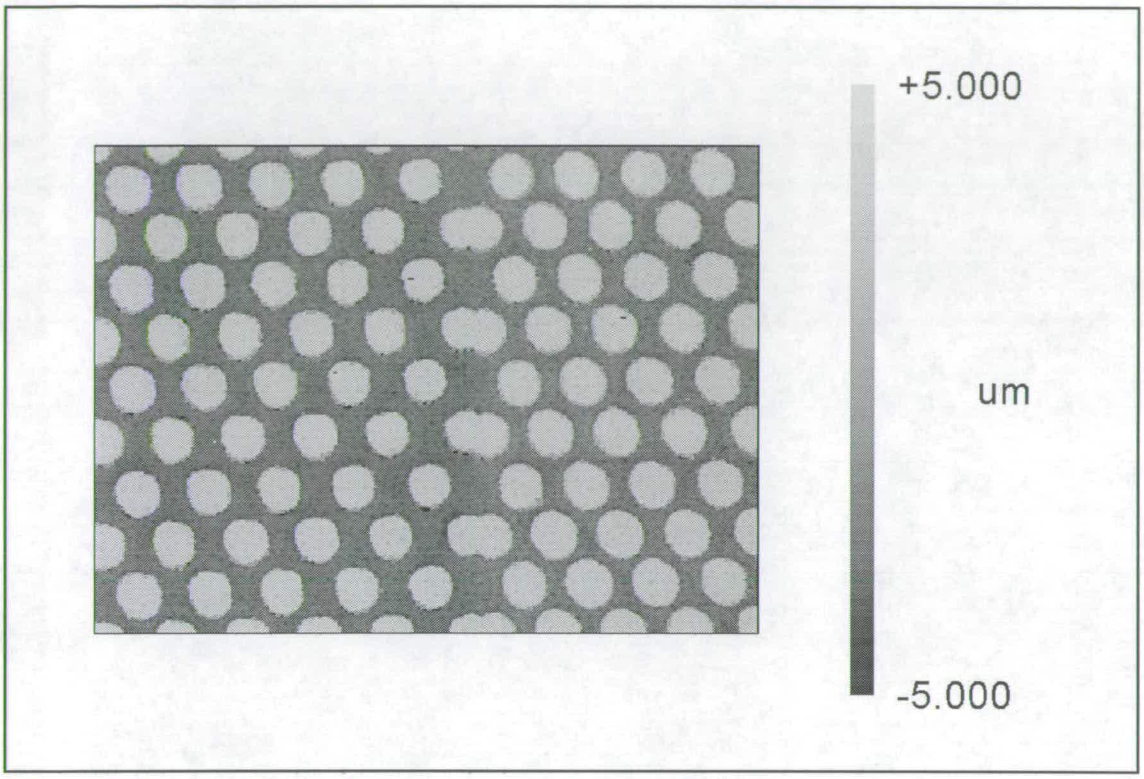


Figure 71 Roller replica showing print error of one stroke

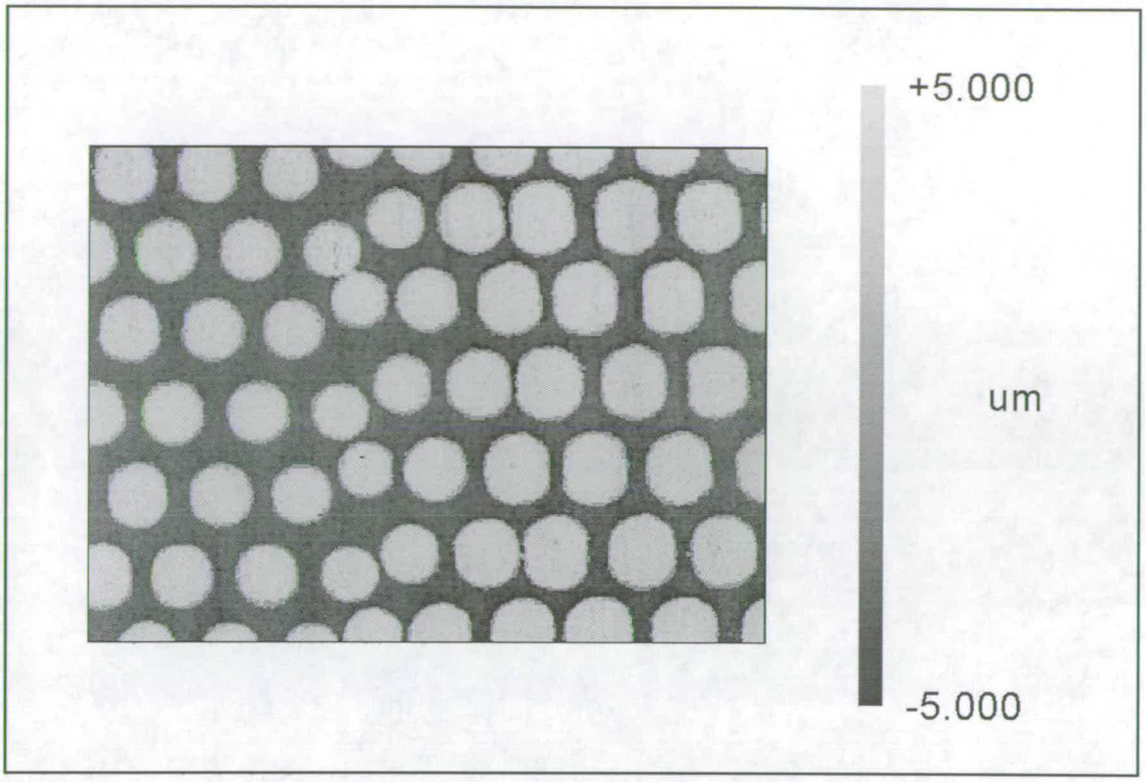


Figure 72 Roller replica showing a pattern error of less than one stroke

The obvious solution to this problem would be to print as a continuous helix but this was prevented by the length of the internal buffer used to store the stroke data for the message to be printed. This was only just long enough to enable a full band of texture to be printed around the circumference of the Hoogovens rollers and would not permit even the smallest rollers to be printed in a helix. It was only in the very final stages of this project that a solution to this was found. A third party add in board was found for the printer which enabled the stroke data to be passed directly from a PC via its parallel port. Unfortunately this was a hardware only product and would need to be controlled at high speed and in real time - something the IBM PC is notoriously bad at. The only way to do this would have been to program the interface software in assembly language running directly under DOS. With no prior experience this had the potential to be unacceptably time consuming at the end of the project. Fortunately a simpler solution was found.

As the stroke data was very simple it was possible to program this and the necessary control functions into an embedded micro-controller (PIC 16C84) which then acted as a real time parallel port controller. The code for this is given in Appendix D. The controller was installed and, using a battery power supply to avoid ground loops, operated most satisfactorily. As the scan in **Figure 47** shows, the ECT process was finally capable of producing fully deterministic textures.

Other Geometries

Although most of the textures in this thesis are the conventional face centred hexagonal of isolated peaks many other types of texture can be created. The nature of the printer means that almost any geometry can be created within the resolution limits of the print head. Perhaps the most directly applicable of these may be the inverse of the conventional texture, i.e. a pattern of isolated craters on the surface of the roller.

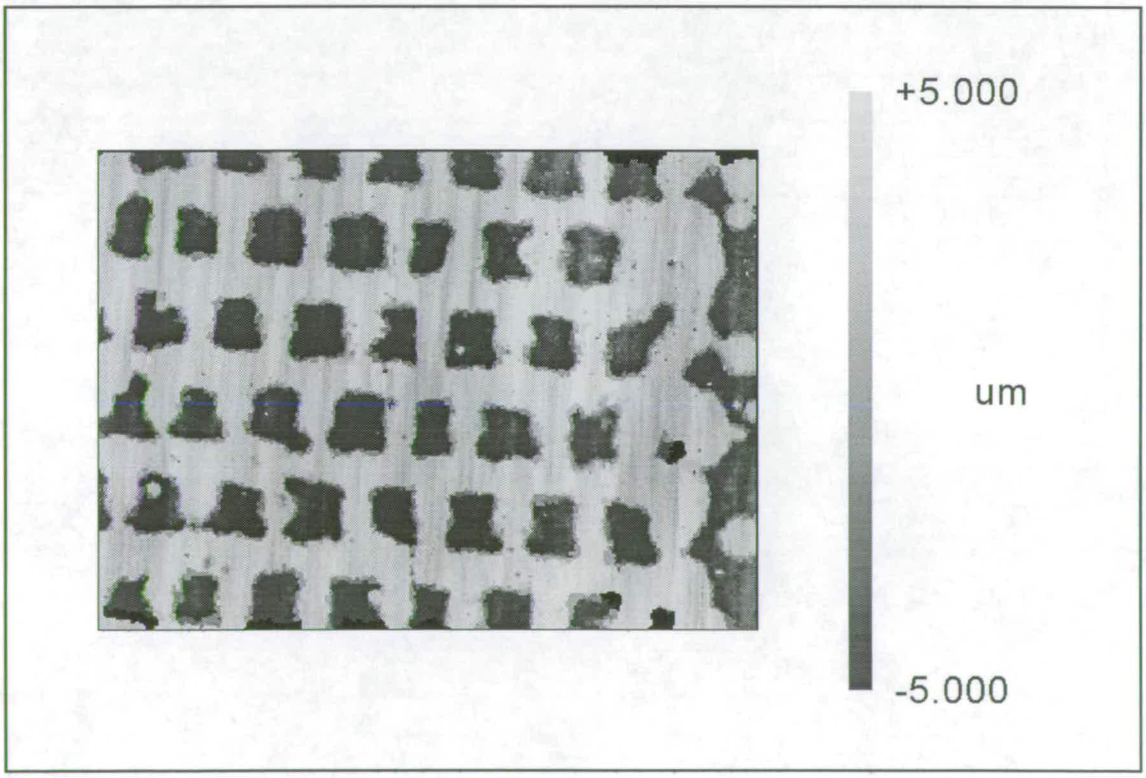


Figure 73 Surface plot showing isolated valley roller structure

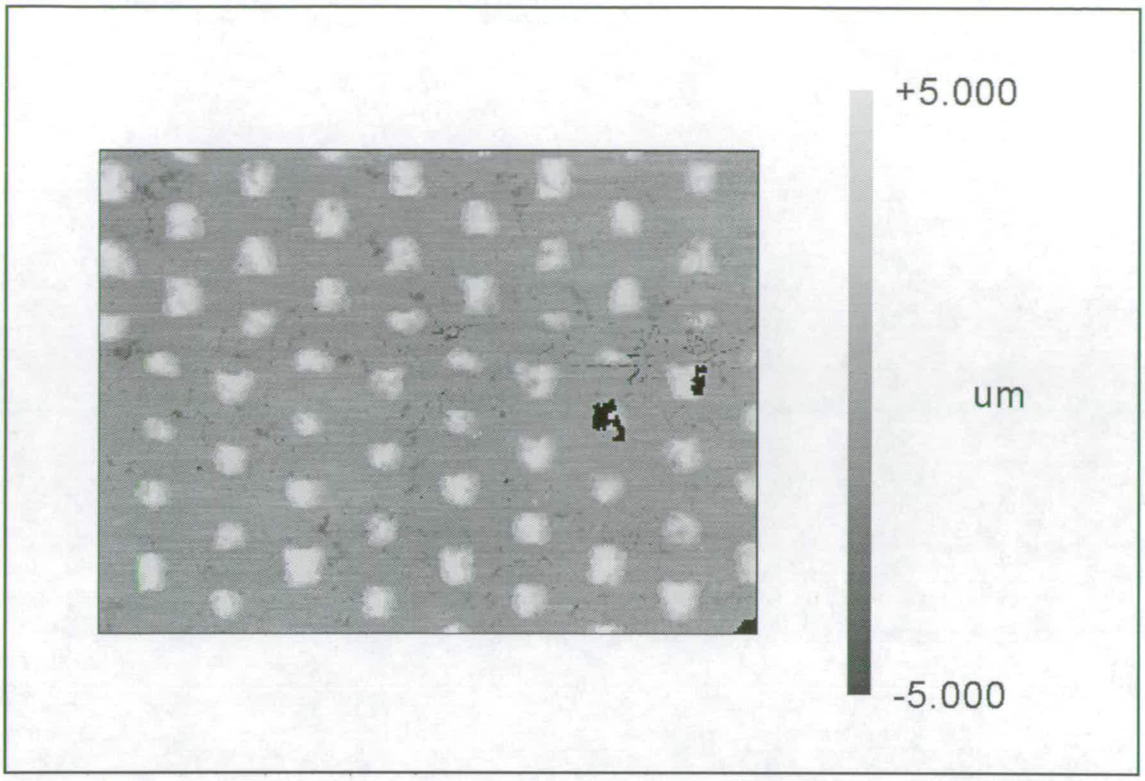


Figure 74 Surface plot of sheet rolled with isolated peaks

An example of this type is shown in **Figure 73**. This can be used to roll an isolated peaks structure onto the sheet as shown in **Figure 74**. While of limited use in temper rolling this may be beneficial on the last stage of the tandem mill where the peaks would act as miniature stand offs to reduce coil sticking during batch annealing. A variation of this is sometimes used with EBT on tandem rolls. There, very high reductions cause sheet to be extruded into the central craters giving the same miniature stand off structure. It is questionable how long this will be of relevance for, as there is a general trend towards continuous annealing lines where the problems of coil stick do not occur.

Corporate logos have also been textured using ECT . An example of this is the Ford logo shown rolled into sheet in **Figure 75**. These graphics have always been limited by the number of drops in a stroke but, with a more sophisticated controller on the parallel port interface, it should be possible to create much larger

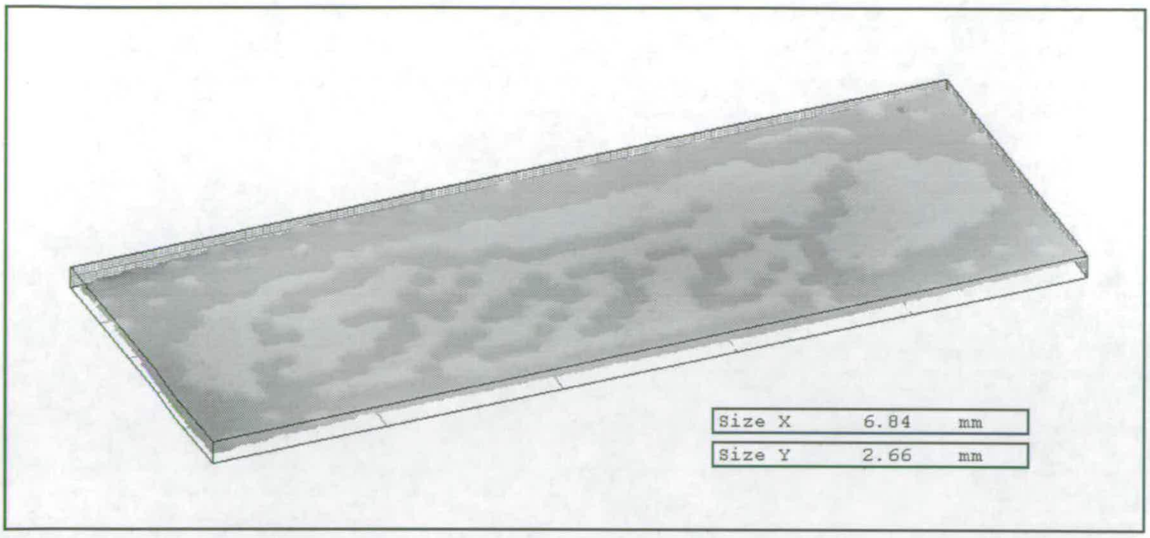


Figure 75 Ford logo rolled into sheet

graphics. These could be designed on PC and then transferred to the printer stroke

by stroke. The potential of logo texturing goes beyond the more obvious aesthetic applications. Larger end users - i.e. the major autobody manufactures - could have sheet rolled with their corporate identification. This would help identify authentic original manufacturer panels thus limiting the revenues lost to counterfeit parts. It is not certain whether this idea would work in practice as the rollers would have to be textured for the specific customer - the processing cost being added to the cost of the strip. Whether this would be countered by the strips added value remains to be seen.

This ability to texture graphics represents a potential advantage over the existing commercial processes. Stochastic methods could not create these textures and LaserTex does not have the circumferential registration required, nor the reliability of peak geometry or wear. EBT is sufficiently deterministic to create the patterns but the structure of hollow peaks - craters - would not have the same image clarity of the ECT texture.

7.1.1.2 Peak Count

ECT has been shown to be capable of creating fully deterministic textures on laboratory rollers with patterns typical of those used in the steel industry today. The next question is wether the resolution of the printer is high enough to give the required peak counts.

When the process was first investigated it was decided to aim for a peak count of 3 to 3.5 peaks per mm. This was the value commonly quoted for Lasertex at that time and seemed to be a reasonable figure to aim for. Since then Lasertex has been superceded by EBT which can offer crater diameters in the range of 90 - 530 μm [80]. This would suggest a maximum deterministic peak count of approximately 5.5 - 6 ppmm. The maximum realistic peak count attainable using a continuous ink jet such as the Domino Pinpoint or the Videojet Excel HR appears to be approximately 3.5 ppmm. This assumes a dot diameter of 0.2 mm which has been attained with both the above printers. This is the highest resolution currently available in this type of machine and manufacturers seem to have little need or desire to go beyond that.

It is conceivable that new technology such as the Domino JetArray will ultimately improve on that limit. This is a multi-nozzle continuous ink jet with each jet having its own gutter, offset from the ink stream. Unwanted drops are deflected into the gutters while printed drops are left uncharged. This currently has 128 nozzles printing a band 25 mm wide. This would relate to a peak count of approximately 3.4 ppmm. The advantage of this machine is its ability to print medium resolution text and graphics at high speeds and its main market is the printing of media circulars, personalised mailings and newspaper updates (lottery numbers, newsflash banners etc.). It is likely that these applications will require increasingly better print quality, leading to higher resolution machines to be designed. It is difficult to predict the future but increasing competition from drop-on-demand technologies will give pressure to increase to 300 dpi resolution at least.

Drop-on-demand printheads have been dismissed for ECT use to date as they tend to be significantly slower than CIJ and suffer from frequent nozzle blockages in industrial applications. One recent development seems to be worthy of further consideration however. This is the XaarJet 1000S which uses a head of 1000 piezo driven channels to print a strip 70 mm wide at a resolution of 360 dpi and a speed of 355 mm/s. This is of interest by its self but the main technological advance of this head is the drop size. Each dot is composed of multiple drops fired at high frequency enabling one of eight different diameters to be printed. This can be varied from dot to dot giving a very high degree of control over the printed texture. The company currently has only water based inks available, meaning it is only suitable for printing onto absorbent surfaces such as paper. It is understood however that solvent based inks are under development.

Both the Domino JetArray and the Xaar Xaarjet 1000S will cost in the region of £30 — 40K, three to four times the cost of the existing printer. This would be offset by a much faster printing time, making them an economically viable option for a full scale system. As these machines have a discrete array of nozzles they would not have the same variability of peak count, although this may be compensated for slightly by tilting the head. Conversely they would not have the same problems of uneven drop placement, raster variations and drop size variation.

Returning to the existing system, does a peak count of 3 ppmm represent a significant barrier to its application? It should certainly be acceptable for press forming / deep drawing applications although this has not been tested due to a lack of usable rolled samples. High peak counts have been traditionally specified for paint clarity but this stems from stochastic processes where low peak counts were related to high waviness. Recent work suggests that wavelengths less than 0.8 mm have little impact on image clarity with one study reporting painting strongly attenuating those below 0.5 mm [?]. This also reported that R_a values greater than 1 micron gave good image clarity if the waviness component was low. Interestingly

OCAS have always claimed that high peak counts are not necessary for good image clarity but are now offering higher peak counts as well. The reasons for this seem two fold. Firstly it is in response to customer demand based on traditional perceptions of what makes good sheet for painting, but it may also be linked to improved zinc coat adhesion. There is very little published research on the influence of surface topography on coating adhesion but there is a commonly held belief in the plating industry that it is related to surface area. Increasing the peak count would increase the area for the same R_a value. Although there is little published research on zinc coat adhesion it is the subject of a significant amount of commercial research. Perhaps the largest ongoing program is the ECSC funded study into the influence of surface texture on coating adhesion and functionality. This is looking at sheet rolled using SBT, EDT, EBT, and ECT and is the program that has lead to the texturing of the Hoogovens rollers described in this thesis. The actual results of this program will not be available until mid 1999 at the earliest, and certainly too late for inclusion here.

To conclude, it appears that the currently achievable peak count is acceptable but that there may be a need to use forthcoming technologies to satisfy industrial perceptions.

7.1.1.3 Roughness Magnitude

Having satisfied the criteria of acceptable texture patterns the limits of roughness should be examined. The factors to be considered here are the ranges of average roughness attainable, the peak heights and the variation of these parameters locally and across the roll. Firstly a discussion of roughness parameters may be in order.

Roughness Parameters

One major problem when characterising textured rollers and sheet is in the choice of roughness parameters. Those most commonly used in industry may not be the most appropriate for a particular application and may indeed represent quite different functionality from one texturing process to another. This is particularly true when comparing deterministic and stochastic processes. As an example **Figure 65** on page 189 shows a selection of roughness parameters for strip rolled on the Hoogovens pilot mill and measured on the Zygo interferometer with 2.5X objective. Each data set represents the average of 15 3D measurements taken on one side of the panel. The parameter definitions are given in the *Notation* section at the start of the thesis, but an R prefix represents roughness filtered data ($\lambda <$ 0.8 mm), W represents waviness filtered ($\lambda >$ 0.8 mm) and I is unfiltered data (input). All other parameters are calculated on the roughness filtered data. The Swedish Height parameter H has been used in this work as the main indicator of peak to valley heigh. This is because it is robust (not sensitive to isolated surface contaminants such as dust) and gives a realistic representation of peak heights for ECT . This can be seen by comparing ECT2 where R3z ≈ H. For the stochastic processes this is not the case as R3z ≈ 2 x H. This distinction may not be as significant as it seems for assessing formability as these high extremities may be readily deformed under loading. The H parameter would be more likely to give errors when assessing the paint performance as the peak heights would need more paint to mask. These factors imply that H would not represent the most suitable peak height descriptor for the stochastic surfaces. Conversely R3z cannot always be calculated for ECT surfaces as the uniform base may not contain sufficient distinct valleys. A further consideration when selecting parameters is frequently the availability on the instrument being used for the measurements. Few people have the time or facility to create specific programs to generate the parameters they require from their data sets.

For analysing the ECT surfaces three main parameters, R_a, Wa and H, have been used. R_a was chosen because it is the most commonly used industrial parameter. Any number of arguments can be made as to its suitability or otherwise but ultimately it is still the standard parameter for characterising roughness. Average waviness, Wa, is used as it is the common, and most appropriate, method for calculating waviness. To characterise peak height H was chosen. As mentioned above it was found to be the most reliable descriptor of the average machined depth. Although not in standard use it is very suited to optical instruments which do not have the same ability to clear light surface contaminants that contact probes have.

