VIBRATORY FINISHING OF STEREOLITHOGRAPHY PARTS

John D Spencer, Richard C Cobb and Philip M Dickens

Department of Manufacturing Engineering and Operations Management,
University of Nottingham, UK.

SUMMARY

Rapid Prototype polymer resin models produced by Stereolithography have, by the nature of the process, a relatively poor surface roughness, particularly on concave and convex surfaces. In many cases this is unacceptable, and slow and tedious manual finishing techniques are often used to improve the surface.

An investigation has been conducted into a range of automated finishing techniques with the aim of producing an acceptable surface roughness. This paper presents the results from two techniques, Vibratory Bowl Abrasion and Ultrasonic Abrasion using components made from Ciba-Geigy XB5081-1 and XB 5143 resins.

Initial results from Scanning Electron Microscopy and surface topography analyses suggest that both techniques are capable of improving the model surfaces.

INTRODUCTION

Since its introduction Stereolithography has become established as the leading commercial Rapid Prototyping (RP) system (Jacobs 1992). A 3D CAD model of the desired component is mathematically 'sliced' into layers which are typically 150μm thick. The slice data is then used to control a UV laser which is guided over a vat of liquid photopolymer and is selectively cured as the laser tracks over it. In this way the part is built up layer by layer with the laser curing the required regions of each subsequent photopolymer layer. A post curing operation is then used to fully solidify the part.

Prototype models produced from the process exhibit a relatively poor surface finish, particularly on concave and convex surfaces. For many applications the usual practice is to sandpaper and polish the models by hand which is a tedious and time consuming operation and also presents a potential health hazard from the resin dust. Although prototypes can be rapidly manufactured, parts can end up after finishing with poorly defined features, and the more complex the model the more difficult it becomes to finish.

Where parts are intended for testing, finishing becomes a critical factor. For example, parts tested in say, fluid or gas chambers may not be representative of the final component as the layer steps could disrupt gas flows. Furthermore, in the production of tooling a poor surface on the model will be reproduced on the tool and removal of the model may be difficult if the tool material keys into the surface roughness.

When manufacturing stereolithography parts layers are produced that can form a curved (or angled) surface and it may be either the internal or the external corners that define the required profile. If the external corners define the profile their removal will cause the profile to become undersize. However if the profile is defined by the internal corners then it will be oversize until the steps are removed, see Figure 1. Where material removal takes place, it is important that the internal corners of the layers are specified as defining the surface, (this is the default setting with 3D Systems machines).

Vertical faces also exhibit a step effect due to the manner in which the laser solidifies the resin. Although the power of the laser spot has a gaussian distribution the resin cures in a parabolic form, thus at the edge of a vertical face it is found that a stack of parabola curves occur, these cause steps on the surface, as seen in Figure 2, (Jacobs, 1992). Even if the model is supplied with a draft angle it is still likely to 'key' into a mating surface as a series of small undercuts will remain.

One of the problems with curved surfaces on SL models is that the size of the steps change as the angle of the curve changes, that is the closer the angle is to the vertical then the smaller the step in the horizontal ('X/Y') plane, as shown in Figure 3. Also, the closer the angle becomes to horizontal, the larger the step in the horizontal 'X/Y' plane. This effect causes problems when using material removal methods as the larger steps, because they require more work to remove them, will still be evident after the smaller ones have been removed, thus effecting the form of the curve.

An experimental programme was therefore constructed with the aim of investigating a range of automated finishing techniques and their potential for smoothing Stereolithography parts without causing any detrimental effect to the 'form' of the part. Although a wide range of options are available to treat the resin surfaces including chemical dissolution and the use of coatings it was decided to concentrate upon the mechanical removal processes and hence test samples were sent to specialist finishing companies.

The first stage of the work detailed three techniques, Abrasive blasting, Barrel tumbling and Centrifugal tumbling (Spencer et al 1993). It was found that abrasive blasting severely eroded models made from two different types of polymer resin, but that centrifugal tumbling was able to smooth the surfaces with improvements in Ra values of up to 81%. However, the process does generate significant damage and the time to process is excessive.

This paper presents the findings from a further two finishing techniques, Vibratory Bowl Abrasion and Ultrasonic Abrasion both of which were applied to the same type of models as in the previous study.

TRIAL COMPONENTS

A standard Stereolithography demonstration component, approximately 50mm diameter, was supplied by Texas Instruments, see Figure 4 and was provided in two different material types :-

Material type 1	Ciba Geigy XB5143	(durable resin)
Material type 2	Ciba Geigy XB5081-1	(general purpose resin)

As indicated below the component provided a range of different design features that any potential finishing technique may have to cope with.

Vertical and horizontal faces	
External corner	(area 1)
Internal corner	(area 2)
Restricted corners	(areas 3 & 4)
The steps on the peripheral radius	(radius)

To assess the ability and limitations of each of the finishing processes, specific areas of the component test piece were identified (areas 1 - 4). Following the surface treatment, each area could be compared with as-cured reference samples of each material.

EXPERIMENTAL PROCEDURE

Experimental Techniques

In order to investigate the effect of each finishing process upon the component, two experimental techniques were adopted. Specific features of the finished models and as-cured reference samples were examined and photographed on a JEOL JSM 6400 WINSEM Scanning Electron Microscope (SEM).

