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OBJECTIVE ON LINE ASSESSMENT OF THE PERFORMANCE OF FLUX CORED WIRES BY REAL TIME COMPUTER BASED MONITORING

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ABSTRACT

The aim of this research was to devise an innovative technique to obtain an objective assessment of the quality performance of tubular cored wires by sensing and measuring the signals available during welding. The work comprised:

Identification of the parameters to assess.
A study of the different monitoring techniques.
Design of specific quality evaluation methods.
The production of a system which allowed a quality index of welding performance to be obtained.

Initially, the arc voltage, arc current, wire feed rate, arc light and arc sound signals were identified as possible sources of useful information. After a useful technique was accepted, the non-useful techniques were abandoned and a quality measuring instrument was built. The work involved development of statistical analysis techniques, Fast Fourier Transforms and mathematical modelling. A new approach to process modelling was devised which provided an objective and very flexible method of assessing, comparing and developing welding consumables.

The final system was evaluated against conventional subjective assessment techniques and very good correlation was obtained.

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I would like to dedicate this work to my baby daughter Jasleen.

"In ordinary traditional thinking we have developed no methods for going beyond the adequate. As soon as something is satisfactory our thinking must stop. And yet there may be better arrangements of information beyond the merely adequate"

- Edward de Bono, 'Lateral Thinking' 1982

CONTENTS

NOTATION

ϵ	Experimental error in a linear model
θ	Ridge regression parameter
σ	Standard deviation
σ_2	Estimate of variance
AVC	Arc (Automatic) Voltage Control
CTWD	Contact Tip-Work Distance [mm]
Wd	Wire (electrode) Diameter [mm]
F	Current or voltage pulse frequency [Hz]
GMAW	Gas Metal Arc Welding (also known as MIG/MAG)
GTAW	Gas Tungsten Arc Welding (also known as TIG)
R_a^2	Adjusted coefficient of multiple determination
R^2	Coefficient of Multiple Determination
r^2	Coefficient of determination
V_b	Background Voltage (mean of values below V_m)
V_m	Mean Voltage [V]
V_n	Nominal Voltage [V] (setting value)
V_p	Peak Voltage (mean of values above V_m)
WFR	Wire Feed Rate [m/min] (also known as W)
DFT	Discrete Fourier Transform
FFT	Fast Fourier Transform
W_m	Wire electrode melting rate
I_a	The arc current
L	Stick out distance (Stand off (CTWD - Arc length)
ta	The arcing period
c	Speed of Light (3×10^8 m/sec)
f	Frequency (Hz)
λ	The wavelength in Metres
IR	Infra Red
UV	Ultra Violet
PWL	Sound Power Level
SPL	Sound Pressure Level (DB)
AC	Alternating Current
DC	Direct Current
QA	Quality Assurance
Σ	The sum of
β	The resistive heating factor
α	The arc heating constant
s	The electrical stick out (also known as L)
I_{sc}	The short-circuit current
I_a	The arc current
t_{sc}	The short-circuit period
t_a	The arc period

T	The cycle period
I_b	The bacground current
T_b	The background duration
PC	Personal Computer
μs	Microseconds
ASCII	American Standard for Coding
M_w	Window Mean
d_n	The sample values for the channel
W_n	The window size (512)
SD_w	Window Standard Deviation
PK_w	Window Peak
d_p	The sample values $> M_w$
W_p	The no. of samples $> M_w$
BK_w	Window Bkgnd
d_b	The sample values $< M_w$
W_b	The no. of samples $< M_w$
MAX_w	Window Maximum
MIN_w	Window Minimum
TP_w	Window Peak Time
t_p	The periods when the samples are $> M_w$
tp_n	The number of peak excursions
TB_w	Window Bkgnd Time
t_b	The periods when the samples are $< M_w$
tb_n	The number of bkgnd excursions
F(	Function of
D	Droplet length
S	The integrated sound data,
Spk	Peak Integr. Sound (Mean of values above mean)
Sbk	Bkgnd Integr. Sound (Mean of values below mean)
A_{dev}	Mean arc length deviation
A_n	Window arc length
A_r	Regress calculated (adjusted) window arc length
A_{adp}	Arc length deviation factor
W_{dev}	Mean melting rate deviation
W_d	Wire diameter
D_n	Window droplet length
W_n	Window wire feed rate
W_s	Wire feed rate at spray transition
I_s	Predicted spray transition current
I_{sp}	Known spray transition current