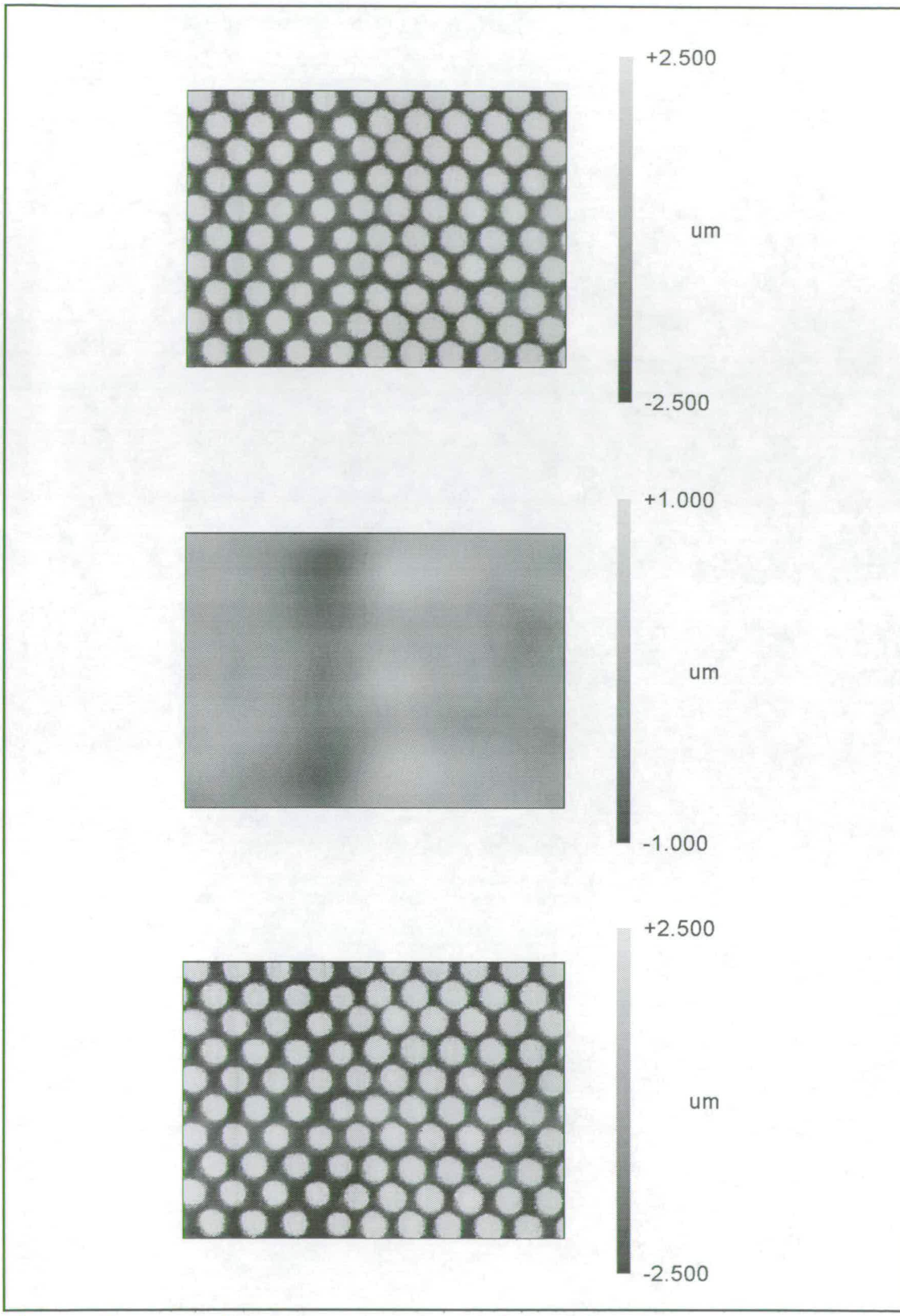


Figure 76 Roughness (top), waviness (middle) and original (bottom) showing artefacts of digital filtering

Digital filtering has been applied to some of the results with mixed effects. In some cases it has been found to give artificially high values of Wa and distorted roughness surfaces. An example of this is given in **Figure 76**. This shows a measurement taken at the join between two bands of strokes. The dots on the left are smaller giving a lower valley level. The transition between the bands results in a slight step change in the base which the filter is unable to accurately reproduce. This results in the classical response where a ridge and trough is introduced into the roughness and waviness plots. Comparison with the unfiltered surface shows that this is indeed an artifact and not a real effect.

Because of this filtered data should be viewed with caution. Waviness values are by definition filtered but R_a and H should be assumed to be calculated without filtering unless specified otherwise.

Attainable Roughness

The first concern is perhaps the range of roughnesses that can be textured with ECT . Using the Hoogovens rolls as a guide textured R_a values have been in the range 1.0 to 2.9 μm on the rollers. The lower limit of the process would be to some extent set by the standard of the original roll surface as the height changes resulting from texturing could be obscured by a rough original surface (for a ground surface and an ECT surface of the same R_a the former will have a greater peak to valley height). The emphasis has been on attaining high R_a surfaces so no work has been done specifically on determining the lower limit. A laboratory roller was textured at 0.65 μm and it seems likely that 0.5 μm would be possible. There would be an ultimate lower limit caused by the concentration of electric field at the edge of the mask. This initially causes machining in these regions resulting in a structure of toroidal craters surrounded by lands. The upper limit depends on the mask adhesion and the time available for machining (i.e. the slower the machining rate the lower the temperature and flow rate and the more durable the ink). The flat sheet experiments showed R_a of 10 μm to be attainable, together with H values of 35 μm. No attempt has been made to exceed these as this is far rougher than would normally be required.

For comparison, commercial R_a ranges for EDT are given to be 0.8 to 10 μm, almost exactly what has been attained by ECT . By this reasoning the range of roughness values achieved for ECT should be acceptable for commercial use.

Machining Variability

Machining variability is dependent on the process control. When machining at constant voltage a distinctive trend (seen clearly in **Figure 39** on page 150) can be seen. After an initial drop the roughness starts to slowly increase with machining time before tending towards a constant. The reason for the initial drop is unclear but it could be due to the introduction of contaminates into the electrolyte, thus reducing the conductivity. Alternatively it could also be attributed to the formation of an oxide film on the surface of the tool causing a drop in potential. The subsequent rise in machining can be attributed to the temperature of the electrolyte which will rise from ambient to some steady state value. As the temperature of the electrolyte rises so does its conductivity, thus causing an increase in the machining rate.

In some experiments a final decrease in roughness is observed. This is caused by a breakdown of the ink mask causing an increase in the exposed surface area. Although the volumetric removal rate will remain approximately constant, the machined depth, and therefore roughness, will decrease.

Variations in flow rate also affect the machining when using constant voltage. Because of the desire to reduce flow rates to a minimum to protect the ink mask, machining current is usually limited by the flow velocity. This was clearly seen in the constant voltage experiment of R11 where peak count and flow rate were varied. The result is that flow rate variations will cause roughness variations. These could be localised, caused by pulsations in the flow or poor tool design, or global, caused by changes in pumping rate, filter blockages etc. Most of these problems are overcome by machining at constant current. In these experiments the current was limited by the power supply while the flow rate was adjusted to ensure that the flow dependent current limit was significantly (typically 3 - 5 A) higher. In this way the dependency of machining on flow rate variations was significantly reduced. Roller 1 of the fourth pair of Hoogovens rollers shows the uniformity that can be obtained with good control of current and ink mask. The standard deviation of R_a across the roller (based on 15 3D measurements) is less than 0.1 μm. This consistency was not matched with roller 2 which showed an initial low R_a rising to the same value as roller 1 on the second half of the roll. This increase in machining rate was accompanied by a slight (5 - 10 %) increase in flow rate. This suggests that some gas may have been trapped in the electrode gap which would have caused a reduction in the machining area of the tool. This is feasible as the current electrode design has the inlet at the top of the tool. Both flow and roller surface are moving against gravity making it difficult for gas to escape through the outlet. A solution to this would be to reconfigure the tool such that the outlet was at the top and to rotate the roller in the opposite direction.

The other main source of roughness variation was the variation in drop size and pattern mismatch. This is discussed more fully in the geometry section and has been significantly reduced through the combination of direct stroke control and forced air purging of the print gap.

7.1.2 Waviness Texture

This represents the medium wavelength components of the surface structure. In this instance it will be taken to be between 0.8 and 2.5 mm although some people are now considering the band of 1.5 to 8.0 mm to be more appropriate. As already discussed the main concern from waviness is its correlation with image clarity and orange peel in the final painted product.

Waviness on ECT rollers has been found to come from either the texturing process or the original roll preparation. The latter source is caused by the roll grinding and is discussed further under *Roll preparation* in the *Commercial considerations* section. It should be remembered that this will generally set the base level of the waviness which will only be made worse by subsequent texturing (possible exceptions to this are discussed in *Roll preparation).*

The texturing process can introduce waviness through variations in the depth of machining of the exposed areas. This can be caused by flow rate variations, as discussed under roughness, or by changes in the field concentration due to changes in the exposed area. The latter is probably the main concern and is determined by the quality of the printed mask as discussed in texture geometry.

Given uniform machining conditions, especially when using constant current, and accurate texture geometry, there is no apparent correlation between roughness and waviness. This can be seen in **Figure 77** where average waviness and H are plotted against R_a. This is taken from the replica measurements for the third set of Hoogovens rollers and shows a strong correlation between R_a and H but none between R_a and Wa. This is as would be expected as the frequency of the peaks is well within the roughness category. The waviness on the ECT treated rollers is low compared to SBT and EDT. One study [37] looked at two SBT and two EDT campaigns (a total of 207 steel coils) and concluded that $Wa = 0.35\ R_a + 0.085$ μm. For the rollers of **Figure 65** on page 189 this would represent an increase in waviness of up to 700% over the ECT surface. Waviness figures are not available for EBT rollers but it is assumed that these would be similar to ECT and based on the waviness of the ground roller. It is likely that the capacity for process induced waviness would be even lower for EBT as it is selectively modifying discrete features rather than machining the whole plateau as is done with ECT .

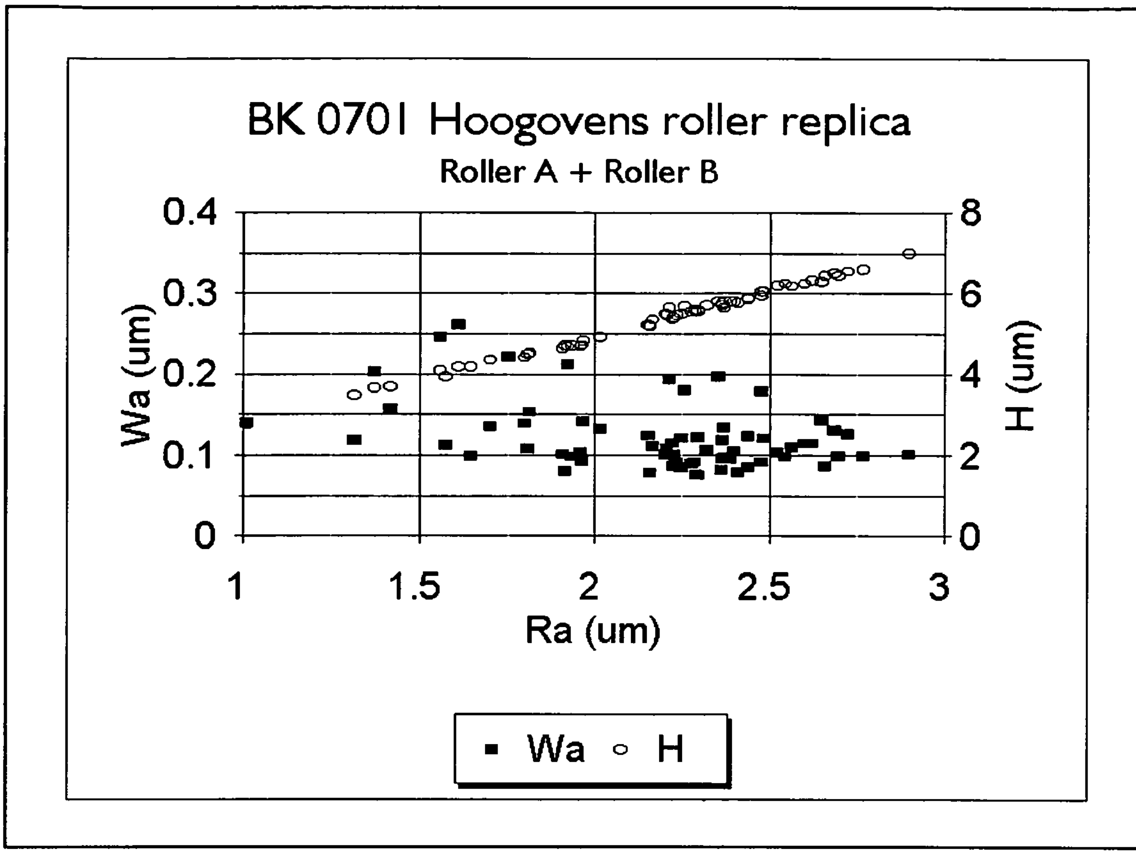


Figure 77 Variation of waviness and H against Ra for Hoogovens roll pair 3

The replicas of Hoogovens roller pair 4 show a Wa of 0.2 - 0.3 μm. While this is low compared to the stochastic processed it is still a factor of two greater than was expected. The reason for this can be traced to the original roll grinding as shown in **Figure 64** on page 188. The distinctive pattern of low and high ridges can be seen in the unfiltered plot where it passes between high and low areas alike. If this was a product of the ECT stage then it would be apparent only on the machined lower areas. This supports the view that with a well applied ECT finish the main source of waviness would be from the roll grinder.

7.2 Commercial Considerations

This section is primarily concerned with those aspects of the process which are perhaps less significant, or easily overcome, at laboratory scale but which must be considered when trying to assess the feasibility of a texturing process.

7.2.1 Reliability

Much of the work to date has been hindered by a lack of robustness of the process. This has largely been concerned with the different aspects of the print system. Printer reliability has been a major source of problems and delays. This may appear strange as this type of printer is designed to work almost continuously in production environments where reliability is paramount (in many cases production will stop if a printer fails). There are two likely explanations for these problems. Firstly the machine used for the project was a very early version of its type and there were some problem which were removed in later machines. Secondly, and more significantly, the machine was only used intermittently with delays of days weeks or months between uses. It may seem unintuitive that under-use would cause reliability problems but the printer consists of many fine bore tubes, filters, nozzles and valves which can partially or completely block when left with M-E-K based ink in them for prolonged periods.

The two other main concerns of reliability are interlinked - ink adhesion and electrode mask adhesion. There is always a concern of the ink mask breaking down during machining. If the ink has not keyed to the surface sufficiently then it will tend to be lifted off by the electrolyte flow. This is typically caused by one of three things. These can be briefly stated together with their usual solutions.

- Surface contamination: The ink will adhere to any oil films or contaminating particles. Solution is to clean roller surface first.
- Insufficient curing time: The solvent has an etching effect on the substrate. This increases the surface area of the bond. If machining follows printing too closely then the ink may just lift away. The solution is

to increase the cure time or to use different inks and solvent bases.

- Flow rate too high: If the adhesion is poor it has been observed that too high a flow rate will increase the tendency of the mask to fail. Reducing the flow rate will improve adhesion.

7.2.2 Texturing Time

One crucial factor which will influence the feasibility of the ECT process is the time it takes to texture a roller. A process where the texturing time was significantly longer than the service life of the texture would be difficult to sustain. Texturing time, when quoted, is often expressed as time per roller, time per pair of rollers, or the number of rollers / pairs per shift. An exact figure can be misleading as the roll size can vary significantly with lengths from 1.5 to 2.5 m and diameters of 300 to 600 mm being common. This means that the area to be textured may vary by a factor of three or more. Additionally the texturing time may vary depending on whether the texture is rough or smooth with high or low peak counts. Although the ECT process has not been tested on any full size mill rolls it is still possible to estimate the time required for printing and etching from data gathered from smaller rollers.

The ECT texturing time will increase with increasing peak density - more drops need to be deposited - and with increasing roughness - more material needs to be removed. Peak count and roughness are also linked as increasing peak density reduces the amount of material to be removed to give a particular average roughness or peak height. Calculation of texturing time is included in Appendix E.

At two to seven hours, the texturing time for ECT seems greater than other processes, but this is for a single print head and a 1 cm^2 electrode. To achieve these texturing rates an EDT machine may have over 30 electrodes or channels. By increasing the number or area of electrodes the ECT machining time could be reduced proportionally. Similarly the printing time could be halved or more by using extra print heads.

It may be useful to consider the machining rates of different non-conventional machining processes. Although it is not directly applicable to texturing, they do still give some indication of relative machining speeds. The figures in **Table 8** for machining rates of non-conventional machining processes were taken from a standard manufacturing textbook [81]. Although approximate they give an idea of the relative speeds of the processes.

Chemical machining	0.025 - 0.1 mm / min
Electro-chemical machining	2.5 - 12 mm / min
Electro-discharge machining	0.15 mm/ min

Table 8 Non-conventional machining process removal rates

The machining rate for EDM is directly proportional to the electrode area. This is because there can only be one spark (and therefore machining at only one point) at any given time, irrespective of the electrode area. Even assuming a small electrode of 1 cm^2 the feed rate is significantly lower than that achievable with ECM.

In terms of texturing time it appears likely that an ECT system could be developed to compare with the speed of the EDT and EBT processes but this does not take into account the time needed to prepare the roller before and after. Pre and post cleaning for ECT is discussed elsewhere but unless a reliable automated system is developed then these stages could increase the overall roll processing time significantly. Again it is difficult to make a direct comparison as surface cleaning of EBT rolls must be essential for operating in high vacuum and it is not known either how this is done or whether this time is included in the texturing time. Similarly an increasing number of EDT rolls are chromium plated after texturing to increase the service life. It has been suggested that the greater wear resistance of EBT makes this un-necessary and the rolling data gathered from the Hoogovens pilot trials suggest that this may also be true for ECT .

To conclude, it is very difficult to make direct comparisons of texturing times but it seems likely that ECT could be developed to be on par with other processes as long as cleaning can be sorted.

7.2.3 Texturing Costs

The roller texturing time is important but so is the cost. The cost of the process has ultimately to be met through profit from the sale of textured strip. If this cost is too high then it will not be met by the customer and the process will become unviable. EDT machines vary in cost, depending on design and specification, up to around £3 M for a multichannel purpose built device for full size work rolls. The only deterministic process currently available is EBT. This is very expensive, estimated to be in the region of £3.5 M for a full sized machine, and is unlikely to scale down significantly for smaller machines as it is purpose built equipment (not retrofit) and based around only one machining head. Other systems such as EDT use multiple heads to increase texturing times and so can be scaled down more economically by removing heads. This difficulty in scaling down EBT (there are currently no machines available for use with rolls less than 2 m as the original prototype appears to have been scrapped) may remove it from one significant market sector.

The use of mini-mills for the final processing of strip products appears to be becoming increasingly common. This may be due to the variety of gauges and finishes of product required for current fabrication practices. An example of this is the use of tailored blanks where one panel blank is comprised of different patches of steel laser welded together to ensure that the properties of a given section of the blank are matched to what is required. For a door panel for instance the areas requiring high strength can be made from heavy gauge steel while those which are lightly loaded can use a lighter grade. This gives significant weight savings over a panel made from just the heaviest grade required . By using this approach the Ultra Light Steel Auto Body (ULSAB) project demonstrated a body in white weight saving of 25% compared to traditional methods of steel construction [82]. Some mini-mills can provide product with stochastic or semi-deterministic texture (at least one company [83] appears to have in house capability for both laser and EDT). As customer specification of deterministic textures increase there will be an increasing market for a low cost deterministic system for small mills which EBT, for reasons outlined above, may find it difficult to satisfy. The ECT system has been developed a retrofit to an old (35 years old) lathe with the idea that if it will operate successfully on that then it should work satisfactorily on equipment found in commercial roll shops (this was vindicated on the visit to Hoogovens to texture their first set of work rolls when it was installed on one of their lathes without difficulty).

The capital cost of the prototype retrofit ECT system was approximately £15 K. These prices are based on one off costs and with OEM discounts it is likely that this cost could be reduced to almost £10 K. Some costings are included in Appendix F. These show that the main cost increase for a larger system would be in the linear actuator required for moving the print head and electrode assembly. A high resolution ball screw actuator has been costed at £24,500 but it is possible that the combination of low stage mass and low accelerations would make the necessary resolution achievable through the use of a much cheaper timing belt based system.

Reducing the texturing time will lead to increased system cost. Adding another print head would cost approximately £8,000 for the printer but an automated print height control system would be needed to ensure that the two printed strips were correctly synchronised and aligned. The electronics for this may cost a further £1000. Reducing the etching time would be more cost effective initially. Typical machining conditions have been 10 A current and 0.2 l/min flow rate. As the power supply is rated at 100 A and the pump at 1.2 l/min then increasing the electrode area would be possible with the present system - at least a factor of 8 reduction in the machining time should be achievable with good electrode design.

It should be remembered that in ECM current is being conducted simultaneously over the whole surface of the electrode such that for a given current density material removal rate will be proportional to the area. It also means that multiple electrodes can be run in parallel from a single power supply if required. This is in contrast to EDM where there will always be just one spark per power supply, irrespective of the number or area of electrodes. Each additional EDT channel needs an independent power supply and electrode servo and controller. Each additional ECT channel may need only the masked electrode and a linear slide, which would represent a major cost advantage when scaling ECT up to larger machines.

A full costing of a commercial ECT system is out with the scope of this work but the early indications are that it would be comparable with EDT for a small single channel machine, becoming cheaper as the system size increases. EBT is not available for small systems and would be unlikely to be cost effective if it were. For full scale systems it would appear to be significantly more expensive that a comparable ECT system. The danger here is that it is difficult to compare like with like. Operating costs for commercial systems are not generally available and the quoted system costs include overheads to support significant commercial research and technical support. On capital costs alone however available information suggests that ECT would be significantly cheaper than competing technologies.

7.2.4 Texture Service Life

This is a measure of how long a roller can be used before retexturing is required. The lower the frequency of roll changes the lower the operating costs of the texturing equipment and the higher the productivity of the strip mill - put in example of changing rolling times. In recent years a number of measures have been utilised to increase this service interval, including the use of high chromium and high speed steel (HSS) work rolls [84] and through chromium plating of the roll surface after grinding or texturing [31]. As mentioned elsewhere the it has been claimed that EBT rollers are rarely replaced because of wear and that chromium plating may not be required. It is not known whether this is normal operating practice but it does neglect the fact that chromium plating serves other purposes as well, notably reducing friction and acting as an anti-corrosion barrier.