Measurements of the surface roughness (Ra) of all of the samples were made and recorded in the X, Y & Z axis using a Rank Taylor Hobson Taly Surf 4. In all cases the same region of the component photographed on the SEM was measured for surface roughness. The Ra value of the irregularities on a surface is defined as the average value of the departures, both above and below it's centre line, for a prescribed sampling length. In the case of both the X and Y plane measurements the section was accurately mounted on a micro X/Y adjustable table.

The surface topography was traced before indexing the sample across 0.07mm and another reading and trace of the surface taken; this was repeated for 5 passes on each section in the X,Y and Z planes. The average of the values measured in each axis was calculated and recorded as was the average of all the readings.

RESULTS

Reference Samples

As-cured reference samples of materials type 1 (XB5143) and 2 (XB5081-1) were mounted and examined on the SEM (see Figures 5-8). By viewing the component in this way the individual slices can be clearly seen, and the surface finish in the 'Z' (vertical height) plane consists of a series of small steps. The size of these steps will depend on the thickness of each layer which can vary between 64-760μm. This stepping effect is most noticeable on faces that make an angle to the normal (vertical/horizontal) plane (eg 45° slope).

On further examination it can be seen that in addition to the step formations, the component exhibits a texture on the horizontal surfaces. The surface consists of lines of solidified resin, each $\approx$ 200μm in width, running parallel to one another in the 'X' plane, 100μm apart with an identical layer, in the 'Y' plane beneath it. The micrograph indicates that approximately 50-75μm of the surface material would need to be removed for the horizontal surface to become smoother, Figures 5 & 6.

Comparison of the photographs for each of the materials, Figures 5 - 8, shows that, although the test piece is the same geometry and dimensions, and the layer thicknesses are the same, the two parts are quite different. In contrast to reference material 1 , material 2 has much 'smoother' vertical faces with steps of width 130μm for the former and 50μm for the latter.

Another feature of the component made from material type 1, again on the vertical face, is the two pitch cyclic pattern of 'bumps' which step across a one half pitch each layer, Figure 5. These two pitch cyclic bumps are thought to be a fault of the machine control in that it would seem that the laser beam used to cure the resin has scanned too far (Galvanometer overshoot).

Vibratory Bowl Abrasion

Finishing is achieved for this process by vibrating, at constant speed, a 'U' shaped bowl containing the abrasive media and the model. As the media recirculates around the bowl the surfaces become abraded. This is a less aggressive process than the tumbling processes which caused damage to the models in the earlier study, (Spencer et al 1993).

Samples of each material were sent to Invicta Super Finishers Ltd, Grantham, UK, who processed them using two different media types, 30mm diameter x 10mm angle cut cylinders and 13mm green plastic cones.

Material type 1 (XB5143) was processed for 1¼ hours using 30mm diameter x 10mm angle cut cylinders.

On the exposed vertical walls, 'steps' and 'bumps' have been partially removed, and localised abrasion is clearly evident, see Figure 9. At exposed external edges and corners abrasion is also apparent together with a loss of definition; an approximate radius of 0.5mm is seen. Toward confined regions such as the basal internal corners illustrated in Figure 10, wear is reduced probably as a result of the large size of media used.

With ϕ13mm Green plastic cones as the processing media and for an equivalent exposure time of 1¼ hours, results were not as favourable in smoothing the vertical walls and steps could still be identified. However, the horizontal surfaces did receive a smoothing effect but damage also took place on exposed corners, see Figure 11.

Material type 2 (XB5081 - 1) was processed under the same conditions as for XB5143 but, for both forms of media the process was too aggressive creating extensive damage to the corners of the model.

ULTRASONIC ABRASION

Experiments were conducted at Branson Ultrasonics, Hayes, Middlesex, UK to investigate the use of ultrasonic abrasion as a means of finishing. Carborundum abrasive grit, particle size 250μm was used to partially fill a small 100mm diameter containing vessel. The resin model was then laid upturned on the surface of the grit and the ultrasonic horn contacted to the model. A frequency of 20kHz was used at an amplitude of 80μm.
Material type 1 (XB5143) was processed under these conditions for 2 seconds.

The main beneficial effect of the process has been on the horizontal surfaces where some smoothing has occurred with localised abrasion evident. Some of the original roughness still remains, as indicated in Figures 12 and 13. There appears to be more erosion at the exposed vertical edge, and as with the models processed by the vibratory bowl method holes have been exposed as a result of the 'skin fill' top surface being removed.

Unfortunately, material type 2 was completely destroyed on the application of 7 seconds exposure with no apparent improvement to the areas under investigation.

Surface roughness results

Table 1 shows the mean Ra values of surface roughness measurement of components in the X, Y and Z directions. The mean of the three mean values has then been calculated to allow direct comparison between the processes. From the overall mean values the overall percentage improvement of each of the processes has been calculated, compared against the original value.

From the table the reference material XB5143 appears rougher than the general purpose resin XB5081 - 1. Furthermore, it can be seen that the Vibratory Bowl abrasion process has achieved a good surface finish in a reasonable amount of time with improvements of around 73% for the XB5143 material. However, there has been a degradation of the form as radiusing of corners and edges has taken place in addition to the exposing of underlying holes in the surface.