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1. INTRODUCTION

1. INTRODUCTION

In recent years, there has been a gradual shift to semi-automatic Metal Inert Gas (GMA) welding. This has improved the productivity and thus the economics of fabrication. The improvements in transistor power sources have assisted this trend, however due to commercial limitations, there has been little development in solid wire GMA consumables. The need for bulk manufacture has meant a limitation in wire composition and hence mechanical properties. Such limitations can be overcome by using tubular cored welding wires.

Tubular welding wires have been widely accepted in the USA, but their use in the UK is still limited. They are more tolerant to changes in process conditions and hence are easier to use. Tubular wires can be welded with higher deposition rates than solid wires and are therefore more economical to use.

The manufacture of tubular wires is much more complicated than for solid wires. This imposes additional quality assurance problems in their manufacture. The current quality standards for tubular wires only consider the physical properties of the wires and the deposited metal. However, the weldability of the wire can also be used as a measure of the quality.

Although, the manufacturing stages of these consumables may be automated, the performance characteristics after manufacture currently rely on the verdict of an experienced welder. In such cases, the process parameters for welding are dependant on the welder's opinion and the performance characteristics will depend on the difficulty the welder has in making the consumable weld to his satisfaction.

The aim of this research was to devise an innovative technique to obtain an objective assessment of the quality performance of tubular cored wires by sensing and measuring the available signals. The work comprised identifying the parameters to assess, studying different monitoring techniques, designing specific quality evaluation methods and producing a useable system to output a consistent quality index of welding performance.

Initially, the arc voltage, arc current, wire feed rate, arc light and arc sound signals were identified as possible sources of useful information. After a useful technique was accepted, the non-useful techniques were abandoned and a quality measuring instrument was built. The work encompassed hardware and software design, statistical analysis techniques, Fourier transforms, mathematical modelling and computer programming. A new approach to process modelling was devised which provided an objective and very flexible method of assessing, comparing and developing welding consumables.

2. LITERATURE SURVEY

2. LITERATURE SURVEY

2.1 Introduction

One of the main objectives of recent welding research efforts has been to identify, quantify and thereby control variables which cause unsatisfactory performance of a welded joint. These variables may result from inherent properties of the material being welded, they may be due to the welding conditions used or they result from deficiencies due to the filler material reacting with main metal. The identification and control of these variables can help to match the material to the process.

It has been recognised that although a parameter that affects performance may be identified, its elimination may be costly or physically difficult. In such circumstances, it is important to quantify the parameter in order to assess its significance and develop effective control techniques (F R Coe 1968).

To obtain an accurate picture of the significant factors which control the process, it is necessary to observe as many factors as possible and eliminate low influence parameters from the measurements. In order to concentrate the research programme in the most productive areas, it was necessary to carry out a review of the published literature of research being carried out in similar projects. The scope of this review is limited to the various subjects involved in reaching the objective of this research.

The aim of this research was to devise an innovative technique to obtain an objective assessment of the quality performance of tubular cored wires by sensing and measuring the available signals. Welding with tubular cored wires is a fairly recent development. The manufacturers are continually carrying out research programmes to improve the welding quality produced by their wires. The welding process used is normally Gas Metal Arc Welding (GMAW) and the fundamentals of the GMAW process and the Welding Arc are described.

In this work, the factors observed were arc voltage, arc current, wire feed rate, light and sound. The sensing fundamentals and the published literature on previous attempts at monitoring the 'light', the 'sound' and the 'electrical' signals for quality assessment are also described.

There are many available techniques to analyze the data obtained, these include Statistical Analysis, Statistical Modelling and Fast Fourier Analysis (FFT) amongst others. Since all of these techniques were essential to complete this work, the theoretical aspects together with some of the published literature on other researchers' attempts to use these and other techniques for similar purposes are described.

2.2 Gas Metal Arc Welding (GMA) Fundamentals

Since the work carried out for this thesis utilised the gas metal arc process, a brief description of the fundamentals and modes of transfer is essential.