Roll wear was one area of concern for ECT as all other processes have some means of - theoretically at least - increasing the surface hardness of the roll. Shot blasting causes work hardening on the roll surface, but the initial roll hardness is itself limited by the hardness of the grit used for texturing. EDT was thought to cause thermal hardening but further studies have found that the surface layer is quite soft. The peaks from laser texturing are formed by the solidification of the local melt pool causing a hardened surface. A lack of control in this solidification means that the peaks are left very brittle and frequently poorly adhered to the roll surface. This has led to poor wear life for LT rolls with very rapid texture degradation. EBT features are formed in a very similar manner to LT but with two significant distinctions. The process takes place in a vacuum so there is no contamination of the melt, and the beam energy can be continuously varied enabling the re-solidification and therefore the metallurgical properties to be carefully controlled. This has enabled the low wear life claimed for the process.

With ECT there should be no thermal or work hardening of the surface to increase the wear resistance - the only likely effect would be a preferential etching of the grain boundaries which may be expected to accelerate wear. In the first Hoogovens rolling trial it was compared with SBT and EDT rolls, made of the same material grade, rolling the same substrates under the same operating conditions. Roll roughnesses were measured before, midway and after the rolling campaign and are shown in **Figure 35** on page 144. The results show a significant initial wear of the EDT and SBT rolls but none on the ECT . These values are taken from 2D profilometer readings directly on the roll surface so may not accurately represent the true R_a value for the ECT surface but it does show a significantly lower wear rate for the ECT rolls. **Figure 36** on page 145 shows a replica taken from the roll surface at the end of rolling. It shows how the edges of the peaks have been rounded but the peak remains substantially intact. This suggests that the rolling load is being spread over the large surface area of the peaks such that any material removal has little effect on the overall roughness of the surface.

The second Hoogovens rolling trial provided roughness data from before rolling and after a limited number of panels had been rolled. This should show if there is any appreciable initial wear on the surface of the roller. The results show no significant decrease in roughness over this interval. This is supported by the measurements in **Figure 53** which show the same area before and after rolling. There is no appreciable change in topography and any variation in roughness parameters may be attributed to slight variations in the measurement area. This result is significant as if the edges of the peaks were found to be rounding off rapidly at the start of rolling it may result in unacceptable levels of particle contamination on the first strip to be rolled. This may result in unusable product which would not plate properly - plating onto loose particles would lead to powdering in the press - and could cause galling and jamming of presses.

Another possible use of ECT may be to texture directly onto the roller after chromium plating. In this way the roller would be ground and then plated after which it would be masked and machined. Although this has not been attempted chromium is commonly machined electrochemically and few problems with this would be anticipated. The main advantage of this - in addition to the normal benefits of plating - would be that each time the roller was re-ground it would be the plating, not the roll, being removed. This may significantly increase the number of times the roller could be retextured before its diameter was reduced below the minimum required for satisfactory rolling. This would increase the tonnage of steel which could be produced before the roller was scrapped. Another benefit of texturing the plating would be the removal of any tendency for the roller to corrode before the texturing process was completed.

Texturing the plating would also have a number of disadvantages. Firstly chromium has a typical dissolution valency of 6, compared to between 2 and 3 for iron. This means that it would take between 2 to 3 times longer to machine the coating to the same roughness than it would to treat the steel surface. This would put an increased burden on the ink layer requiring it to withstand either a higher current density - and therefore higher flow and temperature - or an increased machining duration. The other concern is with the machining of chromium. Chromium (VI) compounds produced during machining are toxic. Prior to disposal in toxic waste landfills these have to be reduced to chromium (III) ions [85] - a process which would add to the operating costs of the system. This may be balanced by the increased texture life and the increased roll life but the economics would have to be very carefully costed .

The early studies of roll wear with ECT have shown a significant improvement over SBT and EDT although it was not possible to draw a direct comparison with EBT. These results appear encouraging but on cautionary note it should be considered that early studies of EDT and LT showed improvements in wear which failed to materialise in production.

7.2.5 Initial Roll Surface

Whatever texture is applied to a roller it is essentially a modification of the original roller surface finish. This is usually ground as the previous texture will have been removed by grinding at the end of its working life. In some cases with stochastic processes - where the roller has been removed because of wear rather than damage - the new texture can be applied directly over the previous without the interim grinding stage but this is not common. It is true to say that the quality of the finished texture will always be dependent on the quality of the initial surface (although it has been claimed that EDT can sometimes reduce the waviness of the original surface [10]).

Deterministic textures are inherently more sensitive to roll surface finish than the conventional stochastic ones. This is because both EDT and SBT modify the whole surface of the roll -either by deformation or material removal - while EBT and ECT treat selected portions of the roller leaving a significant amount of the original ground roll finish. For EBT this is the area between craters and when rolling this texture may be transferred to the sheet giving a semi-directional texture between the craters. With ECT the ground finish remains on the surface where it was protected by the ink mask. For a roller textured with isolated peaks this means that the ground roll finish is transferred to the bottom of the craters of the sheet where it has little potential to influence the flow of lubricant in the press. This suggests that the process should be relatively insensitive to the original roll finish although in practice this may not be the case.

Experiments on rollers and sheet with rough ground finishes (e.g. $R_a > 0.5\ \mu m$) have shown that the processed surface can be significantly influenced by the original surface. The relocation study in **Figure 78** shows an area of roller - 50 mm diameter EN31 - marked by an etched boundary. It is shown measured in its ground condition, after printing and after etching. The general topography of the original surface can be seen in all plots. Even a well ground finish can be present in the final texture. **Figure 79** shows areas of practice roller 4 which have been ground and at the transition between masked and unmasked areas - both show evidence of the same ground surface topography. This is likely to be a function of the strong throwing power of the NaCl electrolyte and the large gap making the difference in field strength (and therefore machining rate) negligible when the variation of surface height (a few microns) is less than 1 % of the overall gap (> 1 mm).

By using smaller gaps and passivating electrolytes (e.g. Sodium Nitrate) where the field strength is a strong function of gap separation this tendency to 'copy' the original ground surface on the machined surface may be reduced, possibly to the extent that it could be used to reduce the waviness of the original surface. Until then however it should be assumed that a high standard of surface finish may be required on rollers used for ECT if rolling reductions are used which result in high levels of texture transfer with the sheet coming into contact with the machined areas between the peaks.

Although it has not been published it is known that there is a minimum standard of grinding required to operate the EBT equipment. This is possibly due to the need to maintain a high vacuum around the machining head and means that the condition of older rolls or roll grinders often make them unsuitable for use by EBT. This is not true of ECT where original condition of the roll may affect the functionality of the rolled sheet but not the ability of the roll to be textured.

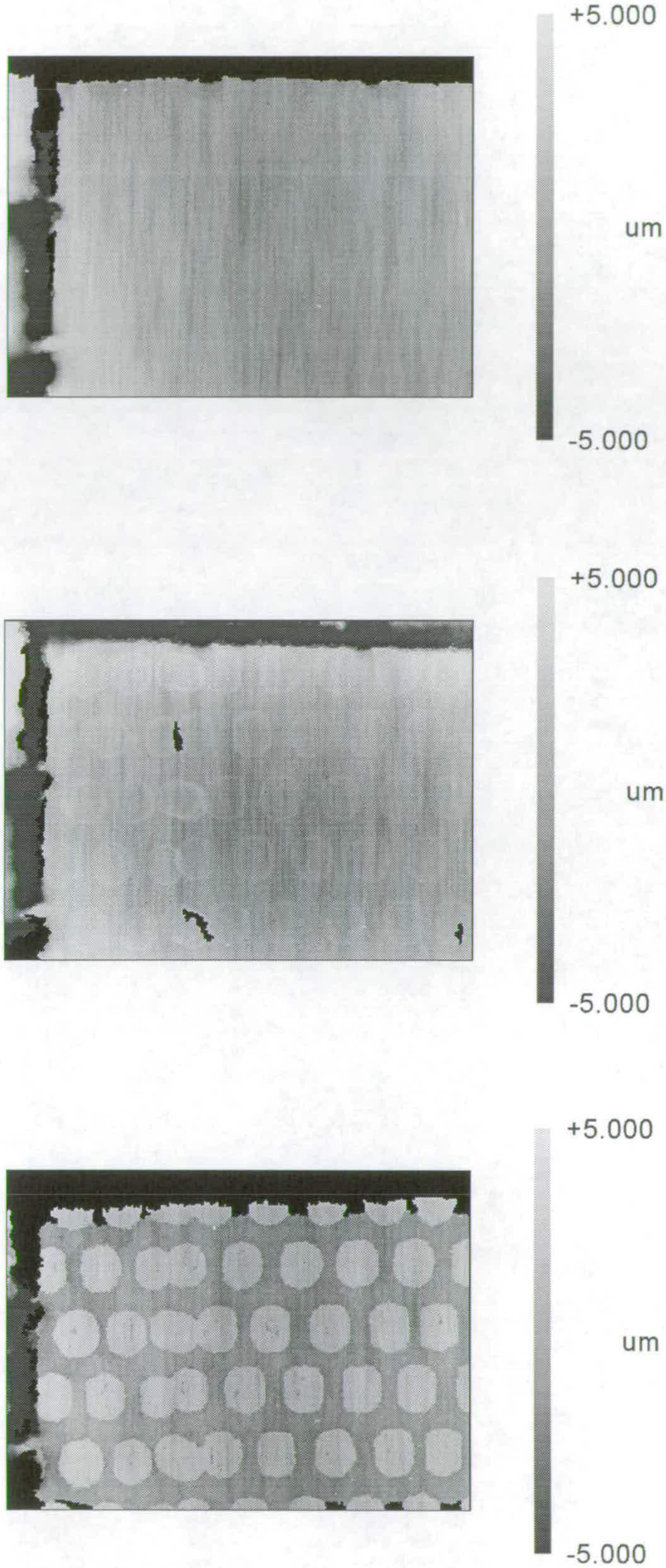


Figure 78 Relocation study of marked area

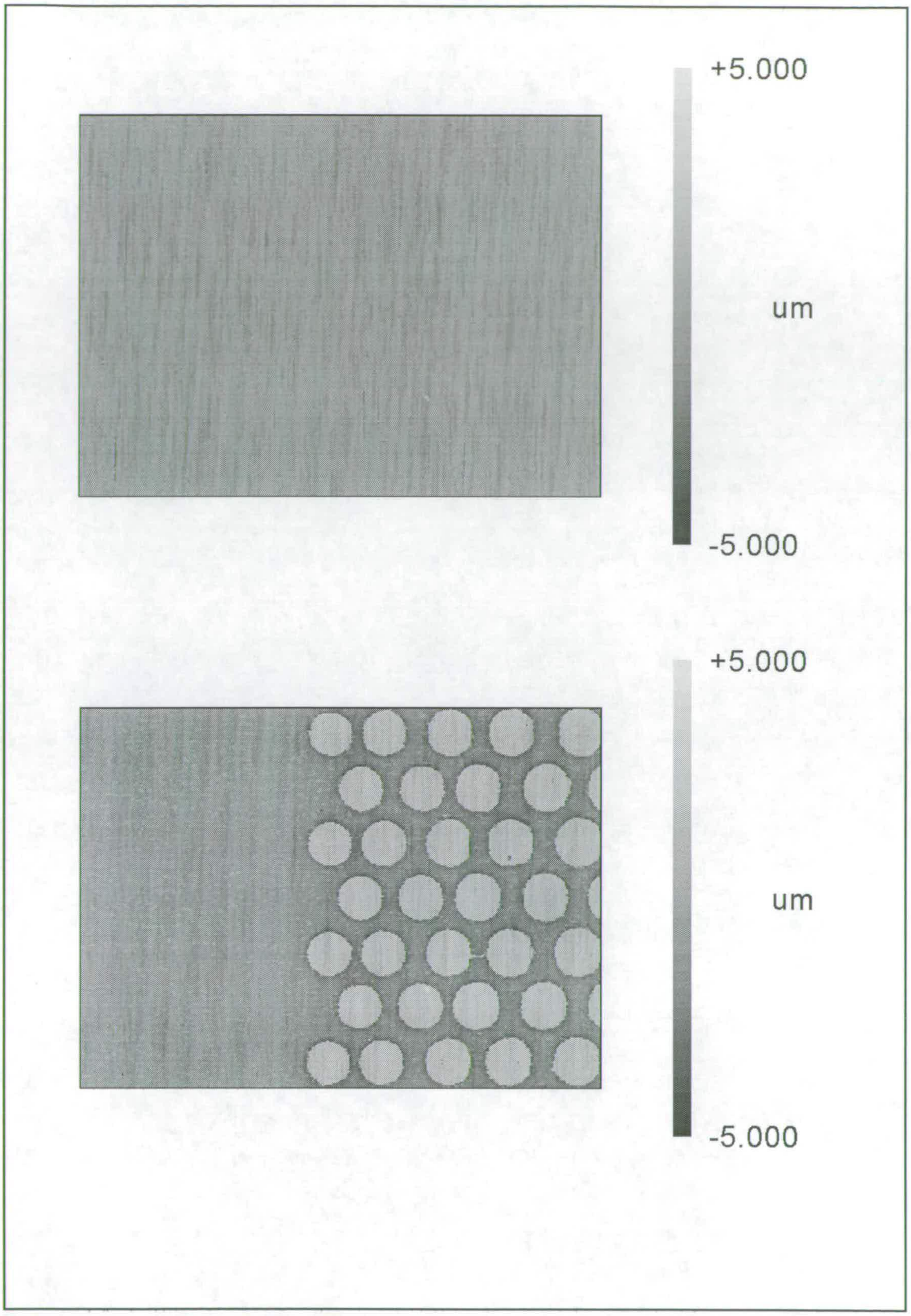


Figure 79 Replicas of practice roller 4 showing copying of original ground surface

7.2.6 Pre and Post Processing

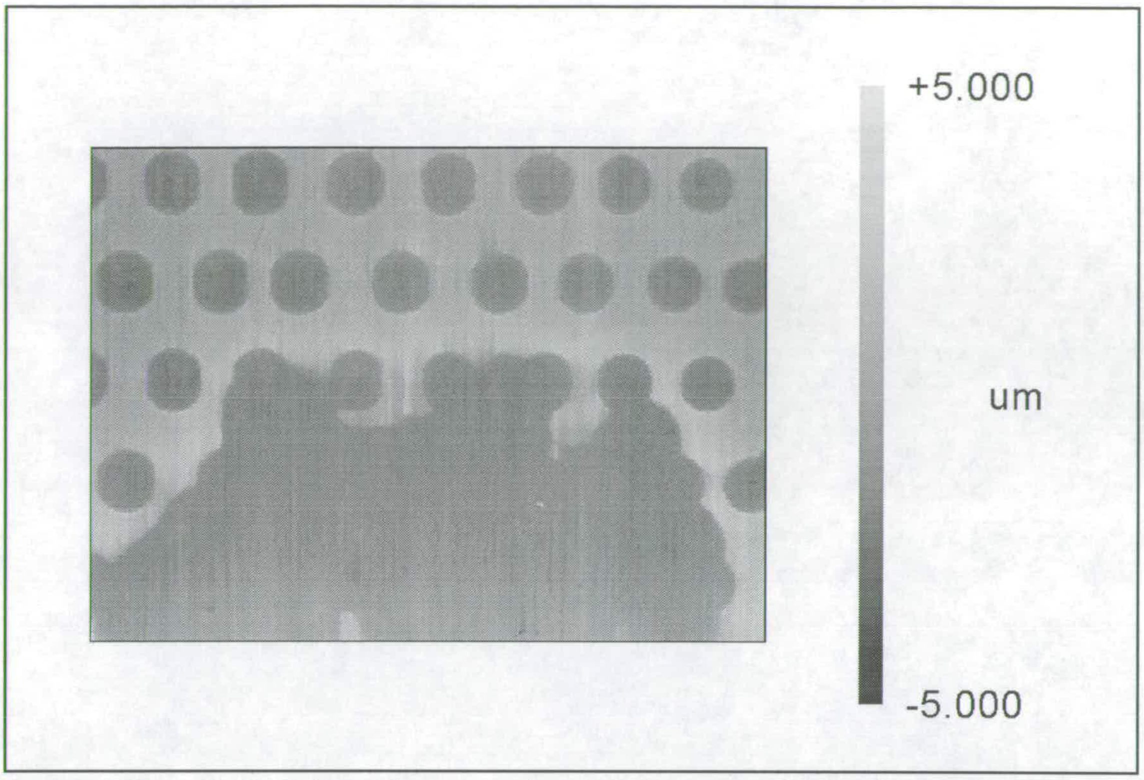


Figure 80 Rolled sheet showing edge of "salt patch" from Hoogovens roller 1 B

The issues of roll cleaning before and afer texturing have already been discussed elsewhere but are perhaps worth mentioning further. These are important issues which would significantly affect the commercial viability of the process. Cleaning of the rollers prior to texturing is of the utmost importance as ink will tend to adhere to any surface deposits and may subsequently be removed during the machining leading to premature mask failure. Similarly surface contamination after printing may lead to areas which are unwittingly masked when machined. One example of this was seen on the second of the first set of Hoogovens rollers. A small amount of salt solution was left on the surface during the setting up of the print head. This subsequently dried to a crystalline layer but was not removed as it was assumed that it would return to solution when the machining head passed over it. It was also felt that to remove it may disturb the ink layer at that point. In practice this salt layer was not dissolved and acted as a further mask against machining, resulting in an un-textured area in the centre of the roller. This can be seen clearly on the rolled sheet samples as a ground finish patch as seen in **Figure 80**. If that was commercial product it would almost certainly lead to its rejection, at least for autobody applications.

The contamination of the surface between printing and etching should be avoidable through careful practice ensuring that no fluids are spilled or splashed onto the roller and that airborne contamination is minimised. This does not mean that a clean room type environment would be required but some form of overhead canopy may be beneficial in some cases.

Pre-cleaning is obviously important and, on a full size work roll will not be a trivial matter. Many options have been discussed for this, from simple manual systems to lasers and air knives. It should be realised that this high level of surface cleanliness is also required for other connected technologies such as EBT and chromium plating. The methods used for EBT rolls are not known but the standard practice in one chrome plating plant visited involved a tank of Flash household cleaning solution and a scrubbing brush. The conclusion from this is that the issue of pre-cleaning would be solved through the application of existing commercial cleaning techniques, possibly combined with an air knife in advance of the print head to remove any settled airborne deposits.

Post cleaning may be more problematic as it will be necessary to remove all traces of electrolyte prior to rolling. This is especially true for sodium chloride which would cause corrosion of roll and strip, but even traces of passivating electrolytes may cause problems with subsequent processes such as zinc plating. The use of a peristaltic pump on the electrode return line of the present system works well and will often leave the roll surface dry after machining. Some salt will remain but in solid form where it may be feasible to remove it in situ using laser ablation or possibly air knives. The current method of manually wiping with a succession of damp wipes is time consuming but appears to be effective. After cleaning and oiling rollers have been stored for over six months without signs of corrosion. Similarly sheet rolled with the first set of Hoogovens rollers is still corrosion free after two years. This suggests that manual cleaning may be feasible (it is already done prior to chrome plating where it also provides a valuable opportunity to check for defects on the textured surface) provided that excessive corrosion can be prevented before the etching has finished. This does not seem to be a problem when sodium nitrate is used or when small amounts of residue have dried onto the surface.

The other substance to be removed at the post cleaning stage is the remaining ink mask. This is currently done using the base solvent of the ink (MEK) but this is both toxic and volatile and its use should be avoided where possible. Laser cleaning has been shown to be effective at removing it as has abrasion by a Scotch-Brite type pad. Alternatively it is possible that the ink would be removed by the first few metres of rolled strip. This has not been verified but the abrasion of relatively soft surfaces with low contact loads (such as the electrode masks) can cause significant scoring or chipping of the ink. If rolling without lubrication then it is likely that there would be direct abrasion between the ink and the sheet, but if lubricant was present then there may be a squeeze film formed on the top of the peak. This would act as a barrier and may help protect the ink from damage by the sheet. It is unlikely that the ink would need stripping prior to rolling if it was removed when starting.

7.3 Rolled Sheet

This is the end product of the process - the consumer requires textured sheet not textured rollers. The preceding sections have discussed the ability of the ECT process to create suitable textures on the roller, but how well do these transfer to the strip?

The Hoogovens experiments have shown that texture transfer of 80% or greater is possible with dry rolling. It also showed that there is a lower limit to the rolling load, below which little or no transfer takes place. Above this limit, transfer was high but increased slightly with increasing load. This non-linear behaviour may be explained by the steepness of the bearing area curve. Initially there will be a relatively large area of contact as defined by the top surface of the peaks. When the plastic limit of the strip is reached the texture will start to transfer. As the peaks are depressed into the surface the bearing area will increase only slightly (due to the wall angle of the machined areas) until the base of the roller is reached. At this point large increases in rolling load will result in only small increases in transfer. This is in contrast to the behaviour of the stochastic textures where the approximately gaussian height distribution results in the initiation of transfer at a much lower initial load (due to a small contact area on the highest peaks). Roughness and peak count transfer will then increase as roll load increases. As noted previously the transfer, once initiated, of ECT peak count is effectively independent of roll load or roughness.

The transfer characteristics of ECT will need further study to determine wether they are beneficial or not. One advantage is the open structure which will not entrap fluid during wet rolling. This should give better transfer during lubricated rolling than is obtained from SBT, EBT or EDT. All these other textures have closed volumes which will cause hydrostatic pressure build up, preventing full transfer of the texture. Conversely the lack of dependence between roll load and texture transfer may create difficulties in varying the range of roughness which can be produced from one roll. Other problems from rolling at low roughness transfers include the variation in roughness caused by local changes in peak spacing, as seen in the rolled ECT sample H15. This sample also showed a variation in roughness from one edge of the sheet to the other which may suggest a sensitivity to roll alignment or strip thickness variations.

The results from the temper rolled sheet suggested that waviness transfer was also high. This should be beneficial as the waviness of ECT is significantly lower than for the stochastic processes. Although the grinding of the fourth pair of Hoogovens rollers resulted in a higher than expected level of waviness it was also beneficial in that it had a very distinctive structure and amplitude. This made it easier to identify the waviness from the roller transfered to the sheet. The original tandem rolled (EDT) sheet shows a non-directional waviness. With one percent reduction there are already signs of the grinding waviness being superimposed on the sheet waviness. By 2.5 % reduction the grinding transfer is almost complete with little evidence of the original EDT waviness. This suggests that if the ECT roller had "zero" waviness then this also would be transferred to the sheet, negating the waviness of the tandem stage.