The application of Ultrasonics for finishing these models has resulted in a mixed improvement to the surface finish. In the best case an improvement of 66% has been achieved with little degradation to the component form, in a very short space of time (2 seconds).However, from the photographic evidence it can be seen that this has been at the expense of the external corners and edges which were destroyed by the process.

DISCUSSION

Examination of the components with the Scanning Electron Microscope has clearly illustrated the difference in resin types for similar designs of part and for similar build patterns. From the investigation it is evident that, of the materials initially employed, Ciba Geigy XB5143 was the most responsive to surface abrasion with Ciba Geigy XB5081-1 being more resistant and too brittle for both processes.

Both of the processes examined have demonstrated improvements to the surface finish for material XB5143 smoothing the surfaces by up to 73%. Vibratory Bowl Abrasion produced a good finish in a reasonable amount of time and even though the selection of media for this technique was not optimum it provides encouraging results for future work as different medias sizes and types will be examined. The short unmanned processing time is very attractive compared with traditional hand finishing.

Ultrasonic Abrasion removed material very quickly but as the abrasive media was unconstrained wear took place mainly on the horizontal surfaces although vertical edges were badly abraded. Further work will address a range of conditions so that all parts of the models can be accessed. The short processing times were fast and the high energy levels applied had a detrimental effect on the material causing local melting in the area of the component at the centre of the ultrasonic horn.

CONCLUSIONS

1) Components manufactured from XB5143 are more responsive to surface finishing techniques than XB5081-1 which appears to be unsuited to most of the abrasive processes due to its brittleness.

2) Both Vibratory Bowl Abrasion and Ultrasonic Abrasion have demonstrated that they are potential techniques for deburring polymer Stereolithography parts with encouraging results at short processing times.

3) Further investigations need to be undertaken into all of the finishing techniques with regard to the abrasive medias used.

ACKNOWLEDGMENTS

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REFERENCES

1. Jacobs, P.F., "Rapid Prototyping and Manufacture: Fundamentals of Stereolithography", Society of Manufacturing Engineers, 1992.

2. Spencer, J.D., Cobb, R.C., and Dickens, P.M, "Surface Finishing Techniques for Rapid Prototyping", Proceedings of the SME Rapid Prototyping and Manufacturing Conference, Dearborn, Michigan, 11-13 May 1993.

TABLE 1 SURFACE TEXTURE READINGS (Ra VALUES)

PROCESS	MEDIA	MATERIAL TYPE	Ra VALUE				% IMPROVEMENT
			AREA				
			X	Y	Z	MEAN	
REFERENCE SAMPLE		XB5143	5.35	7.34	7.0	6.56	_
		XB5081 - 1	6.46	7.68	3.0	5.71	_
VIBRATORY BOWL ABRASION	30mm x 10mm angle cut cylinders	XB5143	1.22	2.62	1.2	1.68	74
	13mm diameter plastic cones	XB5143	1.32	2.3	1.9	1.84	72
ULTRASONIC ABRASION	250μm Carborundum grit	XB5143	1.74	3.0	2.0	2.25	66
		XB5143	1.82	3.32	3.0	2.75	58

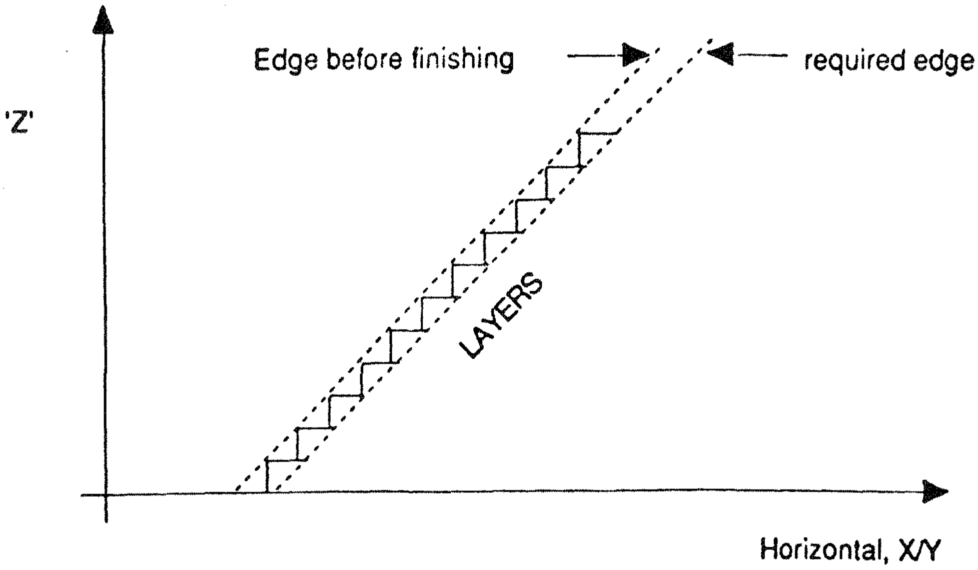

Figure 1 Showing how on removal of steps the component will be the required size when internal corners define the component profile.