In GMA welding the continuously fed wire is melted then transferred to the weld pool. To achieve acceptable weld quality, the metal transfer in the arc must be stable. The stability of the arc depends on the optimal combination of the following parameters:

Arc current
Arc voltage
Shielding gas
Wire diameter
Wire composition
Electrical stick-out
Arc length etc.

The optimisation of these factors to obtain good arc stability and metal transfer is a continuous area of discussion for researchers. There are three distinct types of metal transfer that can occur over the voltage and current ranges,

i. Short-Circuit or Dip Transfer
ii. Globular Metal Transfer
iii. Spray Metal Transfer

In short circuit transfer, the wire is fed into the molten pool at a rate faster than the wire is melted. The wire short circuits with the weld pool causing a rise in current which heats up the wire until the wire is detached. At this point the process commences again Fig 2.1. In globular transfer, the metal droplets are large in size. This mode of transfer is naturally unstable and can cause lots of spatter since the large droplets swing about the wire end. In spray metal transfer, the metal droplets are small and are melted at high frequency across the welding arc to the weld pool. This mode is very stable by nature.

The transfer of molten metal from the electrode tip to the weld pool affects various aspects of the welding quality. These include the amount spatter or fume level, the bead characteristics, process stability and performance etc. The phenomenon of metal transfer in the GMAW process has caused considerable attention since its development (Modenesi 1990).

During the last two decades, this area of interest has been increased, due to the advantages provided by advances in this area such as the Synergic Pulsed GMA welding process and Flux Cored Wires. Reviews of the fundamentals have been given by Lancaster (1984, 1987, 1987) and more recently by Norrish and Richardson (1988). A basic review of the research within this area will be discussed later.

2.3 General Arc Principles

To utilise the electrical signals of the arc for monitoring, it is necessary to have a basic understanding of the structure of the welding arc. In a welding arc, electrons are emitted from the negatively biased cathode and collected by the positive electrode or anode. Between the electrodes is the arc column, the region of gaseous conduction which separates the electrodes (S G Trapaga 1987). This column may be regarded as electrically neutral and generally in thermal equilibrium. An ionised gas which is electrically neutral is termed a **plasma**. This plasma will be composed of neutral particles such as atoms and molecules in both excited and non-excited states, as well as charged particles such as electrons and ions in equal numbers. Since the column is electrically neutral there is an electric field which has an average value of the order of 1000 V/m (Lancaster 1984).

The arc can be sub-divided into three zones Fig 2.2 which are related to the arc potential. Unlike the plasma column which can extend to several mm in length, the electrode region can only extend approximately 1 x 10^{-6} mm from the surface and exhibits much higher electric field strengths and current densities than for the arc column. The potential drop across the arc can be expressed as

$$V = Vanode + Vplasma + Vcathode \qquad (2.3.1)$$

The potential across a welding arc is a function of several variables, including plasma gas composition, arc length, current, pressure and electrode composition. In the case of welding arcs, one electrode is usually a rod, whilst the other is a plate, so that the arc current diverges generating a plasma jet. The formation of the plasma jet will depend on factors such as electrode coating, formulation and shielding gas.

The flow of current in the arc occurs by drifting of the charge carriers (Lancaster 1984). Electrons are emitted from the cathode and move towards the anode. The positive charge carriers originate in the arc column by thermal ionization and move towards the cathode. The arc potential is the result of the drifts in charge carriers in either direction.

The cathode fall zone is very small (approx 10^{-6} mm) but has a large potential fall (around 10V) resulting in a very strong electric field. Similarly, the anode fall zone is also very small and also has a very large potential drop across it. The arc column has a relatively low electric field strength and thus dependant on the ionization potential of the gas.

For steady state conditions the voltage current characteristics of a welding arc at constant arc length can be expressed as

$$Va = A + BI_a + \frac{C}{I_a} \qquad (2.3.2)$$

where A,B C are functions of the shielding gas and the arc length.

Fig 2.3 shows the V/I characteristics at constant arc length, and Fig 2.4 shows the effect of arc length on the arc voltage at constant arc current (Lancaster 1984).

Arc voltage is normally measured between the contact tip of the GMA welding torch and the workpiece. This measured voltage consists of 4 parts:

(a) The real arc voltage
(b) The voltage drop between the contact tip and the wire surface.
(c) The voltage drop in the electrical stick out/extension.
(d) The voltage drop from the base plate to the measurement system.