7.4 Machining Comparison

After the initial phase of the project the decision was taken to switch from a chemical machining process to an electro-chemical process. This was made on the basis of a number of assumptions. Ferric chloride is very corrosive which made design of etching equipment both difficult and expensive (due to the materials required for construction). Vapour is also corrosive and readily causes surface oxidation on exposed parts. The chemicals are expensive and require frequent replenishment or replacement. Finally the removal rates were very slow without using spray etching (which would increase problems of design and vapour corrosion). The intention was, by changing to an electro-chemical process, that many of these problems would be countered. The success or otherwise of this move will be discussed below.

Corrosiveness

This has been improved significantly over the chemical etchant. Vapour corrosion is no longer apparent although surface corrosion on the roller or apparatus is still possible if electrolyte residues are not removed or neutralised. This would be further improved by utilising a passivating electrolyte such as sodium nitrate.

This reduction in corrosiveness has also had the expected dividends in design freedom and cost reduction. Even with concentrated NaCl solutions the use of stainless steel parts has been possible, allowing many components to be sourced from manufacturers. For ferric chloride even straightforward parts such as probes and fasteners often had to be made to order or in house.

Cost

In addition to savings in hardware costs mentioned above, the chemical costs were significantly reduced. A tank full of ferric chloride may cost in excess of £50 (for the laboratory system) and suffer continual depletion in use thus needing frequent replacement. The equivalent tank of NaCl would be significantly less than £1 and is essentially non-depleting as the removed material forms a preciptate which can be removed by settlement and/or filtration. One tank of electrolyte was used in the laboratory for over six months before eventual replacement (due to reduced volumes from system leakages).

Machining

The local electro-chemical etching rate is undoubtably significantly faster that the previous immersion etching. This has resulted in a machining time of less than one minute for the laboratory jeweller's mill rollers, a reduction of more than 50%. The chemical process acts on the whole length of the roller so the theoretical machining time would be independent on the size of the roll. By this reckoning the Hoogovens rollers would have machined in approximately half the time that it took electro-chemically with a single electrode. This would make the chemical process significantly faster for a full sized work roll although this advantage would be significantly reduced by the use of multiple electro-chemical heads. Uniformity of machining for the chemical process has not been properly studied but should be good even over a large area as long as temperature gradients in the etch bath were avoided. Certainly there would be none of the stray field effects observed with the electro-chemical work and localised variation should be minimal.

Overall

The decision to convert to electro-chemical techniques has been generally vindicated with significant savings in cost and ease of use. On the issue of speed it does not seem quite so clear. ECM seems to be generally quicker in most trials to date but becomes significantly slower as the roller size increases. While ECM still represents the most favourable way forward the economics of chemical etching at large scales is certainly worth further consideration. Certainly development of a pilot system for processing mini-mill rollers would be a worthwhile exercise.

8 Conclusions

The aim of this project was to research the combination of ink jet printing technology and chemical and / or electro-chemical machining as an alternative process for the texturing of rollers for sheet steel production. This has resulted in a new process, termed *ink-jet texturing*. The thesis starts with a technological proof of concept using a chemical machining process. The chemical process was subsequently replaced by an electro-chemical one for reasons of speed, cost and environmental responsibility. The majority of the research was concentrated on the electro-chemical texturing (ECT) which culminated with the production of samples of rolled sheet for analysis. Issues of texturing time, cost, wear and reliability have also been investigated to enable the commercial viability to be assessed. Apparatus has been designed, constructed and tested for both chemical and electro-chemical texturing and the results appraised in the context of existing processes.

A significant challenge in the research concerned the reduction of waviness in the machined surface. Three main sources of waviness were identified. Firstly the initial grinding of the rolls introduces waviness which cannot be removed by the texturing process. The solution was in careful control and specification of the grinding. Secondly, non-uniformities in the electrolyte flow cause localised variations in machining rate. This is minimised by careful electrode design and by ensuring that the pitch of the tool feed is less than the inlet diameter of the electrode, thus enabling an averaging of machining over subsequent passes. The final cause of waviness was deficiencies in the printed mask. Variations in drop diameter and spacing cause localised changes in electric field concentration and therefore machining rate. At low rolling reductions this also causes localised variation in the texture transfer to the sheet. Optimum printing conditions were established to minimise these effects.

A further challenge involved the adhesion and integrity of the ink mask under machining conditions. A number of failure methods were identified as were the factors contributing to them.

The conclusions of the thesis may be summarised, in terms of the initial aims, as follows.

Primary Aim

The process was successfully investigated at the laboratory scale with adequate performance of the ink mask under controlled conditions. The experimental results may be summarised as follows.

- A variety of rollers from 50 mm to 140 mm diameter have been successfully textured with roughnesses from 1 to 10 μm R_a. This is comparable to existing processes.

- Fully deterministic textures, including graphics, have been created on smaller rollers. Some problems were encountered with printing larger rollers which may be attributed to the condition of the lathe which the equipment was retro-fitted to.

- Peak counts of up to 3.8 ppmm were obtained. This is slightly lower than is available from existing processes although it should still be acceptable. Peak count may be increased by different printer technologies.

- Very low waviness was attainable - 0.05 - 0.15 μm Wa - on both rollers and rolled strip, but was found to be very dependent on the uniformity of the ink mask and the electrode design. Any waviness from the initial roll grinding was also retained and was transferred to the sheet under high reductions.

Secondary Aim

A number of factors concerning the commercial feasibility of the process were addressed. Although the functionality of the textured strip could not be addressed, due to lack of samples and test facilities, some data was achieved from a commercial pilot mill. A number of problems have been highlighted which may be encountered on a commercial scale, although many, such as roll cleaning, will have to be addressed by existing technologies also. When balanced against the significant cost reduction of Ink Jet Texturing and the improved roll wear, it seems likely that the process will have a good chance of commercial success. Whether the process can be established as a commercial competitor to the existing texturing systems, especially electron-beam texturing, remains to be seen. Unfortunately its future may well be decided more by politics than technology as further industrial funding will be needed to progress towards a full prototype system. The following points can be summarised.

- Roller wear appears to be very good, especially in comparison to equivalent shot blast and electro-discharge rollers. This can be attributed to the high bearing area of the surface and to an absence of thermally affected layers.

- Conventional MEK inks provided an adequate barrier to both chemical and electro-chemical methods but did fail under extreme conditions or prolonged exposure. Further development would be required to get suitably robust inks for commercial use.

- Cleaning of the roller surface was found to be critical both before printing - to ensure good adhesion - and after machining - to prevent corrosion. This was attainable under laboratory conditions but may provide difficulties on large rollers.

- Predicted costs suggest a significant cost saving over existing technologies, especially for smaller machines, while maintaining equivalent levels of throughput.

The process also has application in areas distinct from rolling, some of which are already under investigation. Whatever the outcome it seems unlikely that this, the first thesis on ink-jet texturing will also be the last.

8.1 Future Work

Much of the future research will be directed towards the support of a full scale prototype machine. This would be capable of texturing rollers up to 4 m barrel length and 600 mm diameter. Areas to be addressed in this will be better control of the machining process, such that a given roll roughness can be specified by an operator and subsequently achieved. In support of this an online vision system will be required to monitor the printed pattern for errors, but also to give a local value for the masked / unmasked ratio. This would be fed back to the machining system to ensure a uniform roughness was maintained in spite of variations in the printed drop diameter. Further research will also be required on the electrode design to ensure optimum flow conditions over a larger machining area and better mask durability.

More research is also required on the printing to determine optimum print conditions and ink formulations. Effective printer triggering and stroke generation will also need to be addressed, as will other printing technologies.

Finally there are many other technologies which may benefit from the application of Ink Jet Texturing. Some of these are already under investigation but many others have also been identified.

[1] Muhl, J.; Alder, G. M. "Direct printing of etch masks under computer control." International Journal of Machine Tools and Manufacture, Vol 35, January 1995, pp 333-337

[2] Muhl, J. "Generation of controlled textures and corporate logos on rolled steel sheet by ink-jet texturing." She Met'95 International Conference, 26-28 June 1995, pp 349-357, ISBN 09527664 0 X

[3] Muhl, J. "Application of Electro-Chemical Machining to Ink Jet Texturing", SheMet'96 International Conference, 01-03 April 1996, Vol. 2, pp 77-87, ISBN 90-365-08045

[4] Muhl, J. "Surface Treatment of an Object", PCT/GB95/00396, Filed February 1995

[5] Boyd, M.; Laurenson, I.; Gilmour, K.; Muhl, J. "The influence of waviness on the squeeze film during the deep drawing process" SheMet'96 International Conference, 01-03 April 1996, Vol. 1, pp 367-376, ISBN 90-365-08045

[6] Paul, S.; Laurenson, I.; Gilmour, K.; Muhl, J. "A comparison of measurement techniques utilised for assessing the surface characteristics of drawing quality steel" SheMet'96 International Conference, 01-03 April 1996, Vol. 1, pp 283-293, ISBN 90-365-08045

[7] Storey, J.M.; Engelmann, D.M.: Surface topography effects on friction in the forming of aluminium sheet. Proc. IDDRG'94, Lisbon, 1994, pp 165 - 176

[8] Davies, W.J.:Roll etching of cold mill workrolls. I&SM, 1984, pp 37-41

[9] Simao, J et al: Simulated laser texturing using a modified electrical discharge arrangement. In: Advancement of Intelligent Production. Amsterdam, 1994

[10] David Aspinwall, private communication

[11] Ahmed, M. S.; Knight, J. A. G., Roll texturing by EDT", Proc. Mechanical and Steel Processing, 1988, p 405-413

[12] Aspinwall, D. K.; Zhao, F. L.; El-Menshawy, M. F., "Electro-discharge texturing (EDT) of steel rolls.", Surface Topography 2, 1989, pp 123-141

[13] Bragard, A.; Crahay, J.; Smul, W. De, "Texturing the roughness of work rolls of rolling mills by means of laser pulsers: the process of tomorrow?", Proc. Advances in cold rolling technology, Institute of Metals, London, 1985, p 94-101

[14] Yamada, Y.; Saisu, M.; Ujihara, S.; Nagaoka, M., "Development of high image clarity steel sheet laser mirror.", Mechanical Working and Steel Processing Conference Proceedings v 28, Iron & Steel Soc of AIME, Warrendale, PA, USA. p 259-265

[15] Wang, K.; Yang Y., "Study on texturing the surface topography of rolls by means of laser pulses", Advanced Technology of Plasticity, 1990, Vol. 2, p 749-754

[16] Crahay, J; Bragard, A "Production of surface textured work rolls by means of laser pulses", Proc.12th International Congress, IDDRG, S. Margherita, May 1982, pp 153 - 164

[17] Abe, H.; Satoh, S.; Obara, T.; Kato, T.; Isunoyama, K.; Shibazaki, O.; Uesugi, N. ,"Development of extra-deep drawing cold-rolled sheet steel for integrated automobile parts.", Stahl und Eisen n Spec Is Sep 14 1990 p 113

[18] Thoms, V.; Schlott, C., "Effect of the sheet surface in steel sheet forming.", Stahl und Eisen n Spec Is Sep 14 1990 p 80

[19] Mueller, R., "Lasertex steel sheet for bodywork.", Stahl und Eisen n Spec Is Sep 14 1990 p 140-141

[20] Deroo, H; De Graef, L; De Soete, D; De Mare, C; Gadeyne, Y "The EBT-texturing and its influence on coating, forming and painting of steel sheet" Metec Congress 94, Vol. 2, Verein Deutscher Eisenhuttenleute e. V., Dusseldorf, June 1994, pp 363 - 371

[21] Steinhoff, K "The influence of different texturing systems on the functional behaviour of the work rolls used in temper rolling processes", Rolls 2000, The Institute of Materials, Birmingham, April 1996, pp 186 - 195

[22] Defourny, J. A. ; Leroy, V. M.; Nilles, P. E. "Update of developments in Lasertex technology" Iron and Steel Engineer, August 1991, pp 39 - 45

[23] Dolves, J "Electron beam texturing of rolls" Iron and Steel Engineer, August 1991, pp 38 - 38

[24] De Graef, L.; De Soete, D. "Controlled Roll Roughness, a dream or reality", Rolls 2000, The Institute of Materials, Birmingham, April 1996, pp 166 - 175

[25] Iguchi, T; Kawasaki Steel Corporation; "Process and equipment for micropattern forming on roll surface, metal sheets for press working prepared by the roll and methods of preparing same"; European Patent application no. 89303908.1, Filed 20.04.89

[26] Nishiura, T et al; Nippon Steel Corporation; "Method of surface treatment of a roll", European Patent application no. 92916142.0, Filed 30.07.92

[27] Ike, H. "Metal sheets with designed surface microgeometry" 1st International Conf. on Processing Materials for Properties, The Minerals, Metals &Materials Society, 1993, pp 975 - 978

[28] Ike, H. "Fabrication of 3D controlled surface microgeometry by the technology of plasticity" Proc. Fourth Int. Conf. on Technology of Plasticity, International Academic Publishers, 1993, pp 55-60

[29] Ike, H. "Properties of metal sheets with 3D designed surface microgeometry prepared by special rolls" Journal of Materials Processing Technology, Vol. 60, 1996, pp 363-368

[30] Ike, H.; Qian, W. -J. "Processing of surface microgeometry of rolls by ion beam etching and passive rolling of metal sheets" Journal Japanese Society for Technology of Plasticity, Vol. 36 No. 411, 1996, pp 377-383 (in Japanese)

[31] Thomas, J. P.; Morgan, B. W. "A review of the development of the use of electro-discharge textured and hard chromium plated work rolls within British Steel Strip Products" Rolls 2000, The Institute of Materials, Birmingham, April 1996, pp 176-185

[32] Hollander, F "Metal Sheet: a dedicated resource" SheMet'96 International Conference, 01-03 April 1996, Vol. 1, pp 23 - 36, ISBN 90-365-08045

[33] Simao, J; Aspinwall, D. K.; Wise, M. L. H. ; Subari, K. "Surface texture transfer in simulated tandem and temper mill rolling using electrical discharge textured rolls" Journal of Materials Processing Technology, Vol. 56, 1996, pp 177 - 189

[34] Pawelski, K. et al"The influence of different work-roll texturing systems on the development of surface structure in the temper rolling process of sheet steel used in the automotive industry" Journal of Materials Processing Technology, Vol. 45, 1994, pp 215 - 222

[35] Olijar, S. ; Themelis, G. A. "Development of improved surface texture for automotive product" Mechanical Working and Steel Processing Conference Proceedings v 34, Iron & Steel Soc of AIME, Warrendale, PA, USA, 1993, pp 93 - 100

[36] Kellock, B. "Laser-EDM challenge to shot blast texturing" Machinery and Production Engineering, Jan. 1988, pp 87-97

[37] Bastawros, A. F. et al "Evolution of surface texture during temper rolling" Mechanical Working and Steel Processing Conference Proceedings v 34, Iron & Steel Soc of AIME, Warrendale, PA, USA, 1993, pp 485 - 489

[38] El- Menshawy, F.; Snaith, B. "Advantages in electro-discharge texturing (EDT) for cold mill work rolls" Iron and Steel Engineer, August 1991, pp 57 - 59

[39] Bastawros, A. F.; Speer, J. G. "A procedure to determine surface waviness" Mechanical Working and Steel Processing Conference Proceedings v 34, Iron & Steel Soc of AIME, Warrendale, PA, USA, 1993, pp 491 - 498

[40] Snaith, B.; Probert, S. D.; Pearce, R., "Characterization of laser-textured cold-rolled steel sheets", Wear, 109, 1986, p 87-97

[41] Nishimura, K. et al "Development of high image clarity steel sheet by laser texturing" Iron and Steel Engineer, August 1991, pp 46 - 51

[42] Stout, K. J. et al "The development of methods for the characterisation of roughness in three dimensions" Report EUR 15178 EN, 1993

[43] Vermeulen, M. et al "3D-Characterisation of EBT-steel sheet surfaces" International Journal of Machine Tools and Manufacture, Vol 35, January 1995, pp 273 - 280

[44] Bastawros, A. F. et al "Effects of steel surface texture on appearance after painting" SAE Technical Paper Series, 930032, March 1993

[45] Jonasson, et al, "Influence of Sheet Metal Surface Topography on Appearance after Painting", Proc. 5th International Conference on

Sheet Metal, Belfast, April 8-10, 1997, ISBN 1-85923-072-5

[46] Nilan, T. G.; Scialabba, B. J. " Relationship of sheet surface roughness texture to painted sheet appearance" Proc 19th Mechanical Working and Steel Processing Conference, Pittsburgh, 1977, pp 148 - 157

[47] Allen, D. M. "The principles and practice of photochemical machining and photoetching" Adam Hilger, Bristol, 1986

[48] Ueda, R. "Chemical machining with a ferric chloride etchant" Corrosion Engineering, Vol. 38, 1989, pp 271 - 282

[49] Allen, D. M. et al "Three - dimensional photochemical machining" Annals of the CIRP, Vol. 36/1, 1987, pp 91- 93

[50] Wible, P. M. "Regeneration of etchants" PCMI Journal, Vol. 6, 1981, pp 7 - 11

[51] De Barr, A. E.; Oliver, D. A. (Eds) "Electrochemical machining" MacDonald Press, 1968

[52] Wilson, J. F. "Theory and practice of electrochemical machining" John Wiley & Son, London, 1971

[53] McGeough, J. A. "Principles of electrochemical machining" Chapman and Hall, London, 1974

[54] Datta, M. "Anodic dissolution of metals at high rates" IBM Journal of Research and Development, Vol. 37, 1993, pp 207 - 226

[55] Datta, M. , Romankiw,L. T. "Application of chemical and electrochemical micromachining in the electronics industry" Journal of the Electrochemical Society, Vol. 136/6, 1989, pp 285c - 292c

[56] Datta, M. "Microfabrication by electrochemical metal removal" IBM Journal of Research and Development, Vol. 42/5, 1998, pp 655 - 669

[57] Osenbruggen, C., Regt, C. de "Electrochemical micromachining" Philips Technical Review, Vol. 42/1, 1985, pp 22 - 32

[58] West, A. C., Newman, J. "Current distributions on recessed electrodes" Journal of the Electrochemical Society, Vol. 138/6, 1991, pp 1620 - 1625

[59] West, A. C. et al "Shape changes during through-mask electrochemical micromachining of thin metal films" Journal of the Electrochemical Society, Vol. 139/2, 1992, pp 499 - 506

[60] Alkire, R., Deligianni, H. "The role of mass transport on anisotropic electrochemical pattern etching" Journal of the Electrochemical Society, Vol. 135/5, 1988, pp 1093 - 1100

[61] Alkire, R. et al "Effect of fluid flow on convective transport in small cavities" Journal of the Electrochemical Society, Vol. 137/3, 1990, pp 818 - 824

[62] Shenoy, R. V., Datta, M. "Effect of mask wall angle on shape evolution during through-mask electrochemical micromachining" Journal of the Electrochemical Society, Vol. 143/2, 1996, pp 544 - 549

[63] Mangin, P. J. "Digital printing: the future of printing?" Pulp and Paper Canada, Vol. 98/12, 1997, pp 93 - 97

[64] Le, H. P. "Progress and trends in ink-jet printing technology" Journal of Imaging Science and Technology, Vol. 42/1, 1998, pp 49 - 62

[65] Schneider, J. M. "Hard copy and printing technologies" Proceedings of SPIE, Vol. 1252, pp 183 - 193

[66] Raleigh, F. R. S. "On the instability of jets" Proceedings of the London Mathematical Society, Vol. 10/4, 1878, pp 4 - 13

[67] Krause, P. et al "A micromachined single-chip inkjet printhead" Sensors and Actuators A, Vol. 53, 1996, pp 405 - 409

[68] Diepold, T. et al " A micromachined continuous ink jet print head for high resolution printing" Technical Digest MME'97, Southampton, 1997, pp. 176-179

[69] Wallace, D. B. "Automated electronic circuit manufacturing using ink-jet technology." Journal of Electronic Packaging, Vol. 111/2. 1989, pp 108-111

[70] Teng, K. F., Vest, R. W. "Microprocessor-controlled ink jet printing system for electronic circuits." IEEE Transactions on Industrial Electronics, Vol 35/3, 1988, pp 407-412

[71] Lindner, F. H., PC Proto Inc. "Computer aided printer-etcher" United States Patent No. 4,767,489

[72] Sachs, E. "Three-Dimensional Printing. Rapid tooling and prototypes directly from a cad model."Proc Manuf Int 90 Part 4 Adv Mater Autom. Publ by American Soc of Mechanical Engineers (ASME), New York, NY, USA. p 131-136

[73] Hauber, D. "Automated production of P/M parts directly from a computer aided design model" International Journal of Powder Metallurgy, Vol. 24/4, 1998, pp 337 - 342

[74] Teng, K. F.; Vest, Robert W.; "Liquid ink jet printing with mod inks for hybrid microcircuits"; IEEE Transactions on Components, Hybrids and Manufacturing Technology, Vol. CHMT-10/4, 1987, pp 545-549

[75] Whitehouse, D, J. "Handbook of Surface Metrology" IOP Publishing, 1994

[76] P. de Groot, L. Deck, "High-speed non-contact profiler based on scanning white light interferometry", Int. J. Mach. Tools and Manufact., Vol 35, No2, pp. 147-150, 1995

[77] Liam Blunt, private communication

[78] Alan Ross, private communication

[79] British Steel Welsh Laboratory, private communication

[80] Staeves, J. et al, "Surface qualification in the sheet metal domain", SHEMET'98, Twente, 1998

[81] Kalpakjian, S. "Manufacturing Engineering and Technology", Addison-Wesley, 1992

[82] ULSAB Press Release, "ULSAB concept becomes real", Web Page, www.ulsab.org/public/news/feb98release.htm, February 1998

[83] Cold Metal Products, Inc., Web Page, www.ColdMetal.com

[84] Ninneman, P, "High-speed vs. High-chrome rolls", New Steel, November 1997

[85] Tönshoff, H. K. et al, "Environmental and Safety Aspects of Electrophysical and Electrochemical Processes", Annals of CIRP, Vol 44/1, pp 553 - 568, 1995

Appendix A: Paper I

J Muhl & G M Alder "Direct printing of etch masks under computer control" International Journal of Machine Tools and Manufacture, Vol. 35/2, 1995, pp 333 - 337

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DIRECT PRINTING OF ETCH MASKS UNDER COMPUTER CONTROL

JONATHAN MUHL AND GEORGE M. ALDER

DEPARTMENT OF MECHANICAL ENGINEERING, THE UNIVERSITY OF EDINBURGH, UK

Abstract

A new technique has been developed using a microprocessor controlled printer to directly deposit a controlled ink film to act as a barrier against etchants. The process is similar to photochemical machining but removes all the stages of photo-processing and mask making. The method has been developed for the controlled texturing of steel rollers for the automotive industry but also has potentials in other areas of photochemical machining. This paper introduces the concept and describes early experimental work in the texturing of steel rollers.