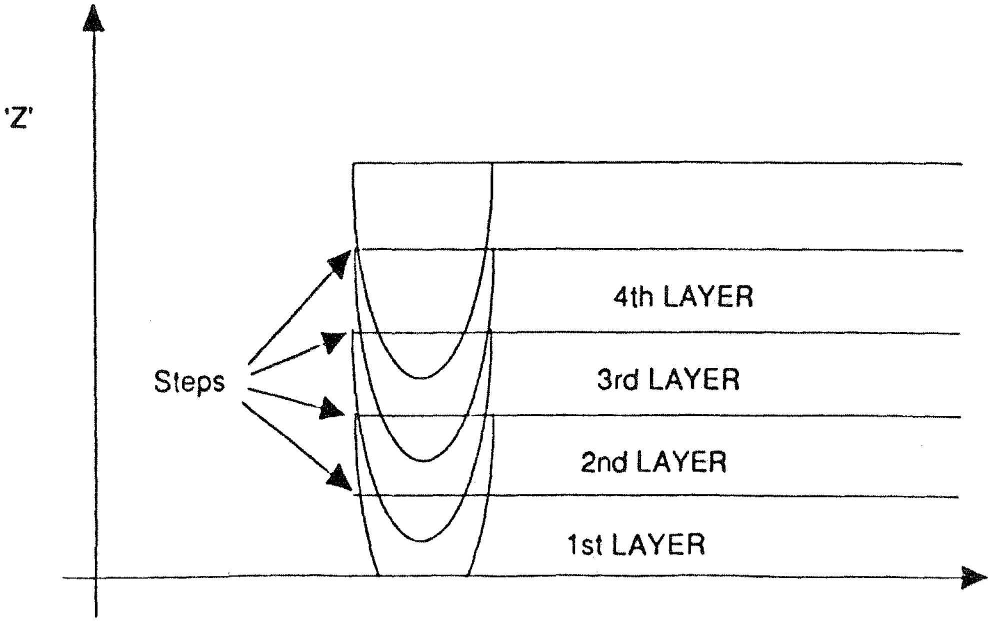

Figure 2 Showing how steps are caused on vertical faces due to the 'parabolic' nature of resin cure (Jacobs 1992)

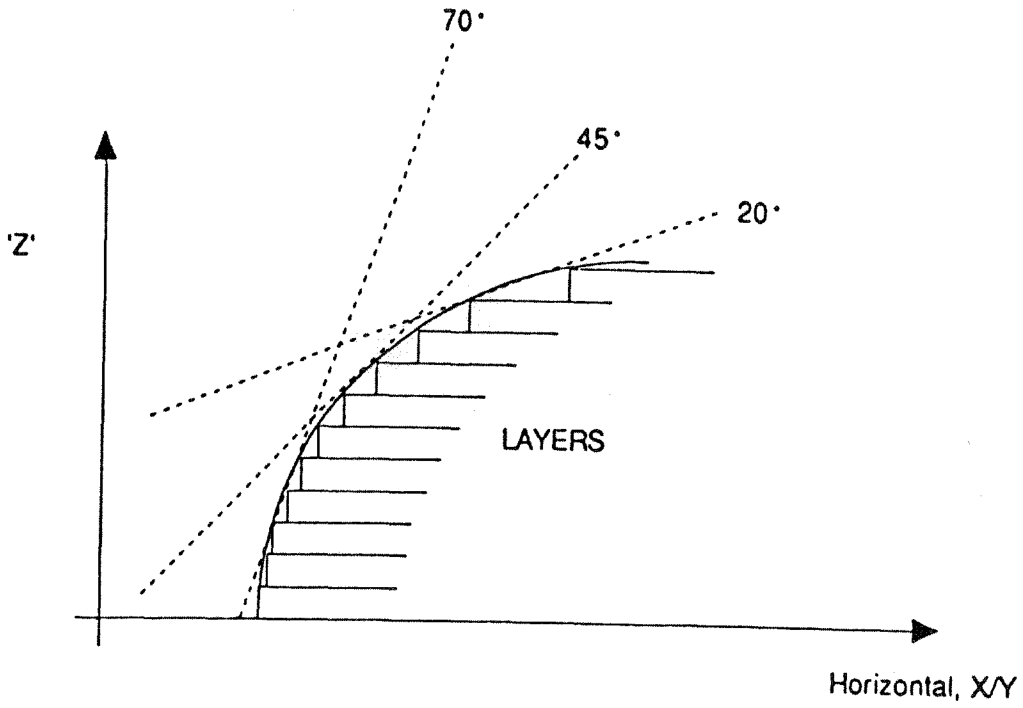

Figure 3 Showing how steps increase in the X/Y plane as arc tends towards horizontal.