The latter voltage drop (d) is normally small, but increases with current. The voltage across the arc and the voltage across the stick-out provide significant variations in arc behaviour for differing process situations.

In terms of welding, it is necessary to maximise the heat delivered to the welded metal and minimise the heat loss to the environment thereby increasing the arc efficiency. For effective welding to occur, the heat generation in the welding arc must be controlled and metal transfer must occur without spatter. However, neither the heat generated nor the arc behaviour can be preset before welding. In order to achieve a stable metal transfer, all of the process variables must be carefully controlled.

For the GMAW process it has been reported that the arc voltage, the wire feed speed and the inductance of the power source are the most important process variables. To obtain a welding condition, the combination of these three variables must be optimised. Several researchers have investigated the effects of these variables on arc stability and metal transfer (A Smith (1962), T Mita et al (1987), Popov et al (1970), H Fujimara et al (1987), T Maruyama (1988), etc.).

The relationship between these variables is complex but some of the physical relationships have been established as empirically derived mathematical equations.

The wire stick out is an important process variable since it effects both the arc voltage and the wire melting speed. Halmoy (1987) provided the well known burn-off relationship,

$$W_m = \alpha I_a + \beta I_a^2 L \qquad (2.3.3)$$

where W_m is the wire electrode melting rate,
I_a is the arc current,
L is the stick out distance.
α, β are constants.

During the arcing period, the wire is melted and the volume of the metal drop (V_d) is thus,

$$V_d = \left(\frac{\pi d^2}{4}\right) \int_0^{ta} (\alpha i + \beta i^2 L)dt \qquad (2.3.4)$$

where i is the instantaneous current.
ta is the arcing period.
d is the diameter of the wire.

The V/I characteristics of the arc are directly influenced by the physical properties of the shielding gas. It is therefore essential that the gas shielding is not contaminated by the surrounding atmosphere. Insufficient gas shielding results in metal spatter and porosity. The presence of water moisture, oil and rust on the joint may also change the composition of the arc atmosphere and affect the welding process (Xiaojin Xie 1989). Welding parameter selection, process optimisation and modelling techniques indirectly attempt to optimise the parameters that influence arc behaviour and metal transfer, in order to improve the welding quality. Hence, the optimisation of these techniques depends on the ability to monitor the most suitable arc parameters.

2.4 Light

2.4.1 Introduction

Welding arcs emit a wide spectrum of non-ionising radiation which varies from Ultra Violet (UV) through the visible range to Infra Red (IR). The wavelength of visible light is 400-800 nm; Infra-Red has longer wavelengths than visible light whilst Ultra Violet has shorter wavelengths than visible light. The generally known relation between frequency and wavelength is:

$$\lambda = c/f \qquad (2.4.1)$$

where

c is the velocity of light (3×10^8 metres/sec)
λ is the wavelength in Metres
f is the frequency in Hertz

Since the IR, UV and X-radiation are similar in nature to visible light, many of the sensors and techniques applied to visible light may be applied to some extent to these adjacent regions of the electromagnetic spectrum (J J Carr 1988).

2.4.2 Light and Welding

Ultra Violet, Visible and Infra Red radiation is produced by all arc welding and cutting processes. The intensity of radiation produced by a welding arc is a function of the welding process itself and of the welding variables.

Van Someren and Rollason (1948) considered that about 5% of the radiation produced by the welding arc is in the UV region. Bennet and Harlem (1980) estimated the UV emissions by analyzing heat balance figures for welds. It was estimated that 20% of the total radiated energy is in the ultraviolet region. The calculation gave a similar result for both TIG and GMA welding processes. By making assumptions of the temperatures at the electrode and the weld pool, it was calculated that the greatest contribution of UV was from the plasma.

Approximately 26% of the radiation produced by a welding arc is in the visible range between 400 and 750 nm. However, very few authors have researched in the visible portion of the welding arc. Patee et al (1973) suggest that welding variables such as arc voltage, arc current, arc length, shielding gas and flow rate have a direct influence on arc radiation.