1.0 Introduction

The issue of sheet steel surface texture attracts a great deal of interest from both producers and end users. Surface finish is generally believed to be of importance in painted appearance, paint adhesion and formability of steel sheet and as such is of great interest to the automotive industry. A fine surface texture is applied to the surface of the steel during the final temper rolling stage of the cold strip mill to give the surface finish specified by the end user. This is achieved by texturing the steel roller and transferring the pattern to the sheet. The rollers are presently textured by one of three techniques. The traditional process is shot blast texturing, otherwise known as SBT. This involves firing particles of aluminium oxide or other hard material at the surface of the roller. This leads to limitations in the hardness of the roll as it must be softer than the shot being used to texture it. It also suffers by being difficult to accurately control, resulting in wide variations of peak height and a poor bearing ratio. This combined with the hardness limitation also reduces the wearability and thus the service life of the roller.

The SBT technique has been replaced in many areas by the more recent processes of electrical discharge texturing, (EDT) [1 2 3], and laser texturing, (LT) [4 5]. Both of these offer greater control than SBT and are effectively independent of roll hardness. The EDT approach is based on the well established process of electro-discharge machining. The roller, mounted on a lathe, grinding machine or similar, is rotated at constant velocity while the tool electrode is traversed along its length at constant rate on a zero backlash servo system. A dielectric fluid such as paraffin flows between the tool and the roll. This breaks down when a suitable voltage is applied across the electrodes, the resulting spark melting a small crater in the surface of the roll. By controlling the frequency, duration and current of the spark different surface roughnesses can be created.
The LT process uses a laser beam to remove material from the surface of the roller. The unfocussed beam is chopped by a rotating disk then focused into a spot, typically 0.1 mm in diameter, on the roll surface. This causes the metal to first melt and then vaporise. When the beam is removed the surface cools leaving a pit. The rotation of the roller and the pulsing frequency of the beam set the spacing of the craters, and thus the peak count on the textured sheet. This produces a surface which has reportedly good pressing and painting performance [6 7], although there have been reports of the regular pattern of the texture causing diffraction patterns on the surface of the painted sheet [8].

The random processes, SBT and EDT, have a large waviness ($\lambda > 0.8$ mm) component in their texture (particularly SBT) which has been linked to a reduction in image clarity of the painted sheet [9]. It is also claimed that roughness ($\lambda < 0.8$ mm) is effectively covered by painting. These findings have been questioned by a more recent report [10] which studied the progression of surface texture through a high quality paint process, using fine, medium and coarse grades of SBT, EDT and LT sheets. A commercial bright sheet was also studied for comparison. This paper concluded that all processes gave very similar results with initial waviness and peak count statistically insignificant, waviness being inherited primarily from the painting process. It also observed that roughness features could be detected through the paint, both through spectral analysis and, in the case of the LT sheets, visually.

The work in Edinburgh started as an attempt to find a viable alternative process which would retain the favourable aspects of LT, good bearing surface, low waviness, consistent peak height, and independence from roll hardness, but without the deterministic pattern which causes interference effects through the paint. It was hoped that a process which would retain the good forming characteristics while improving the paint performance could be developed.
Photochemical machining [11] was initially considered as having the potential to satisfy the above criteria. This is where the work piece is coated in a light sensitive chemical called photo-resist. The required image is projected onto the surface to selectively expose the resist. A developing solution is then used to strip all the areas required to be exposed to the chemical etchant. Unfortunately there were limitations in trying to expose the images required onto the curved surface of the roller. These could probably be overcome but not without greatly adding to the complexity of the solution. It also had too many processing stages to appear cost effective. It was decided to try and replace the photoresist stages (coating, exposure, and developing) with a single stage etch mask, deposited directly onto the roll surface via an ink jet printer. This process has been termed inkjet texturing, and will hereafter be referred to as IJT.

2.0 The IJT Technique

2.1 Direct Deposition Masks

The technique developed at Edinburgh utilises an ink-jet printer to spray the ink mask directly onto the surface of the roller, as suggested above. This gives full control over the pattern of the texture, something that the existing texturing techniques cannot offer. With the correct interfacing software this would permit the operator to design a pattern using conventional CAD methods and then transfer it directly to the surface of the roller. The patterns generated would be limited only by the resolution of the printer.

2.1.1 Preliminary Experiments

To test the concept a standard office ink-jet printer [12] was used to print onto some mild steel shim. Although this was possibly a worst case arrangement - the printer uses a water based ink, reliant on the absorbtion of the paper to dry - it did provide a quick method of testing the idea.

Strips of 50% shading were printed on pieces of mild steel shim then etched in ferric chloride solution for between 15 and 180 seconds. Convincing results were obtained by degreasing and heating the shim before printing. Some samples were also heated after printing as a form of post-baking.

The surface profiles were examined using a commercial profilometer [13]. These suggested that the ink remained resistant to the etch for up to 30 seconds. This was considered to be quite promising considering the water based make up of the ink.

It was also noticed that the solvent based ink used to label the samples was still forming a strong barrier to the etch after two minutes immersion. This was particularly encouraging and led to attempts to find a similar ink suitable for inkjet printers.

2.1.2 Solvent Based Ink Experiments

Following on from the success of the first experiments it was decided to test some solvent based inks. Two samples were provided by a manufacturer of ink-jet inks [14]. These were sufficient to indicate the general chemical resistance of the solvent based inks.

Samples were coated by dabbing ink on with a fine sponge to give a fine, random pattern. These were then etched as per the first samples. The solvent based ink showed a very good etch resistance with inspection under the Talysurf showing no discernable etch penetration, even after two minutes exposure.

These tests confirmed the findings of the first tests that printed ink can be a suitable masking material against ferric chloride etchant.

2.1.3 Roller Processing Experiments

The next stage of the development was to build and test a system to print and etch steel rollers. It was decided to use a lathe to rotate the roll at constant velocity around its central axis while a print head traverses along its length. This required a printhead that could be mounted onto the tool-post of a lathe and was capable of printing a solvent based ink at high resolution.

It was decided retain inkjets for the printhead as they are well established and are suited for non contact and high resolution work. Although a discussion of these machines is outwith the scope of this paper, some background may be useful. Two basic types exist; drop on demand (DOD) and continuous ink jets (CIJ).

The former consists of an array of nozzles from which individual drops are fired when required. Drops are ejected either by the movement of a piezo-electric plate or by a heating coil which causes thermal expansion in the inks. Most desk top inkjet printers are of this variety and have high resolutions but generally slow printing times.

The latter type, CIJ, typically consists of a single nozzle with a continuous jet of ink. This is broken up (when leaving the nozzle) into individual drops which then pass through a charging tunnel. Here a charge is applied relative to the desired position of the dot with those not required for printing being left uncharged. They then pass under a high voltage deflection plate which deflects the drops to their desired positions while those uncharged continue straight into a catcher which returns them to the ink reservoir. This process is analogous to the beam in a cathode ray tube. CIJ printers are faster but not quite as high resolution as DOD's and are commonly used in industry for product labelling applications.

A major drawback of the DOD printers is their aversion to solvent based inks. These tend to dry in and block unused nozzles leading to printing errors. Although it may be possible to use them with other suitable mask materials they would require prior modification. Because of this it was decided to try a CIJ type industrial printer, with a slight trade-off of resolution.

A suitable industrial ink-jet printer [15] was found. This machine is designed for contactless printing of items moving past the printhead, which is connected to its control console by means of a two meter umbilical. The print head has a nozzle diameter of 36 microns and a dot frequency of upto 80 kHz. Although the stated resolution is 170 dots per inch, higher resolutions can be obtained.

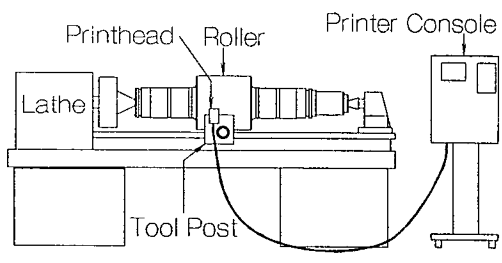

Figure 1: Lathe based mask coating.

The system used for coating the rollers consists of a small precision toolmakers lathe and the ink-jet printer as shown in Figure 1.

2.2 Etching

Having applied a mask to the surface of the roller, the next stage was to remove the exposed surfaces. This is done using conventional etching techniques. Ferric Chloride solution, $FeCl3$, was chosen as a readily available, effective etchant which is also relatively harmless to work with.

The etching process must be capable of meeting two main criteria:

(1) It must be capable of etching to the required depth without complete undercutting of the mask.

(2) It must maintain the integrity of the ink mask for the duration of the etch.
These factors may be influenced by the following parameters.

(1) Etch time.
(2) Etch concentration.
(3) Etch temperature.
(4) Agitation/circulation of etchant.
(5) Delay time between mask printing and etching.

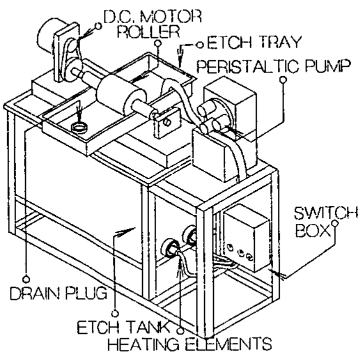

Figure 2: Original roller etching tank.

Basic information on etchant parameters was provided by Allen[11]. With this information the system in Figure 2 was built. The etch level in the tray - set by the height of the drain plug and the flow rate of the fluid - is adjusted such that it just touches the underside of the roller. The roller rotates, thereby refreshing the etchant on every revolution. With the pump switched off the fluid level drops and the roller may be removed for rinsing. The system also allows temperature control via the heaters and thermal sensor; circulation via the pump flow rate and agitation via the rotational speed of the roller.

4.0 Evaluation of Process

4.1 Test Equipment

The following equipment was used for the evaluation of the textured rollers.

Rolling Mill: A 'jewellers' type mill with 100mm x 52.5mm rollers and times four reduction gearbox.

Rollers: Top roller textured, made from EN31 bearing steel and quench hardened; bottom roller plain ground as supplied with mill.

Sheet Steel: Strips approximately 50 mm wide by 1 mm thick in the annealed last condition (as it would be before the temper mill in a steel plant), supplied by British Steel Welsh Laboratories.

4.2 Results

The two dimensional traces in this section were produced on the stylus profilometer. This had an analogue output which was sampled into an IBM compatible personal computer. The data processing and graphical presentation was performed using the DIA-PC suite of software.

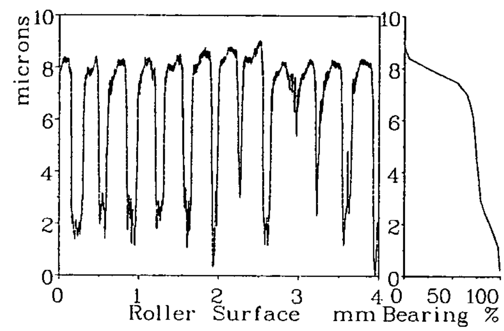

Figure 3: IJT textured roller.

Figures 3 to 7 show five different sample textures. As well as those directly related to the IJT process (the roller surface, textured sheet surface and untextured sheet surface), there are also two samples of commercially textured sheet, supplied by a car manufacturer [16]. Of these the coarse sheet is probably of a deep-drawing grade.

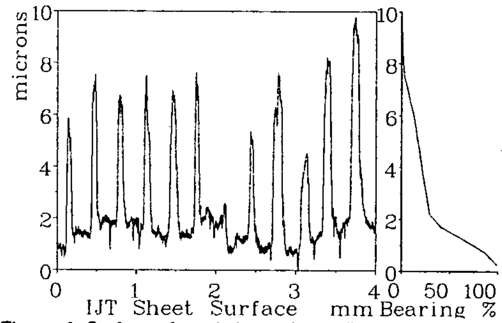

Figure 4: Surface of steel sheet after rolling

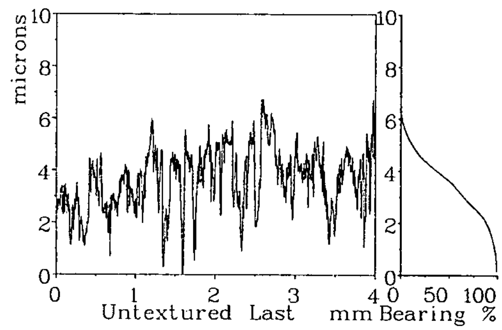

Figure 5: Steel sheet before rolling.

The IJT textured rollers have a plateau type texture, giving a good bearing surface and consistent peak height, as shown in the sample profile of Figure 3. Crater depths are typically 8 ± 2 microns, with peak counts currently in the range of 3 - 4 p/mm. The pattern transferred well from the roller to the annealed steel strip as can be seen in the profile of Figure 4. The waviness of the profile is caused by bending in the steel strip, a combination of coil set and inadequacies in the jewellers rolling mill. The profile shows a good consistency of peak heights even with the coarse texture (peak height approximately 5-6 microns) shown here. This can be compared with the inconsistent nature of the original texture of the steel strip as shown in Figure 7.

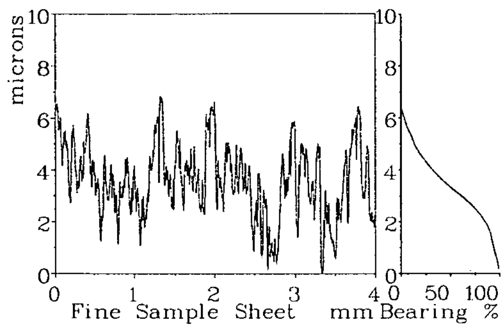

Figure 6: Ford supplied sheet with fine texture.

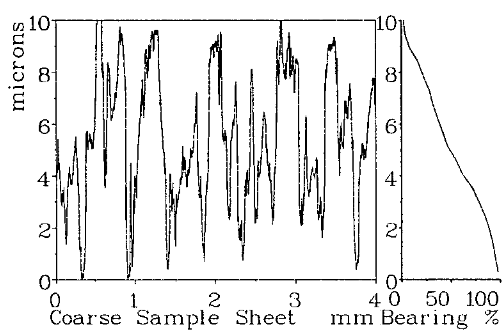

Figure 7: Coarse textured Ford supplied sheet.

Figures 6 - 7 show samples of conventionally textured steel. Figure 6 is a standard panel steel while Figure 7 is intended for deep drawing applications, hence the coarser, deeper texture. Neither exhibit the consistency of Figure 4.

5.0 Discussion

5.1 Mask Printing

Work so far has concentrated on the demonstration of the basic process for the direct printing of etch masks. In principle, there is complete freedom over the pattern that can be printed. The process is under software control, and the print head can be moved to the required position by a number of possible mechanisms (e.g. a conventional ink-jet printer or an X-Y positioning stage).

The resolution of the printed image depends on:

- the accuracy of the print head positioning mechanism
- the diameter of the ink droplets
- the properties of the liquid ink.

A conventional ink-jet printer, using a stepper motor and toothed belt, can position the head to within 0.05 mm. However, even these resolutions could be improved on if it was required. The printer used in this application produces dots about 0.15 mm in diameter. This size results partly from the original droplet diameter (about 0.05 mm), and partly from the degree to which the liquid spreads over the surface before it dries. It seems likely that smaller printed dots could be achieved through the development of a suitable ink.

5.2 Etching Alternatives

Immersion etching is limited by the refresh rate of the fluid at the surface of the roller. One way to improve this is to apply the etchant as a spray so that the old fluid does not become trapped in the cavities forming on the surface. Improved rates of metal removal may make this approach suitable for the processing of large scale rollers, but has few advantages for the small laboratory trials currently being undertaken.

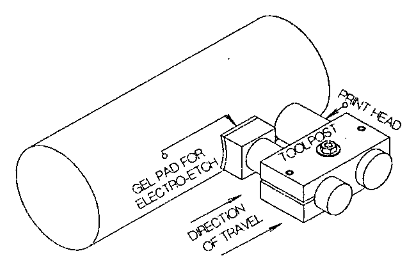

Figure 8: Proposed electro-etching system.

Another method, which may offer ultimate control, is pulsed electro-chemical etching. This would allow control of both crater depth and profile by varying pulse duration and current. Further advantages include less corrosive chemicals and the possibility of integration to make a machine which could print and etch simultaneously. This should help to make the texturing process cleaner, cheaper and quicker. The machine would be similar to the conventional printing system shown in Figure 1 but with the tool-post/printhead arrangement supplemented by an etching pad as shown in Figure 3.

5.3 Other Applications

The controllable nature of the mask deposition combined with the reduction in processing stages should make it a viable alternative in other areas of photo-etching. These include the manufacturing of printed circuit boards and photochemical machining. Although the ultimate resolution of photo-etching may be greater, the direct deposition method offers the potential of providing quick in-house prototyping facilities at relatively low cost. One example of this would be a 'desktop' printed circuit board prototyping unit which could accept standard output from an electronics CAD package to produce a board ready for etching within a few minutes. It may even be possible to do the etching within the same machine.

As well as its application in manufacturing the direct deposition method may offer significant advantages as a tool for more fundamental research into many aspects of sheet steel production. The controllable pattern generation offers the potential to develop optimum textures for such areas as paint appearance, coatings adhesion and press performance (particularly deep drawing).

6.0 Conclusions

A new process for etching metal surfaces has been developed. The key feature of the process is the direct printing under computer control onto the metal surface of the etch resistant mask. The process has some similarity to photochemical machining but removes all the stages of photo-processing and mask making. The advantages of the new method are:

- direct control of the print-head as it lays the mask
- software control of the surface pattern
- adaptable to a range of surface geometries
- potential for development of a continuous print/etch process for large surfaces.

The process has been demonstrated in the laboratory for the particular application of texturing rollers for the production of textured steel sheet.
Potential applications of the new process include:

- texturing rollers for sheet metal production
- texturing rollers for sheet plastics production
- direct etching of plane and curved surfaces under computer control
- alternative to photo-chemical machining (e.g. printed circuit board manufacture)

References

1. Aspinwall, D. K.; Zhao, F. L.; El-Menshawy, M. F., "Electro-discharge texturing (EDT) of steel rolls.", Surface Topography 2, 1989, p123-141

2. Aspinwall, D. K.; Wise, M. L. H.; Stout, K. J.; Goh, T. H. A.; Zhao, F. L.; El-Menshawy, M. F; "Electrical Discharge Texturing", International Journal of Machine Tools Manufacture, Vol 32,No. 1/2, 1992, p 183-193

3. Ahmed, M. S.; Knight, J. A. G., Roll texturing by EDT", Proc. Mechanical and Steel Processing, 1988, p 405-413

4. Bragard, A.; Crahay, J.; Smul, W. De, "Texturing the roughness of work rolls of rolling mills by means of laser pulses: the process of tomorrow?", Proc. Advances in cold rolling technology, Institute of Metals, London, 1985, p 94-101

5. Wang, K.; Yang Y., "Study on texturing the surface topography of rolls by means of laser pulses", Advanced Technology of Plasticity, 1990, Vol. 2, p 749-754

6. Bragard, A.; Crahay, J.; Smul, W. De, "Texturing the roughness of work rolls of rolling mills by means of laser pulses: the process of tomorrow?", Proc. Advances in cold rolling technology, Institute of Metals, London, 1985, p 94-101

7. Mueller, R., "Lasertex steel sheet for bodywork.", Stahl und Eisen n Spec Is Sep 14 1990 p 140-141

8. Muller, R., "Evaluation of the properties of Sheet with Lasertex Surface Texture", Proc. 15th IDDRG, Dearborn, Mich., 1988, pp 99-107

9. Yamada, Y.; Saisu, M.; Ujihara, S.; Nagaoka, M., "Development of high image clarity steel sheet laser mirror.", Mechanical Working and Steel Processing Conference Proceedings v 28, Iron & Steel Soc of AIME, Warrendale, PA, USA. p 259-265

10. Bastawros, A. F.; Speer, J. G.; Zerafa, G.; Krupitzer, R. P., "Effects of Steel Surface Texture on Appearance After Painting", SAE technical paper series No 930032,Society of Automotive Engineers, Inc., Warrendale, Pa, 1993, p 1-14

11. Allen, D. M., "The principles and practice of photochemical machining and photoetching", Adam Hilger, Bristol, England, 1986

12. Hewlett-Packard Deskjet 500

13. Rank-Hobson Talysurf 4

14. Coates Electrographics (Coates International)

15. Videojet International Excel Hr

16. Ford Motor Company

Appendix B: Paper 2

J Muhl "Generation of controlled textures and corporate logos on rolled sheet by ink jet texturing" Proceedings of the 3rd International Conference on Sheet Metal SHEMET'95, Birmingham UK, 1995

GENERATION OF CONTROLLED TEXTURES AND CORPORATE LOGO'S ON ROLLED STEEL SHEET BY INK-JET TEXTURING

Jonathan Muhl
The University of Edinburgh, Department of Mechanical Engineering

ABSTRACT

Ink-jet texturing is a novel new technique for the controlled etching of metallic substrates. It is currently being developed to texture finishing rolls used in the production of cold rolled sheet steel. This paper provides an introduction to the process and discusses its application to the sheet metal industry.

1 INTRODUCTION

Surface Texture

Surface texture is an issue which attracts a great deal of interest from both producers and end users of sheet material. This interest is reflected in the quantity of research into the subject, from surface characterisation and performance assessment through to the invention and development of methods for texture generation. To date most research has concerned the production of sheet steel, driven by the demands of the automotive industry, its largest volume user.

Texture in this context is a pattern of peaks and valleys, typically in the order of microns in height or depth, which is laid over the sheet surface in order to improve the functional performance of the steel. Traditionally paint and press performance have been the main concerns but recent increases in the use of coated steels have added other concerns.

Production

Cold rolled strip first passes through a series of reducing rollers in the tandem mill. The steel

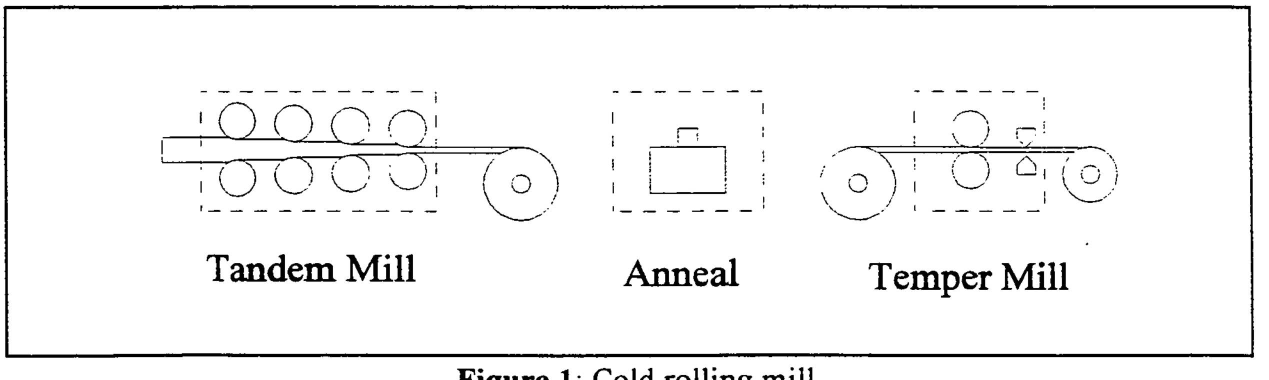

Figure 1: Cold rolling mill

is then annealed to remove the work hardening before being passed through the finishing rollers in the temper mill. Although a primary texture is applied in the tandem mill (to prevent sticking during annealing) the final texture originates in the final cold rolling (temper) stage of sheet production. It is to these rolls that the negative image of the required texture pattern is applied.