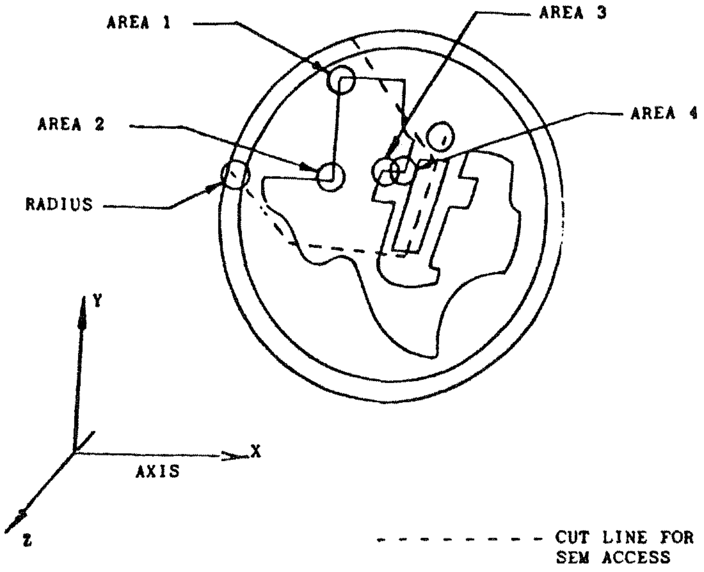

Figure 4 Standard test component supplied by Texas Instruments showing areas of particular interest.

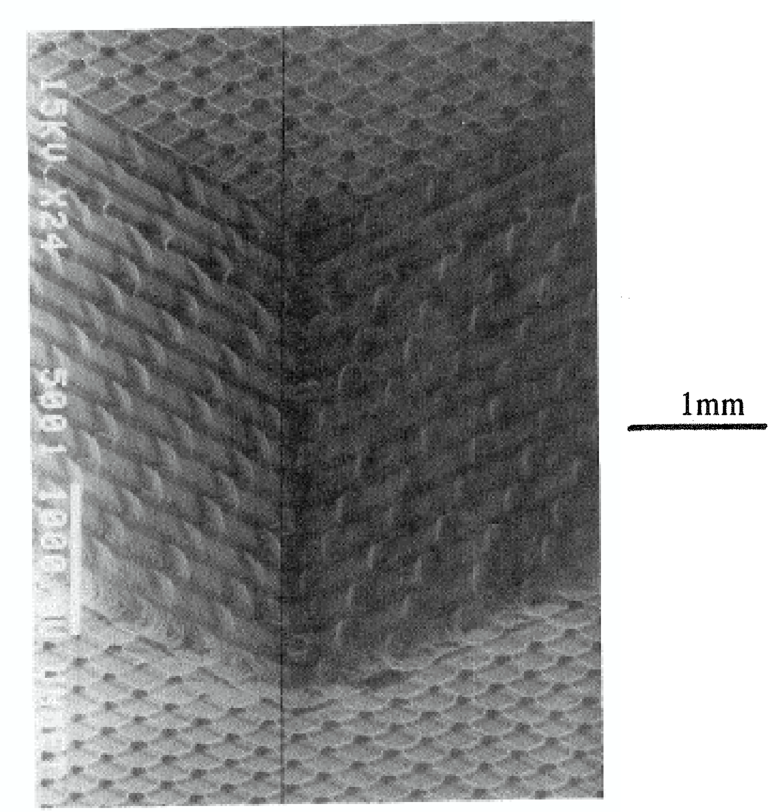

Figure 5 (area 1) Exposed, external corner, showing cyclic 'bumps' and 'steps' on vertical face, as well as a texture on horizontal surfaces. Material XB5143.

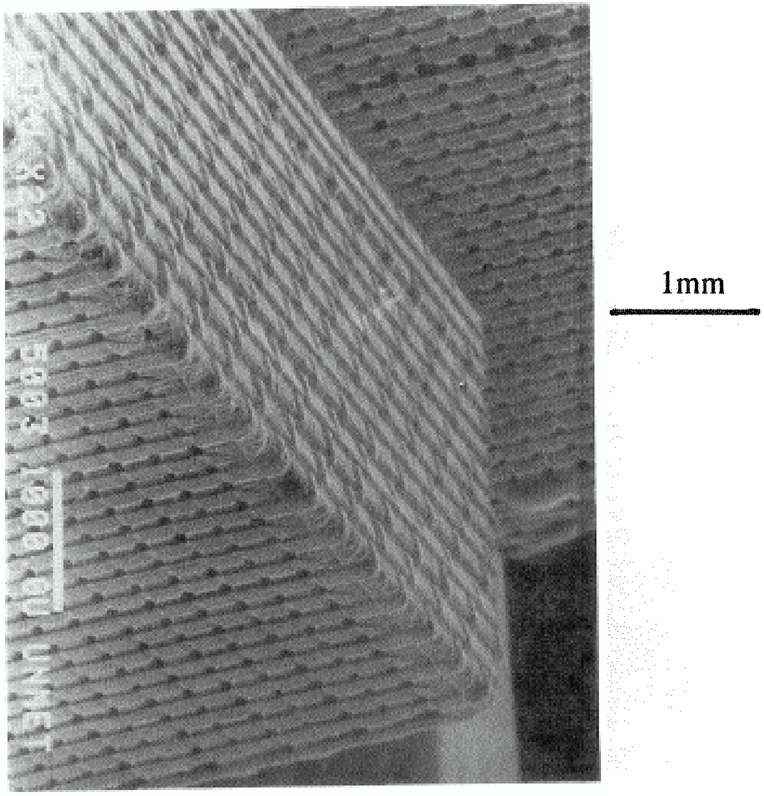

Figure 6 (area 2) Exposed internal corner. Again note the 'steps' and 'bumps' as well as the definition of corners and edges. Material XB5143.