Methods of Texturing

The rollers are presently textured by one of four techniques. The traditional process is shot blast texturing, otherwise known as SBT. It involves firing particles of aluminium oxide or other hard material at the surface of the roller. This leads to limitations in the hardness of the rolls whose material must be softer than the shot being used to texture it. Difficulties of accurate control also cause problems, resulting in wide variations of peak height and a poor bearing ratio. This, combined with the hardness limitation, reduces the wear ability and thus the service life of the roller.

The SBT technique has been replaced in many areas by the more recent processes of electrical discharge texturing, (EDT) [1], [2], [3], and laser texturing, (LT) [4], [5] . Both offer greater control than SBT and are effectively independent of roll hardness. The EDT approach is based on the well established process of electro-discharge machining. By controlling the frequency, duration and current of the spark different surface roughness can be created.Laser texturing uses a laser beam to remove material from the surface of the roller. This produces a surface which has reportedly good pressing and painting performance [6], [7],. Electron beam texturing (EBT) has recently been introduced by a Belgian company [8]. This appears to have good performance and is very controllable . The nature of the machining process used however, leads to very high capital (and presumably production) costs.The random processes, SBT and EDT, can have a large waviness (wavelength, $\lambda > 0.8$mm) component in their texture (particularly SBT) which has been linked to a reduction in image clarity of the painted sheet [9].

2 INK JET TEXTURING

The work at Edinburgh started as an attempt to find a viable alternative process which would retain the favourable aspects of LT (good bearing surface, low waviness, constant peak height, and independence from roll hardness), but without the deterministic pattern which causes interference effects through the paint. It was hoped that a process which would retain the good forming characteristics while improving the paint performance could be developed. Photochemical machining [10] was initially considered as having the potential to satisfy the above criteria. This is where the work-piece is coated in a light sensitive chemical called photo-resist. The required image is projected onto the surface to selectively expose the resist. A developing solution is then used to strip all the areas required onto the curved surface of the roller. Major problems are raised by the requirement to focus a sharp image on a curved surface. These could probably be overcome but not without greatly adding to the complexity of the solution. The method also had too many processing stages to appear cost effective.

These problems could be avoided by replacing the photoresist stages (coating, exposure, and developing) with a single stage etch mask, deposited directly onto the roll surface via an ink jet printer. This process has been termed ink-jet texturing, (IJT). A full description of the IJT process is given in [11] but will be summarised here.

Direct printing of masks

The texturing process consists of two main stages, the mask application and the roller etching. These may be realised by a number of different techniques but here we will consider those used for the first experiments.

Roller coating

The roller is mounted on a machine capable of rotating it about its central axis. In this instance a small toolmakers lathe was used, as shown in Figure 2, but it could also be a roll grinder or similar.

As the roller rotates the printhead is traversed. The mask is thus printed in a helical pattern across the roller surface. Here the printhead is mounted on the lathe toolpost. The pitch of the helix is set using the machines screw cutting mode with the print height being adjusted to ensure accurate butting between strips.

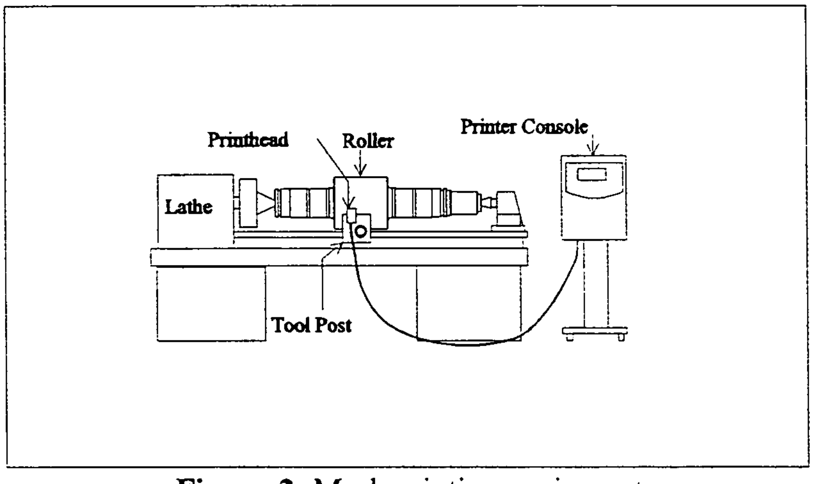

Figure 2: Mask printing equipment

After coating the surface texture is created by selectively etching the exposed areas. The work described here used a wet chemical etching process as shown in Figure 3.

The coated roller is rotated at constant velocity by the D.C. motor. The etchant, in this case ferric chloride solution heated in the tank to a temperature of approximately 50^{0}C, is pumped into the tank at a flow rate which, in combination with the drain plug height, ensures that the solution touches the bottom of the roller. The rotation of the roller ensures that the etchant on its surface is refreshed every rotation. After the desired etch time the flow is stopped and the roller can be removed for rinsing.

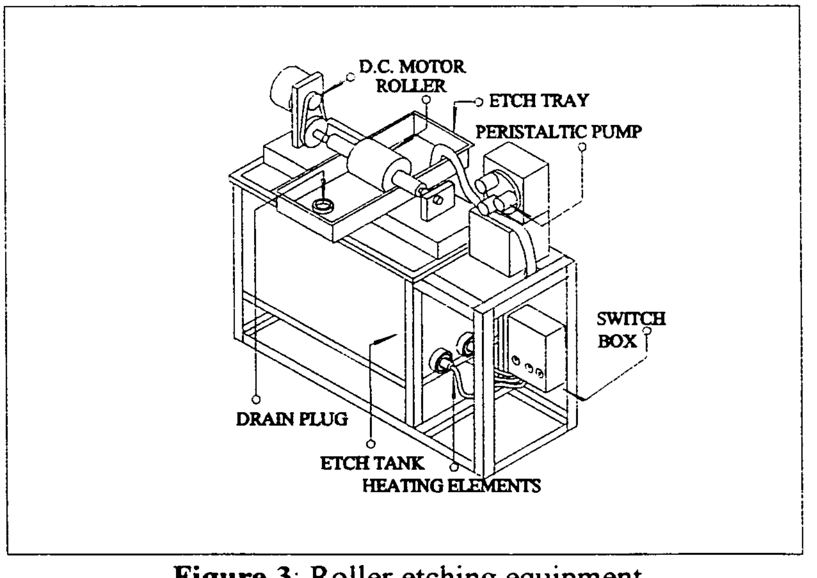

Figure 3: Roller etching equipment

3 RESULTS

Equipment
The equipment used for this section is as follows

Rolling mill: A two high jewellers mill with 100mm by 52.5mm diameter rolls, manual drive and a four times reduction gearbox was used. This gives little control over the rolling process but has considerable benefits in cost saving and ease of handling.

Rollers: Both rolls made from quench hardened EN31 bearing steel with top roll textured and bottom roll plain ground. The process is however largely independent of roll hardness.

Sheet steel: Strips, 50mm x 1mm, in the annealed last condition were textured. The tandem stage texture was generated by EDT. These strips were kindly supplied by British Steel Technical (Welsh Laboratories).

Metrology
Three dimensional surface measurements were taken using a Zygo Newview 100 scanning white light interferometer system. The results have been digitally filtered (cut-off wavelength 0.8mm) to separate roughness and waviness data which are then plotted separately. A selectionof surface parameters are also given. Rq, the rms roughness, is used in preference to Ra as it gives a more accurate representation of non-gaussian surfaces. The Swedish height parameter, H is the separation between the top 5% and the bottom 10% of the surface. This was chosen as it gives a reduced sensitivity to noise and surface contamination. These can

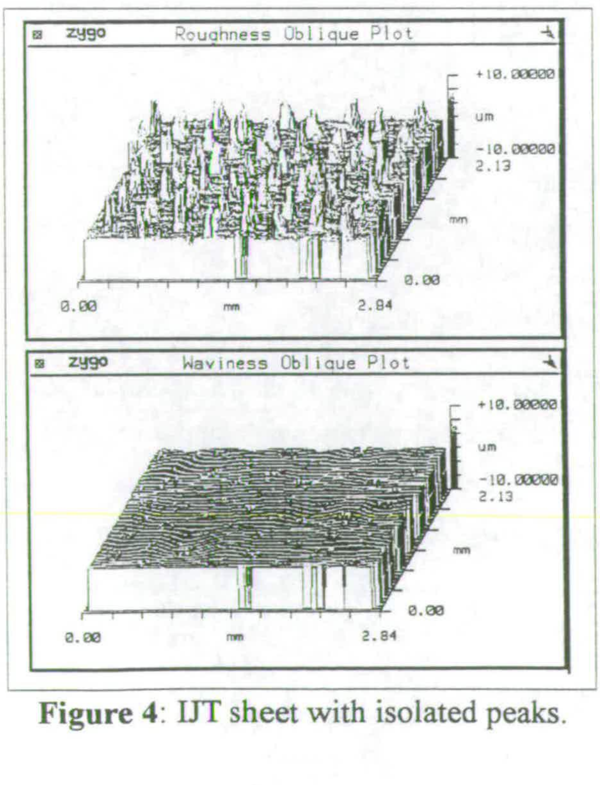

Figure 4: IJT sheet with isolated peaks.

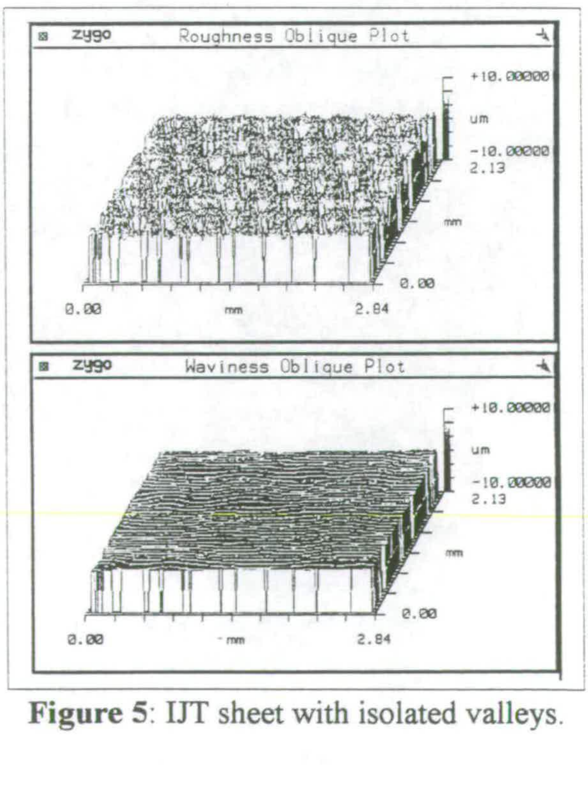

Figure 5: IJT sheet with isolated valleys.

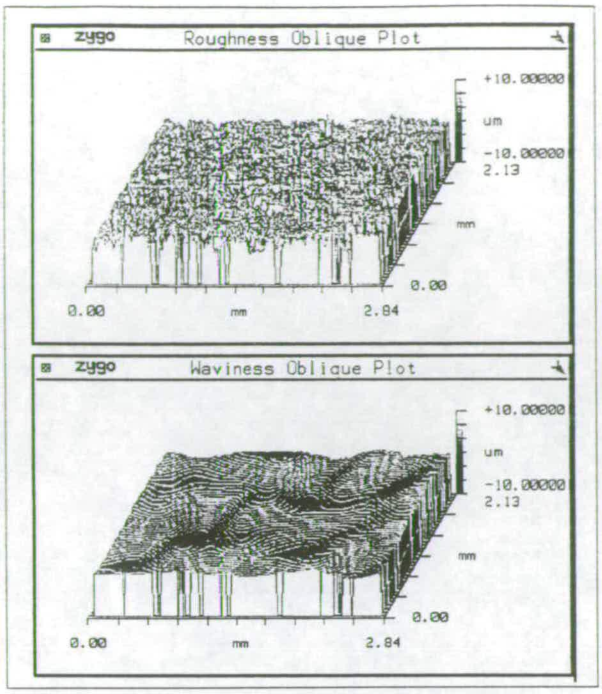

Figure 6: Annealed last before IJT.

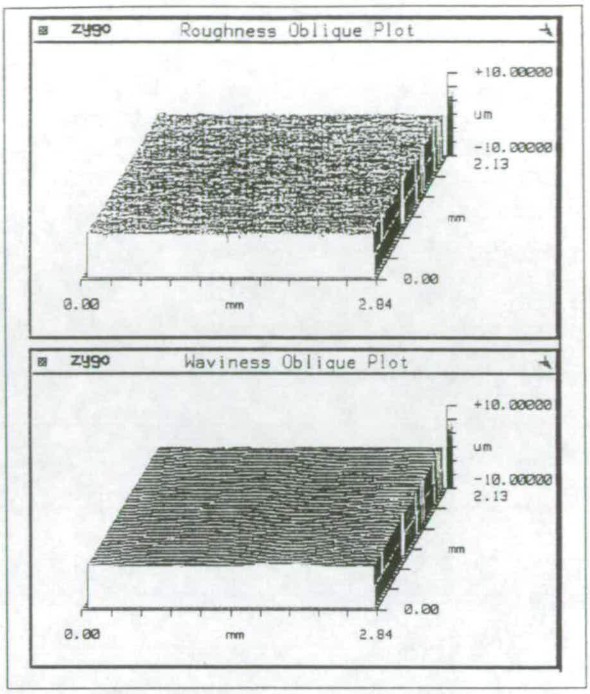

Figure 7: Sheet produced by ground roll.

sometimes produce large spikes with optical measurement systems.

Here we will consider two IJT created surfaces. The first is a series of isolated peaks (Figure 4) formed by a roller with etched isolated valleys. This gives a very good bearing surface on the surface of the roller while the uniform isolated peaks of the rolled sheet could be useful in preventing adhesion during annealing. The second is a series of isolated valleys (Figure 5)

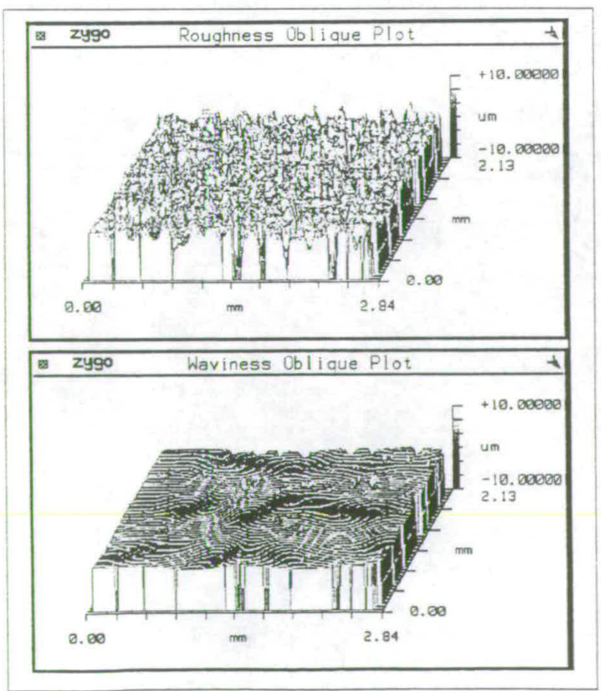

Figure 8: Laser textured sheet.

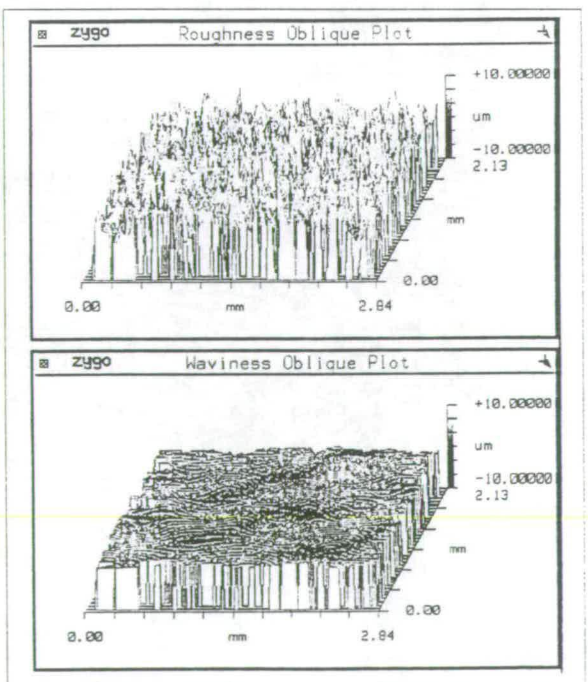

Figure 9: Electron beam textured sheet.

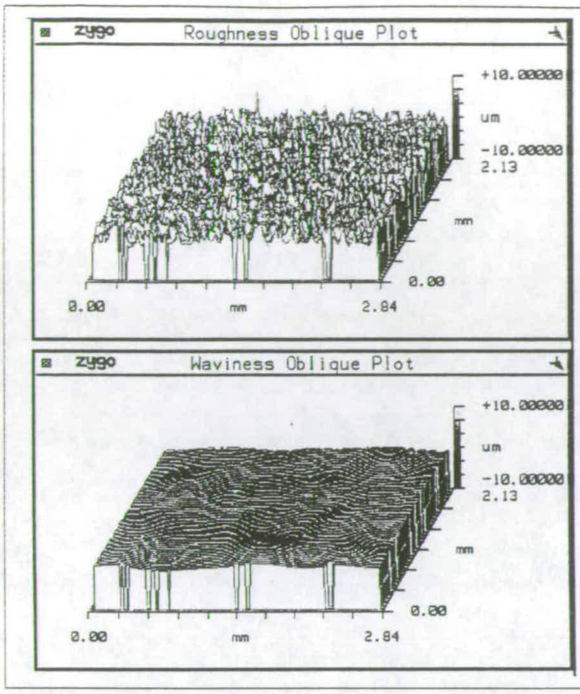

Figure 10: Shot blast textured sheet.

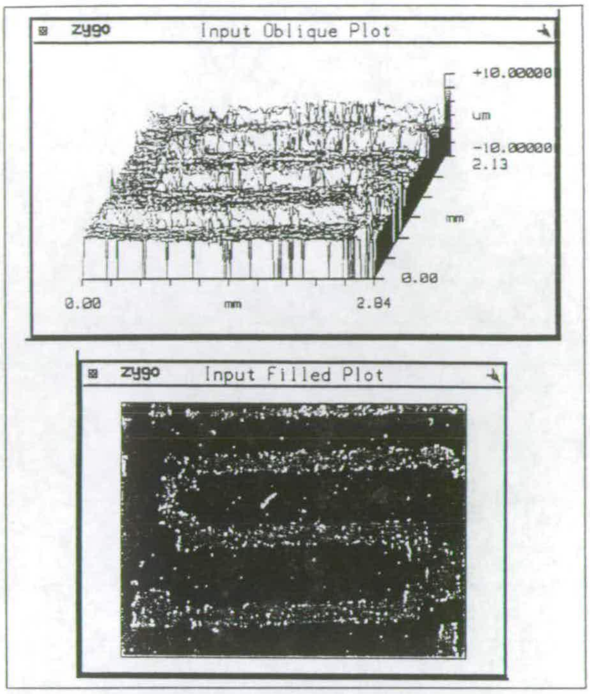

Figure 11: British Steel logo.

formed by a roller with etched isolated peaks. This may be of use for deep drawing applications where the isolated valley topography has been linked to improved performance due to high pressure oil pockets [12]. Figure 6 shows the EDT annealed last prior to IJT rolling, while Figure 7 shows the sheet after passing through a plain ground roller.

Plots of sheet steel produced by other processes are also included for comparison. These are LT (Figure 8), SBT (Figure 9) and EBT (Figure 10). A summary of roughness and waviness parameters for figures 4 - 10 is shown in Table No. 1.

Although two 'functional' IJT created textures have been presented the technique can generate surfaces with almost any bitmap type pattern within the resolution and matrix size of the machine. This means that text and even corporate logos can be textured onto sheet material, such as the British Steel logo in Figure 11 and the Ford motor company logo in Figure 12.

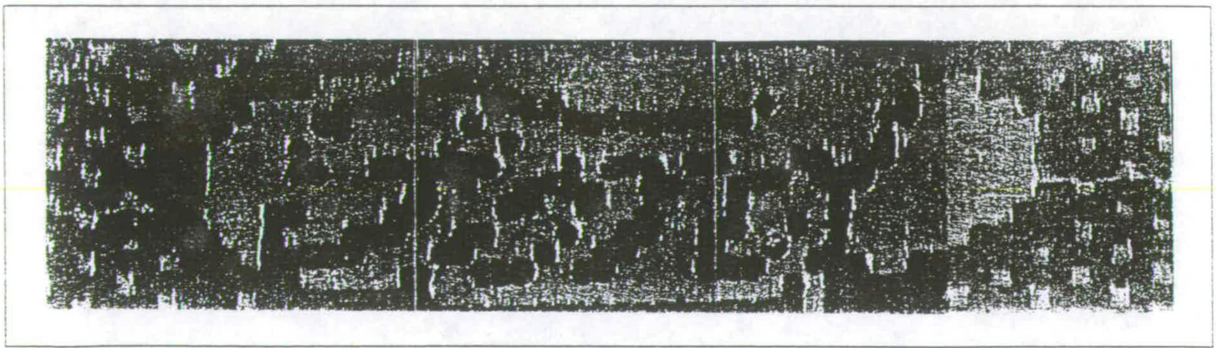

Figure 12: Ford logo.

	Roughness (µm)					Waviness (µm)		
	Ra	Rq	H	Rsk	Rku	Wa	Wq	Wmax
Isolated peak IJT	0.91	1.49	4.72	2.57	10.1	0.15	0.19	1.33
Isolated valley IJT	1.52	1.78	4.88	-0.90	2.35	0.16	0.19	1.13
Annealed Last	1.01	1.25	3.42	-0.79	3.42	0.59	0.73	4.07
Ground rolled	0.21	0.32	0.75	-1.62	11.7	0.16	0.19	0.91
Laser textured	1.29	1.74	4.35	-1.18	5.32	0.39	0.48	2.63
Electron beam	3.41	4.74	12.6	-1.41	4.78	0.40	0.48	2.73
Shot blast textured	0.78	1.15	2.72	-1.76	8.24	0.34	0.41	2.15

Table No. 1

4 DISCUSSION

The results presented here show that IJT is capable of producing rolled sheet metal with highly controlled surface properties. Both isolated peaks (Figure 4) and isolated valleys (Figure 5) have very consistent peak/valley heights and regular spacing. They also have very low waviness: comparable to sheet rolled with a ground roller on the same system (Figure 7). This suggests that the waviness present is generated by the grinding of the roll and not the texturing process. It also appears to be independent of the tandem mill texture which had higher waviness.

For deep drawing applications Figure 5 shows well defined isolated lubricant pockets and a uniformity of the plateau height better than even the deterministic textures of Lasertex and electron beam. The low waviness may also be useful in improving the image quality of the painted sheet. The isolate peak texture may be suitable for tandem mill applications where the uniformly distributed summits could act as standoffs to reduce adhesion during annealing.

The ability to print text and graphics may not be as superficial as it first appears. Advances in press technology have reduced the dependence on surface texture for non-deep drawing applications such as most vehicle body panels. Steel for these applications could be logo textured to enable easy identification of genuine manufacturers spare parts, thus helping to reduce losses due to copying. There is also a growing interest in textural design systems [13] which enable designers to specify both aesthetic and engineering properties of surfaces. At present the final design is transferred to a roll engraver for production: IJT could help such design packages realise their true potential.

5 CONCLUSIONS

The IJT process has been demonstrated at a laboratory scale and samples of textured steel sheet have been successfully rolled. Present work compares favourably with existing processes with regard to uniformity of peak height and reduction of waviness although a full comparison would require the use of a pilot or production rolling mill.

The ability to create new textures in software gives rise to other applications previously only possible by roll engraving.

ACKNOWLEDGMENTS

The support of the Ford Foundation in funding the initial work is very gratefully acknowledged, as is British Steel Technical, Welsh Laboratories, for the provision of steel samples and annealed strip.

REFERENCES

1. Aspinwall, D. K.; Zhao, F. L.; El-Menshawy, M. F., "Electro-discharge texturing (EDT) of steel rolls.", Surface Topography Vol. 2, 1989, p123-141

2. Aspinwall, D. K.; Wise, M. L. H.; Stout, K. J.; Goh, T. H. A.; Zhao, F. L.; El-Menshawy, M. F; "Electrical Discharge Texturing", International Journal of Machine Tools Manufacture, Vol 32,No. 1/2, 1992, p 183-193

3. Ahmed, M. S.; Knight, J. A. G., "Roll texturing by EDT", Proc. Mechanical and Steel Processing, 1988, p 405-413

4. Bragard, A.; Crahay, J.; Smul, W. De, "Texturing the roughness of work rolls of rolling mills by means of laser pulses: the process of tomorrow?", Proc. Advances in cold rolling technology, Institute of Metals, London, 1985, p 94-101

5. Wang, K.; Yang Y., "Study on texturing the surface topography of rolls by means of laser pulses", Advanced Technology of Plasticity, 1990, Vol. 2, p 749-754

6. Bragard, A.; Crahay, J.; Smul, W. De, "Texturing the roughness of work rolls of rolling mills by means of laser pulses: the process of tomorrow?", Proc. Advances in cold rolling technology, Institute of Metals, London, 1985, p 94-101

7. Mueller, R., "Lasertex steel sheet for bodywork.", Stahl und Eisen n Spec, Is Sep 14 1990, p 140-141

8. M. Vermeulen, J. Scheers, C. De Mare, B. De Coomanl; 3D-Characterisation of EBT-Steel Sheet Surfaces; International Journal of Machine Tools and manufacturing, Vol. 35/2, 1995, pp 273 - 280

9. Yamada, Y.; Saisu, M.; Ujihara, S.; Nagaoka, M., "Development of high image clarity steel sheet laser mirror.", Mechanical Working and Steel Processing Conference Proceedings Vol. 28, Iron & Steel Soc of AIME, Warrendale, PA, USA, 1990, p 259-265

10. Allen, D. M., "The principles and practice of photochemical machining and photoetching", Adam Hilger, Bristol, England, 1986

11. Muhl, J; Alder, G.M.; "Direct printing of etch masks under computer control"; International Journal of Machine Tools and manufacturing, Vol. 35/2, 1995, pp 333 -337

12. Roizard, X.; Stebut, J.; "Surface asperity flattening in sheet metal forming - a 3-D relocation stylus profilometric study", International Journal of Machine Tools and manufacturing, Vol. 35/2, 1995, pp 169 -175

13. Rosen, B.G.; Ohlsson, R., Westberg, J.; "interactive surface modelling, an implementation of an expert system for specification of surface roughness and topography", International Journal of Machine Tools and manufacturing, Vol. 35/2, 1995, pp 317 - 324

Appendix C: Paper 3

J Muhl "Application of electrochemical machining to ink jet texturing"
Proceedings of the 4^{th} International Conference on Sheet Metal SHEMET'96, Twente Nl, 1996

Application of Electrochemical Machining to Ink-Jet Texturing

Jonathan Muhl
Department of Mechanical Engineering
The University of Edinburgh

Abstract:

Ink-jet texturing (IJT) is a new technique for the controlled etching of metallic substrates, currently being developed to texture the finishing rolls in temper mills used for the production of cold rolled sheet steel. Existing work has used a chemical etchant to remove the exposed areas of the surface.

This paper reports the current research using an electro-chemical process to replace the chemical etchant (ferric chloride) previously used. A study of the parameters relevant to the process is given, combined with experimental data from directly textured sheet. The relative merits of electro-chemical versus chemical machining is discussed in the light of the above results.

Introduction

Developments in the metallurgy and processing of sheet steel are putting increasing demands on its quality and functional performance. This is particularly true of surface texture, the interface between the sheet and its environment. It is here that the products suitability for painting, forming and coating can be influenced.

The effect of surface texture on functional performance is the subject of many, sometimes conflicting, publications. The random processes, shot blast texturing (SBT) and electrodischarge texturing (EDT), can have a large waviness (wavelength, $\lambda > 0.8$mm) component in their texture (particularly SBT) which has been linked to a reduction in image clarity of the painted sheet [1] while laser texturing (LT), a semi-deterministic process, was reported to give a highly reflective painted finish. Conversely other studies have suggested that the deterministic nature of LT shows through the paint and that the random processes give the better finish [2]. As these studies have all used different steels and different paint processes it is difficult to draw a true comparison without a large test involving different paint processes, manufacturers and texture types. The number of combinations involved in this would make it a very expensive proposal. For deep drawing applications a system of interconnecting valleys, capable of trapping lubricants and debris, has been found less prone to galling and waviness is also considered to be an important factor.

In addition to the three established processes three other deterministic texturing processes are known to be in existance. Electron beam texturing (EBT) has recently been introduced by a Belgian company [3]. This appears to have good performance and is very controllable but the nature of the machining process used leads to high capital (and presumably production) costs. Photo-chemical machining has been the subject of a number of patent applications by Japanese companies [4] [5] but appears not to have been implemented

commercially.
Ink Jet Texturing has recently been developed at The University of Edinburgh as an alternative to the existing deterministic processes. The principles have been presented in previous publications [6] [7] and so will be described only briefly below.

Ink Jet Texturing

IJT uses a chemically resistant mask printed directly onto the roller surface by a high precision Ink Jet Printer. The regions of metal not protected by the ink are then etched to give the required depth of texture. It is similar to photochemical machining but replaces the stages of resist coating, mask generation and exposure, giving significant reductions in processing time and cost. A comparison of the processing steps is given in **Table 1**.

By replacing stage 5, light exposure, by a low power laser, it is possible to selectively expose the photoresist without using a photoplot mask. This would remove stages four and six, reducing the number of processing stages to nine. This is still five stages more than the IJT process and it is of little surprise that it is not in practical usage due to high cost and low processing efficiency[5].

	Photochemical Texturing	**Ink Jet Texturing**
1	Surface activation	Surface cleaning
2	Photoresist application	Ink jet mask printing
3	Drying	Etching
4	Photoplot application	Surface neutralisation
5	Light exposure	
6	Photoplot removal	
7	Photoresist development	
8	Drying	
9	Etching	
10	Photoresist stripping	
11	Surface neutralisation	

Table 1: Photochemical and ink jet processing stages

Both of these chemical removal processes have, to date, used a chemical etching solution (typically ferric chloride) for material removal. This imposes certain handling restrictions as the fluid is by necessity very corrosive with even the evaporated vapour causing surface oxidisation on exposed parts. The chemicals are relatively expensive and machining rates are rather slow.

This paper investigates the feasibility of using electro-chemical machining as the material removal process to try and bypass some of these limitations.

Electro-chemical Machining

The parameters and mechanisms involved in the electro-chemical machining process are quite complex and as its application to surface texturing is new an introduction may be beneficial.

Material removal rate

As an electrolytic process, the theoretical machining rates can be predicted from Faradays laws which state:

1. The amount of chemical change produced by a current is proportional to the quantity of electricity passed.
2. The amount of substance dissolved by a given quantity of electricity is proportional to its weight.

These can be combined to give the amount of material electrolytically removed from the anode (workpiece) as:

$$m = \frac{A}{z}\frac{It}{F} \qquad (1)$$

where m = mass of metal removed (kg)
A = atomic weight of metal
z = valency of dissolving ions
I = machining current (A)
t = duration of current (s)
F = Faradays constant (= 96500 C)

This shows that the theoretical mass of material removed is directly proportional to both current and time, the other factors being constant for a given material. In practice the machining rate is influenced by many other parameters and these are often interdependent. Probably the most significant of these are related to the flow rate as Faraday assumes that the electrolyte is pure and of uniform properties.

In practice the electrolyte in the gap will be affected by hydrogen bubbles, contaminants, localised heating and ion build up on the surface of the anode, all caused by the electrochemical reaction. The machining will therefore be affected by the rate at which the electrolyte is refreshed, ie the *flow rate*. The nature of the flow, and the flow velocity, will also be affected by the separation of the electrodes, ie the *gap height*. This in turn will change the machining voltage for a given *current.*

The *current density* is related to the *machining current*, *electrode area*, and *mask coverage ratio* (the ratio of unmasked surface to total surface area). Machining current is also related to the *machining voltage*, *electrolyte* conductivity, and *gap height*. Electrolyte conductivity is related to its concentration, temperature and type.

Machining time is the product of the time it takes for the electrode to pass over one point and the number of times it passes. This makes it dependent on the *electrode length, surface speed, electrode width,* and *print height.*

The machining rates and surface finishes will also be affected by the *electrolyte type.*

The interdependence of parameters is shown, at least in part, in **Figure 1**. From this it is necessary to select what will be the most dominant parameters and combinations.

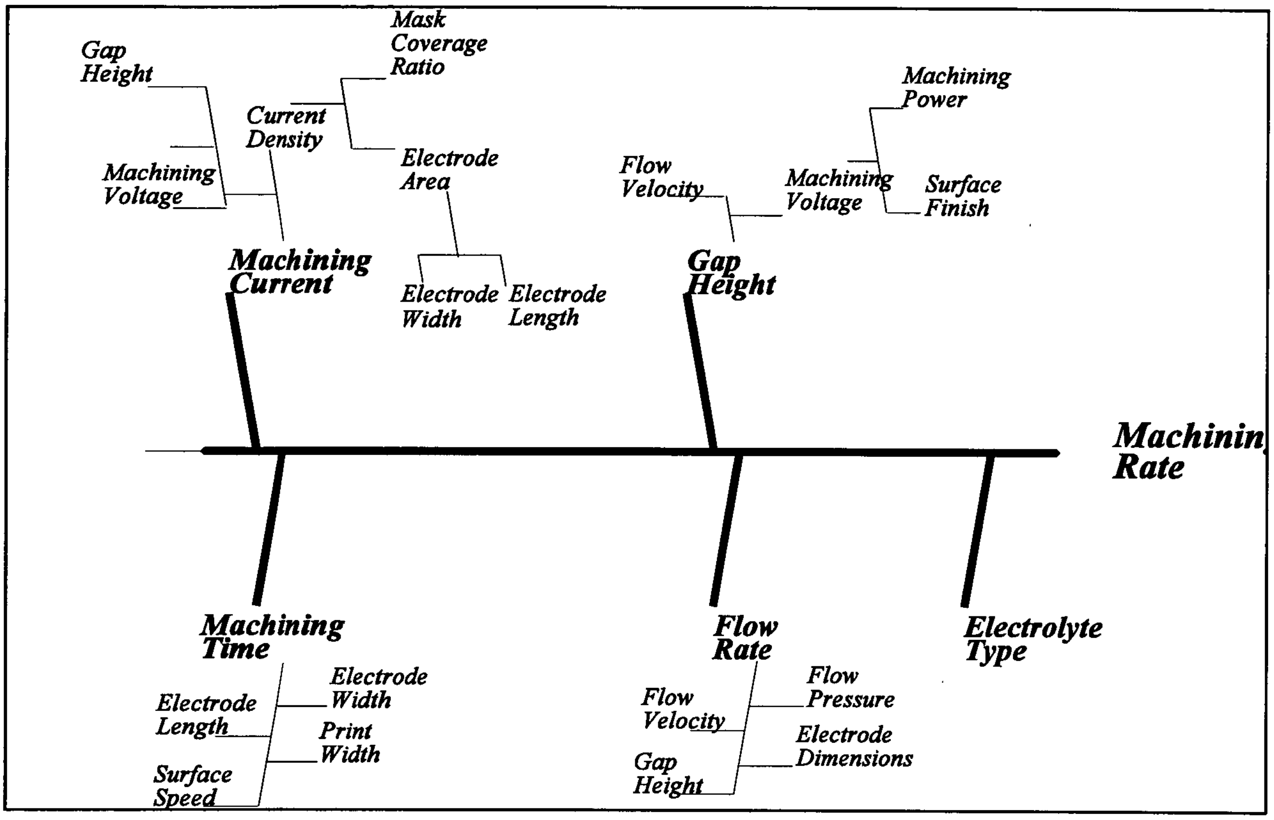

Figure 1 Electro-chemical etching parameters

Mask Integrity
As well as machining rate the integrity of the ink mask is of great importance. If this breaks down the newly exposed areas will be preferentially machined (being closest to the tool) until eventually the surface of the roller is flat. Preliminary studies suggest that this is quite dependent on flow rate, with the mask being eroded at high rates. It is also likely that current density may be a factor in this as it will affect the temperature of the surface and the volume of potentially abrasive contaminants in the flow.

Electrolytes

The electrolytes used in ECM can be classified as two distinct types, corrosive and passivating. With the rollers being a ferrous based alloy a pure salt solution should be adequate without any additives. Of the two most commonly used solutions one is corrosive and the other is passivating as outlined below.

1. Sodium Chloride ($NaCl$) (Corrosive)
   Safe, non-toxic and cheap, it has a good current efficiency over a wide range of current densities. It is also quite corrosive, conductivity is temperature sensitive and tends to leave a loose smutty deposit on the machined surface.

2. Sodium Nitrate ($NaNO_3$) (Passivating)
   More expensive than sodium chloride, combustible and temperature sensitive but is non-corrosive and gives a better surface finish.

The sodium chloride will machine even at very low current densities and large gap separations but leaves a corrosive deposit on the surface requiring prompt removal. The sodium nitrate needs high current densities (>30A/cm^2) and small electrode gaps but leaves a passive surface layer after machining has ceased.

The ideal electrolyte for texturing would probably have the machining properties of chloride and the passivation of nitrate. It is obvious that the chosen solution will be compromised.

Experiments

Machining Equipment

The machining equipment consists of power supply, electrolyte supply and control circuits housed in a standard 19" rack cabinet. The electrolyte is contained in a 25 litre canister in the base of the cabinet, allowing for fast and economical changes of solution. This is fed, via a self-priming stainless steel centrifugal pump through an in line filter to remove contaminants then through a fine metering valve, a flow transducer, pressure transducer and solenoid valve before leaving the cabinet to go to the machining head. The used fluid is returned to the canister assisted by a small centrifugal pump in the return line. Flow is switched on and of by a button on the front panel which activates the solenoid valve. The power supply is a Farnell H30/100. This can operate as constant current or constant voltage, is short circuit protected and can output up to 100A at 30V. For ease of switching the output is wired through a power MOSFET module which is controlled by a switch on the front panel. The electrode gap is monitored by a LVDT connected to a conditioning unit and panel meter in the control rack. The electronics rack contains conditioning for the various transducers and current, voltage, flow rate, pressure and gap height are displayed on the instrument panel.

Masking Equipment

The mask is deposited by a Domino Pinpoint high resolution industrial ink jet printer. This has 40µm diameter nozzle and is capable of creating textures with peak counts up to approximately 3.5 peaks/mm. Texture patterns are generated on a personal computer then stored on EPROM for loading into the printer.

Machine Setup

Although the equipment is designed for mounting on a lathe or similar machine for the texturing of rollers this has some disadvantages from an experimental viewpoint.

1. The rollers are made from EN31 bearing steel, hardened and ground. They are time consuming to prepare and expense prohibits the production of large numbers of them. This means time is lost while rollers are being reground.
2. The sealing required round the roller to protect the lathe from electrolyte increases the time required to change specimens.
3. The range of low speeds on the lathe is limited to 45 or 60 rpm.

Because of this it was decided to perform the initial experiments on a CNC milling machine using flat steel sheet instead of rollers.

A rigid plastic tank was mounte d on the bed of the mill. Within this the sheet was clumpe d to a fly cut alumini um false floor. Fixed length PVC spacers between the floor and the bed ensured that the sheet was parallel to the mill. This is shown in **Figure 2**.

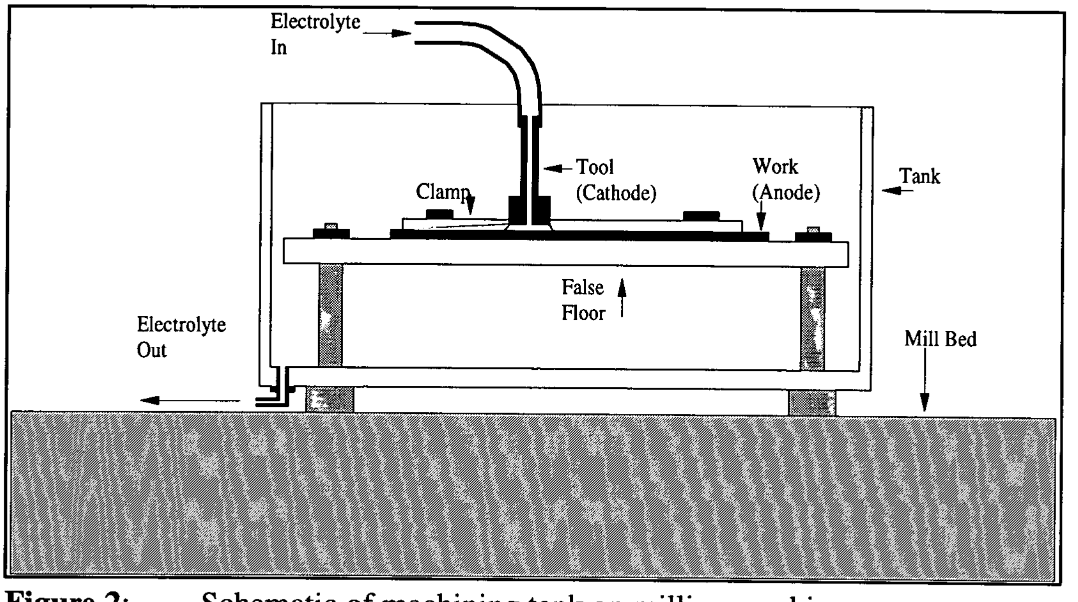

Figure 2: Schematic of machining tank on milling machine

The machine was programmed to traverse a fixed distance in X at a fixed speed. It then returned at rapid speed, incremented in Y and repeated for a predetermined number of cycles. The power supply was switched on during the forward motion and off during the return. In this way it was possible to simulate the machining path of the electrode over the surface of a roller.

The same program was used to print the masks on the sheet. It was not possible to attempt simultaneous printing and etching due to space constraints within the tank.

Tool Design

A very simple cathode design was used consisting of a brass tube soldered into a copper chrome head. Electrolyte passes through a 3mm diameter hole in the head and escapes between anode and cathode.

Metrology

The machined samples were measured on a Zygo Newview 100 scanning white light interferometer. It has a vertical range of 100µm and a quoted vertical resolution of 0.1nm.

The horizontal range and resolution is dependent on the power of the objective used. These are shown in **Table 2** for the objectives available in Edinburgh.

Objective Power	Working Distance	Horizontal Sampling(μm)	Field of View H x V (mm)	Slope Angle (deg)
2.5X	11.1 mm	8.80	2.82 x 2.11	1.0
40X	4.5 mm	0.55	0.18 x 0.13	15.9

Table 2

The measured data was analysed using Metropro, a package supplied with the machine.

Results and Discussion

Experiments were conducted using 12% sodium chloride solution over a range of flow rates and current densities. The main problem was found to be the adhesion of the ink layer, especially at high flow rates and at high current densities. A standard, general purpose ink was used and it may be that other, more suitable inks may be available. It was also noted that the ink layer was thick on the perimeter of the drop but thinned towards the centre. This is caused by the droplet not evaporating on impact but drying from the outside in. On some experiments breakdown was observed to initiate in the centre of the peak where the mask was thinnest. Mounting some form of heater or hot air blower adjacent to the print head may enable the formation of a uniform and more durable layer.

The surface shown in **Figure 3** was machined at approximately 4.5 A/cm^2 with a flow rate of 0.5 L/min. A 25 x 25mm electrode made eight passes at 20 mm/sec giving a total machining time of 10 seconds. The filled plot and bearing ratio plot clearly show a uniform surface on the tops of the peaks, indicating a lack of breakdown in the mask. The same conditions were repeated for a current density of 9 A/cm^2 but with the number of passes reduced to two, giving a machining time of 2.5 seconds. This is shown in **Figure 4.** A recess is appearing in the tops of some of the plateaus indicative of an early stage of mask breakdown. Increasing the machining time at 9 A/cm^2 to ten seconds caused a significant mask breakdown as seen in **Figure 5**. The bearing area plot is now composed of three distinct sections: an initial spike representing the areas where the mask remains intact, a gently angled plateau for the more rounded eroded peaks and an almost level base for the valleys between the peaks. The machining current was increased to 13.5 A/cm^2 at ten seconds and the result is shown in **Figure 6**. By now the mask has been almost completely obliterated with most peaks reduced to gently rounded bumps. The initial spike on the bearing ratio plot has been further reduced and the middle section is barely distinguishable. It can be seen that the exposed peaks are being preferentially machined towards the level of the valleys. An interesting possibility here would be to take a successfully machined surface like **Figure 3** and post process it by removing the mask and re-machining to provide controlled rounding of the peaks.