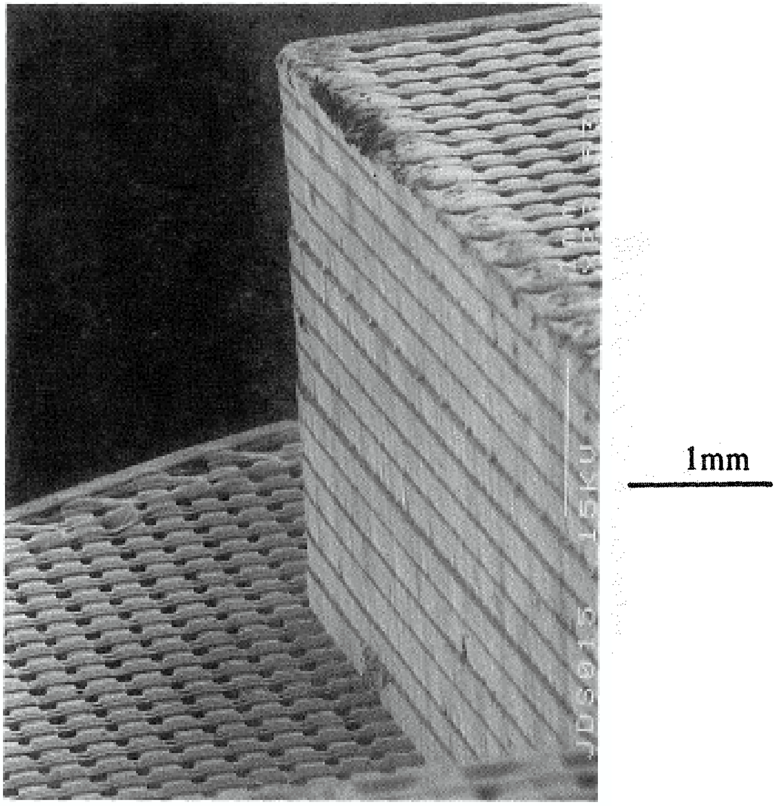

Figure 7 (area 1) Exposed external corner showing 'steps' in vertical 'Z' axis and texture on X,Y surface for material XB5081-1

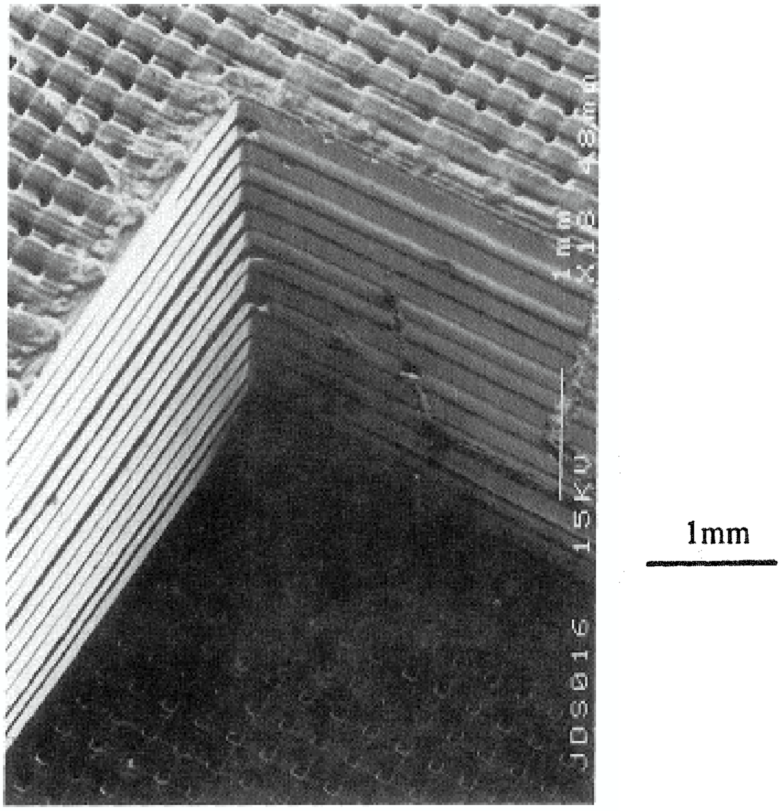

Figure 8 (area 2) View showing exposed internal corner. Of particular note is the definition of the internal edges and corner, also the edge definition into the corner. Material XB5081-1.