	Parameters (all μm)						
Surface	Ra	rms	PV	R3z	Rz	Rtm	H
Figure 3	9.1	10	34	25	27	30	24
Figure 4	4.8	5.4	21	16	16	19	14
Figure 5	5.2	6.9	44	32	34	40	19
Figure 6	5.9	7.7	62	54	55	52	20

Notes:

Ra: The arithmetic average deviation from the centre line
rms: The root mean square average deviation from the centre line
PV: The distance between the highest peak and the lowest valley
R3z: The distance between the third highest peak and the third lowest valley
Rz: The average distance between the five highest peaks and five lowest valleys, also known as the ten point height parameter
Rtm: The average of highest peak to lowest valley in nine sampling areas
H: The distance between the top five percent of the data and the bottom ten, also known as the Swedish height parameter

Table 3

It is interesting to look at the values of some numerical parameters for the surfaces and these are given in **Table 3**. Probably the parameter most commonly used to specify surface finish is Ra yet **Figure 3** with the highest Ra has the second lowest peak height, with a PV of almost half that of **Figure 6**. Observation of the bearing plots shows the surfaces will have quite different functional properties with **Figure 6** as the "rougher" of the two. Although Ra may give an adequate description of a stochastic surface, such as shot blasted, this demonstrates the danger of using it in isolation for a deterministic texture.

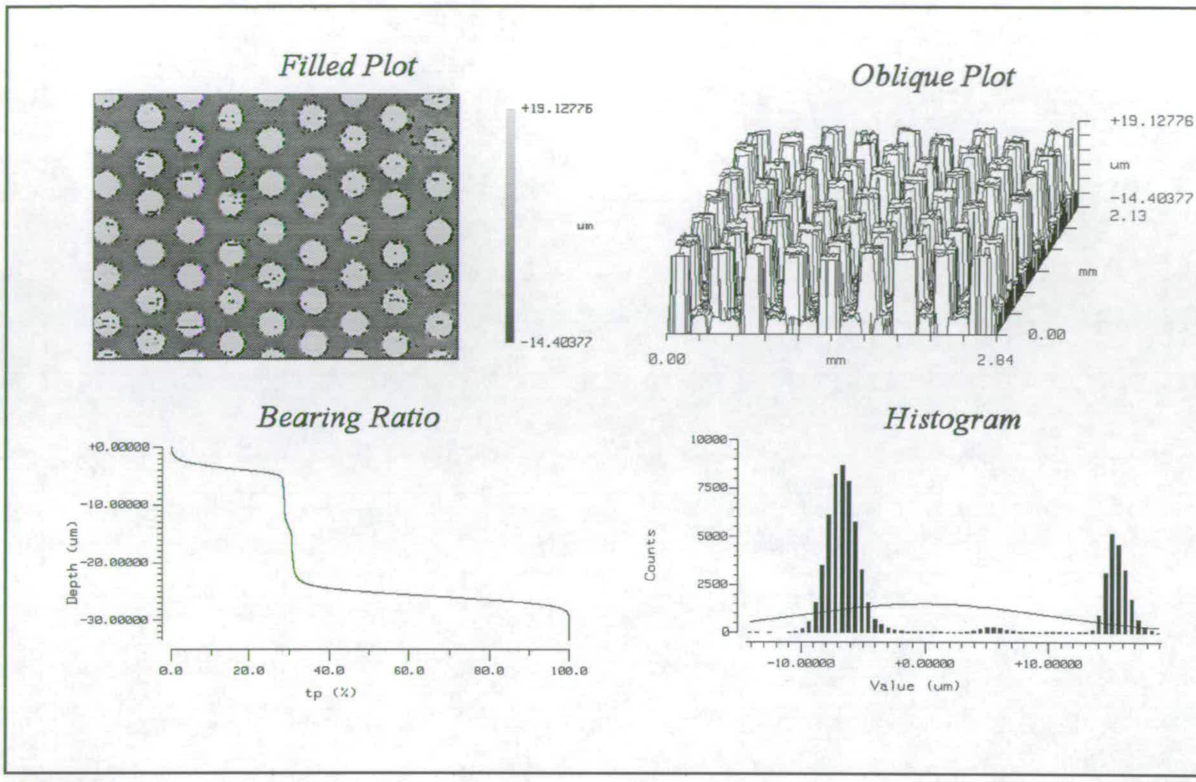

Figure 3

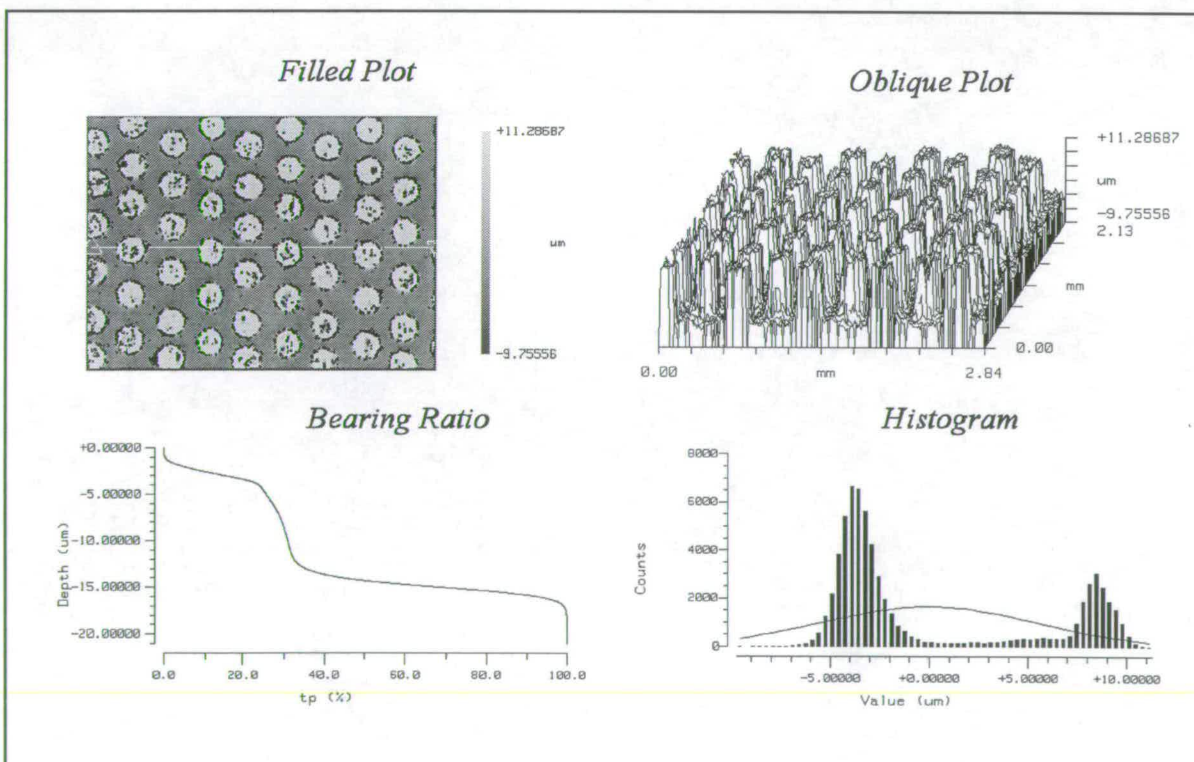

Figure 4

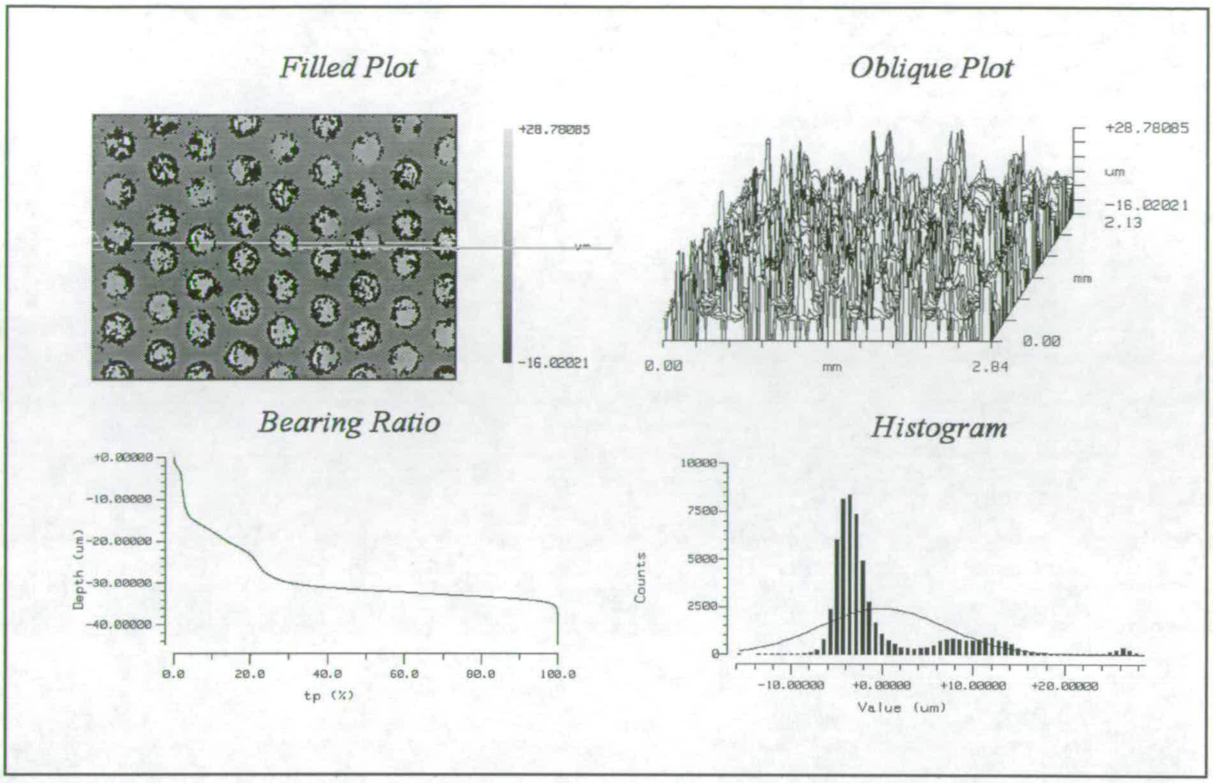

Figure 5

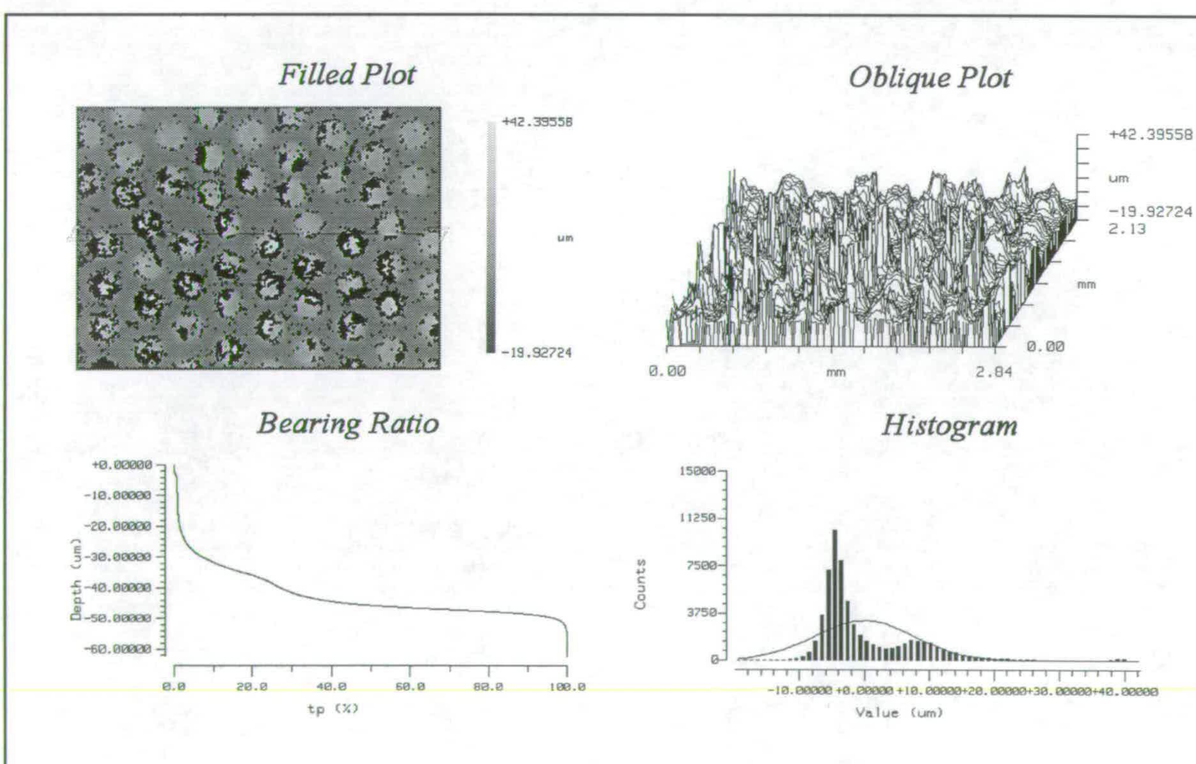

Figure 6

Conclusions

Electrochemical machining has been used successfully in combination with ink jet texturing. Surfaces have been machined successfully to depths in excess of 25 μm using a sodium chloride electrolyte. Beyond this degradation of the ink mask occurred leading to uneven machining of the surface. Mask break down occurs soonest at high flow rates and high current densities. Machining rates are higher than those previously obtained using ferric chloride while the electrolyte is cheaper and less corrosive.

It may be possible to improve ink resistance by heating of the surface immediately prior to printing, by use of different ink types or by the pulsing of power. The latter would allow high current densities to be used at low flow rates while avoiding excess heating in the gap.

Future work will investigate the use of pulsed current and passivating electrolytes.

Acknowledgements

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References

1. Yamada, Y.; Saisu, M.; Ujihara, S.; Nagaoka, M., "Development of high image clarity steel sheet laser mirror.", Mechanical Working and Steel Processing Conference Proceedings Vol. 28, Iron & Steel Soc of AIME, Warrendale, PA, USA, 1990, p 259-265

2.Bastawros, A. F.; Speer, J. G.; Zerafa, G.; Krupitzer, R. P., "Effects of Steel Surface Texture on Appearance After Painting", SAE technical paper series No 930032,Society of Automotive Engineers, Inc., Warrendale, Pa, 1993, p 1-14

3. M. Vermeulen, J. Scheers, C. De Mare, B. De Coomanl; 3D-Characterisation of EBT-Steel Sheet Surfaces; International Journal of Machine Tools and manufacturing, Vol. 35/2, 1995, pp 273 - 280

4.Nishiura, T et al; Nippon Steel Corporation; "Method of surface treatment of a roll", European Patent application no. 92916142.0, Filed 30.07.92

5.Iguchi, T; Kawasaki Steel Corporation; "Process and equipment for micropattern forming on roll surface, metal sheets for pressworking prepared by the roll and methods of preparing same"; European Patent application no. 89303908.1, Filed 20.04.89

6.Muhl, J; Alder, G.M.;"Direct printing of etch masks under computer control"; International Journal of Machine Tools and Manufacturing, Vol. 35/2, 1995, pp 333-337

7.Muhl, J; "Generation of controlled textures and corporate logo's on rolled steel sheet by Ink Jet Texturing", Proc. Shemet95, pp **???** - **???**

Appendix D: PIC Printer Control Program

```
;TITLE    "Basic Pinpoint Printer Controller"
;
;A repetative stroke pattern is assumed, with a repeat of two in the first instance
;Future versions may include front panel setting
;
;The output will drive the Polygon electronics piggyback parallel card.
;
;   Revision 1
;   25-08-98
;   Written by Jonathan Muhl
;
;
        LIST p=16c84, F=INHX8M
;
   include 16cxx.h
;
strk1a equ    0aah          ;stores bit patterns for stroke data
strk1b equ    0aah
strk2a equ    55h
strk2b equ    55h
;
pgstat  equ    0eh    ;status register for printgo


;
        org    00h
        goto   start
;
```

```
;
        org     04h
        goto    start
;
start
        call    initialise    ;sets up the ports as inputs/outputs
standby
        btfss   _porta,3      ; print go high?
        goto    standby       ; No, so wait until it goes high!
        btfss   _porta,3      ; Check again for noise
        goto    standby       ;
go
        btfsc   _porta,3      ; print go high?
        goto    go            ; Yes, so wait until it goes low!
        btfsc   _porta,3      ; print go still low?
        goto    go            ; No, so wait until it goes low!
        bcf     _porta,0      ; Set Phase Request low
        bsf     pgstat,0      ; set print on bit highstrokego
        call    strokeout     ; Check for next complete stroke pulse
        movlw   strk1a        ; Load first byte of stroke 1
        call    strobe        ; and output it
        movlw   strk1b        ; Load second byte of stroke 1
        call    strobe        ; and output it
        call    print         ; Print stroke
        call    strokeout     ; Check for next complete stroke pulse
        movlw   strk2a        ; Load first byte of stroke 2
        call    strobe        ; and output it
        movlw   strk2b        ; Load second byte of stroke 2
        call    strobe        ; and output it
        call    print
```

```
pghigh
        btfss   _porta,3        ; print go high?
        goto    pglow           ; No, so check for new print go pulse
        btfss   _porta,3        ; Yes, so check again for noise
        goto    pghigh          ; No, so back to pghigh
        bcf     pgstat,0        ; Clear status bit
        goto    strokego        ; No new print go so keep printing
pglow
        btfsc   _porta,3        ; Still low?
        goto    pghigh          ; No, so start check again
print_test
        btfsc   pgstat,0        ; Check print status bit
        goto    strokego        ; If set then still original print go high
        bsf     _porta,0        ; Yes, so set phase request high again
        goto    standby         ; and wait for next print go
;
;

initialise
;
;   first set up the I/O ports
;
        bsf     _status,5       ;select page 1
        movlw   18h             ;set portA as
        movwf   _trisa          ;all outputs
        movlw   00h             ;set portB as
        movwf   _trisb          ;all inputs
        bcf     _option,5       ; set rtcc to internal
        bcf     _status,5       ;return to page 0
        movlw   01h
        movwf   _porta          ;set phase request high         return
```

```
;
strokeout
        btfsc   _porta,4        ; stroke go high?
        goto    strokeout       ; Wait for it to go low
        btfsc   _porta,4        ; Still low?
        goto    strokeout       ; No, so back to wait
strokehi
        btfss   _porta,4        ; stroke go high?
        goto    strokehi        ; Not yet so wait
        btfss   _porta,4        ; stroke still high?
        goto    strokeout       ; No, so back to wait
        return                  ; Yes, so return to main program
;
strobe
        movwf           _portb          ; Send bit pattern to output port
        nop                     ; Give time to settle
        bsf     _porta,1        ; Set strobe bit
        call    delay           ; Wait for printer to be updated
        bcf     _porta,1        ; reset strobe bit
        return
;
print
        bsf     _porta,2        ; Send print stroke instruction
        call    delay           ; Wait for it to be recieved
        bcf     _porta,2        ; then clear it
        return
;
delay
        clrf    _rtcc
wait
        btfss   _rtcc,6                 ; wait for 64 us
```

```
goto    wait
return                  ; then return


end ;
```

Appendix E: Texturing Time Predictions

Printing Times

This section represents a brief study of the time required to fully print a roller with the existing printer. The time to print will depend on the size of the roller, the desired peak density, the number of drops in the raster and whether printing is continuous or stepped. Printing times for a range of stroke sizes are given below. They are based on continuous printing of a 2 m roll with 600 mm barrel diameter and a peak count of 3.5 pp mm.

Stroke size	**7**	**16**	**21**
Print width (mm)	0.857	2.286	2.857
Printing time per m² (minutes)	08:42	0.3917	0.715
Printing time per roller (minutes)	32:48	64:37	35:26

These times are directly proportional to the roll dimensions and the peak count and do not include any preparation times. It also assumes printing in a continuous helix, increase these by a factor of two for step print mode.

The reason for disproportionately lower printing rates at larger stroke sizes is due to a need to include extra uncharged guard drops into the raster for the greater deflections involved. The 16 drop raster has 52 drops per stroke therefore the stroke rate is 128 KHz/52, ie 2.46 KHz or 406 μS.

This suggests that the printing time for a large work roll would be just over half an hour for a single print head printing continuously. This may be reduced by adding additional print heads or using different printing technology.

Machining Times

These can be estimated from Faradays Law or derived empirically from experimental data. It can be classified as machined depth, volume removed or surface Ra. Perhaps the later is best considered in the first instance as it is most transparent.

Laboratory experiments prior to texturing the second pair of Hoogovens pilot rolls were done with a 1 cm^2 electrode and a feed rate of 0.91 mm/revolution (28 tpi). Flow rate was maintained at 0.22 l/min and the 30 V supply was pulsed at 1 KHz with variable duty cycle. The roll diameter was approximately 50 mm and roll speed in most instances was 65 rpm. If the rotational velocity is adjusted to maintain the same surface speed then the same Ra's should be obtainable under the same conditions for different roll geometries.

From experimental data the time to texture 1 m^2 to an Ra of 2.5 μm will be one hour and 48 minutes. From this the machining times for roller of different dimensions can be estimated.

Roll length (m)	0.3	1	2
Roll diameter (m)	0.14	0.3	0.6

Texturing time (hh:mm:ss)	0.0099	0.07066	0.28266204

The machining time is dependent on the volume of material to be removed. This means that it will be dependent on parameters such as peak count, dot size and required roughness. Times will also decrease with increasing electrode area (and/or number of electrodes) and increasing current density.

Comparison of Non-Traditional Material Removal Rates

The following figures for machining rates of non-conventional machining processes were taken from a standard manufacturing textbook[1]. Although approximate they give an idea of the relative speeds of the processes.

Chemical machining	0.025 - 0.1 mm / min
Electro-chemical machining	2.5 - 12 mm / min
Electro-discharge machining	0.15 mm/ min [2]

The machining rate for EDM is directly proportional to the electrode area. This is because there can only be one spark (and therefore machining at only one point) at any given time, irrespective of the electrode area. Even assuming a small electrode of 1 cm^2 the feed rate is significantly lower than that achievable with ECM.

1 S Kalpakjian "Manufacturing Engineering and Technology", Addison-Wesley, 1992

2 The machining rate in EDM is inversely proportional to the area of the electrode. This figure assumes an electrode area of 1 cm^2.

Appendix F: System Cost Estimates

This appendix is intended to provide an estimate of the capital cost for a one off commercial texturing system of similar specification to the prototype unit.

Texturing Unit	
Equipment casing	£1,000
Industrial PC controller	£5,000
Pulsed power supply (100A)	£1,500
Electrolyte system	£1,500
Wiring etc	£500
Printing	
Domino Pinpoint high resolution printer	£10,000
High resolution encoder and gearing	£1,000
Cleaning Equipment	
Heaters, extractors etc	£1,500
Positioning	
800 mm linear actuator	£7,500
Controller	£3,250
Total	**£32,750**