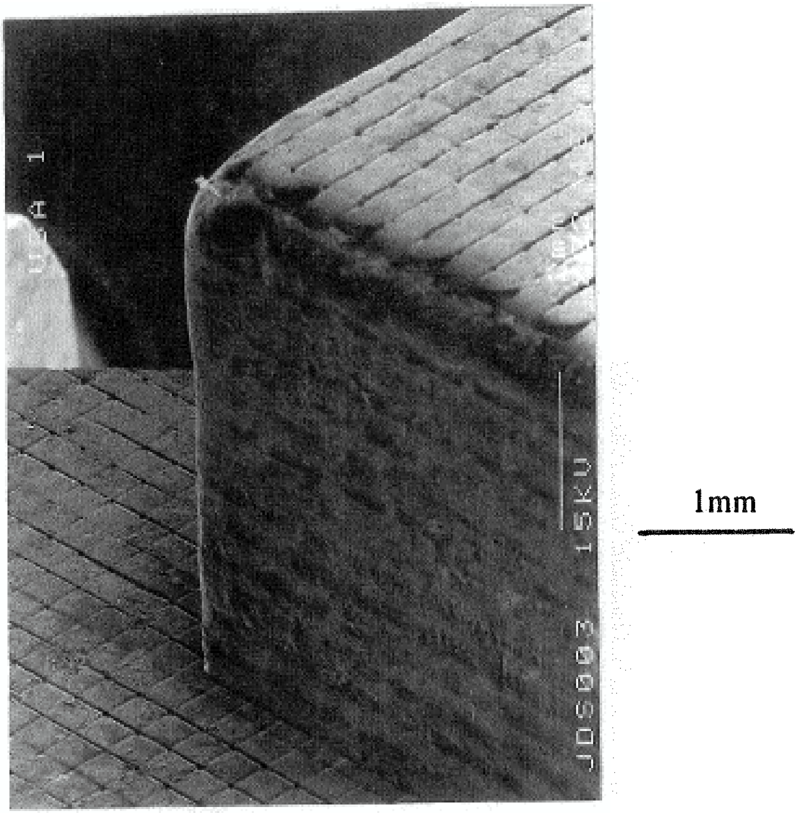

Figure 9 (area 1) Partial removal of steps and rounding to the corner is evident. Material XB5143, media angle cut cylinders.

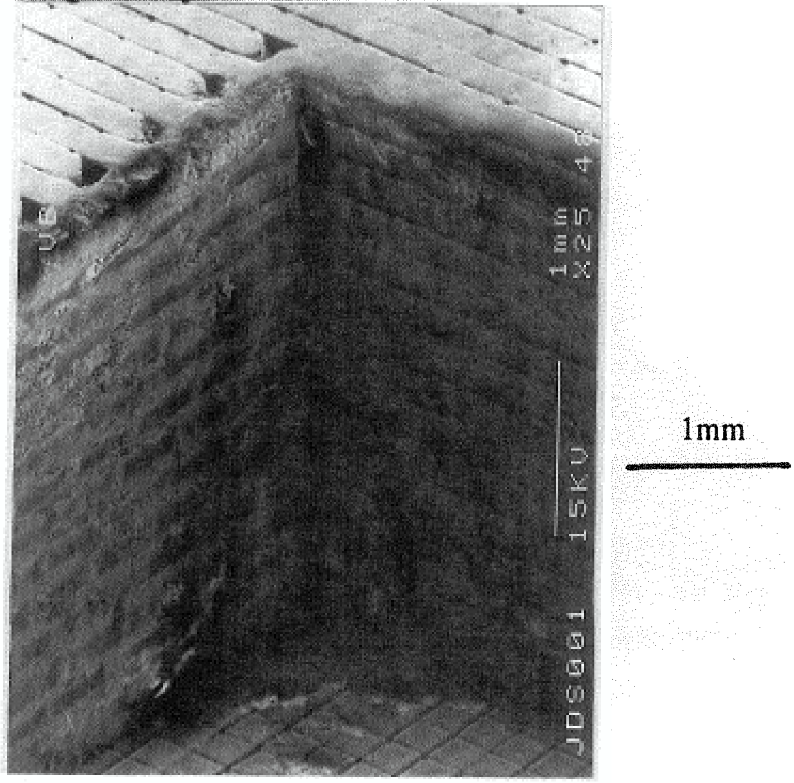

Figure 10 (area 2) View of internal corner showing partial removal of steps but little penetration to the basal junction. Material XB5143.

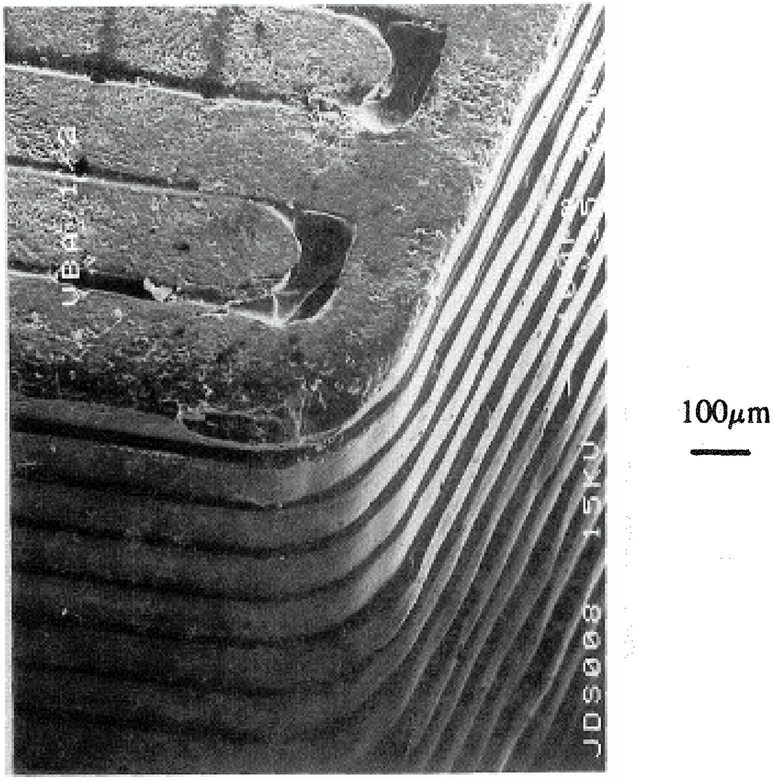

Figure 11 (area 4) Some damage is evident on the corner and little smoothing of the 'steps' is seen. Material XB5143.

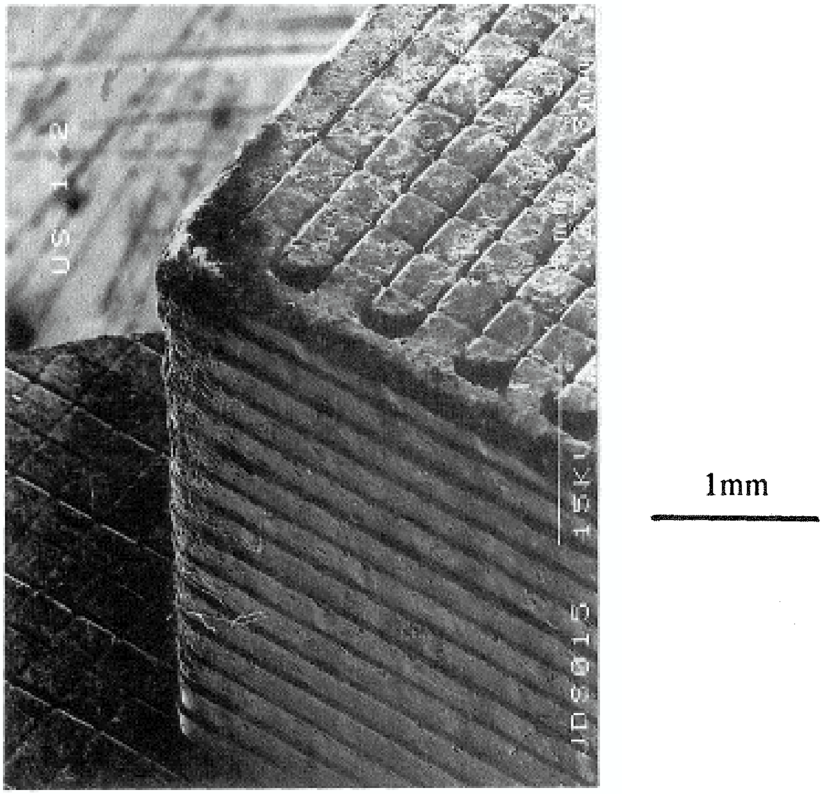

Figure 12 (area 1) Horizontal surfaces have been partially smoothed but some abrasion occurs on the edge. Material XB5143, media Carborundum grit.

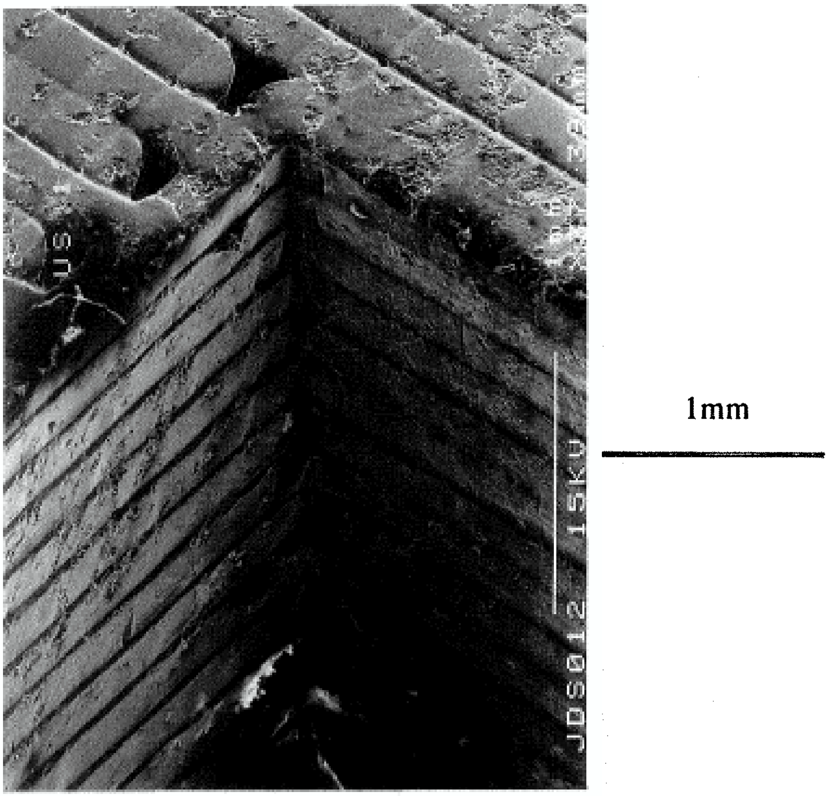

Figure 13 (area 2) Limited abrasion on the internal surfaces. Material XB5143, media Carborundum grit.