Zaborski (1976) studied the radiative energy distribution and suggested that the visible spectrum is of particular consequence for eye protection, especially since IR and UV rays are absorbed by welding filters and a compromise is made in the visible range to obtain good observation of the work. Zaborski maintained that the spectral distribution of welding arcs reveals the predominance of short wave radiation and a considerable decrease in the long waves. Figures given show up to a factor of 10 difference between the ranges. From the calculations he concluded that the behaviour was due to the atomic and molecular radiation of vapours originating from the decomposition of electrode coatings or shielding gases which contribute the spectra of the welding arcs in the visible range.

In order to utilise the light emanating from the welding arc, the correct method of sensing the light must be used. The range of applicable sensors are reviewed below.

2.4.3 Photosensitive Devices

Photosensitive devices may be considered as transducers which convert optical energy or photons to a change in the electrical characteristics of the device (C Peters 1987). The photo sensors to be described depend upon quantum effects for their operation. Quantum mechanics was first introduced by the German physicist, Max Planck in 1900. He suggested the theory that energy existed in discrete bundles, not as a continuum. In other words, energy comes in packets of specific energy levels, other energy levels are excluded. The name eventually given to these energy levels was ***quanta*** and the name given to energy bundles in the visible light range was ***photons***. The energy level of each photon is expressed by the equation:

$$E = ch/\lambda \quad \text{or alternatively} \quad E = hv \qquad (2.4.2)$$

where:

E is the energy in electron volts (eV)
c is the velocity of light
λ is the wavelength
h is Planck's constant (6.62×10^{-34} J-s)
v is the frequency of light.

The basis of light sensors is to make a device which allows electrons to be released from their associated atoms by photons of light. The two principle types of such devices are photoconductive and photovoltaic.

Photovoltaic Devices

Photovoltaic devices convert light energy to electrical energy, they can be used to read or monitor intensities at a point or plane without external biasing or supply systems. Their spectral response is controlled by their material. The photon energy is used to free electrons from their atoms to cause a current to flow. A photovoltaic cell contains a -n junction with a built in voltage differential between the 'p' and 'n' sides because of the doping level. When a resistor is connected across the junction, some of the freed electrons will travel around to attempt to eliminate the difference. As the illumination is increased, more electrons are generated which will flow through the external load. The output energy of photovoltaic cells depends on the cell area and light intensity.

Photoconductive Devices

The most common photoconductive device is the photodiode. The photoconductive element is the variable impedance in which the electrical resistance can be decreased by the bombardment of photons. Photodiodes are silicon based and therefore have a spectral response corresponding to that of silicon. When light of the correct spectral response hits the material, some of the energy is absorbed by valence electrons within the depletion zone of the semiconductor. A portion of these electrons are freed, thereby causing ionised atoms. As a result the electrical field causes a current to flow which is a function of the amount of light absorbed.

Noise

The response of a Photosensitive detector depends upon the noise that arises within the detector. Noise within the detector can arise via a number of sources. Johnson noise is due to the random motion of the current carriers within any resistive material and is usually dependant upon the temperature. Shot noise is caused by the random arrival of photons giving a random fluctuation in photocurrent. This can be a random series of pulses on the current trace. I/f power low noise is attributed to potential barriers at the contacts of the semiconductor and is usually present at low frequencies (C Peters 1987).

The review of the present activity of the monitoring the arc light as a control variable indicates that very little work has been done in this area other than for penetration control. The availability of miniature light sensors should enable researchers to investigate this area further.

2.5 Sound

2.5.1 Introduction

The science of acoustics has evolved during the last century, Stokes and Rayleigh studied the sound generated by vibrating strings and organ pipes. In general, present day research into sound has been mainly concerned with unwanted noises such as jet engines and powerful machinery.

Sound propagates as a wave. In air it travels at approximately 340 m/s. The sound wave evolves as it travels away from the source, diminishing the curvature so that it resembles a one dimensional field propagating radially outwards with a constant speed v.

Because of the enormous numerical range in measuring sound powers a logarithmic scale is used and the power level given in decibels (PWL).

$$\text{PWL} = 10.\log_{10}\left(\frac{\text{sound power output}}{10^{-12}\text{ watts}}\right) \qquad (2.5.1)$$

$$= 10.\log_{10}(\text{sound power in watts}) + 120\text{ dB.}$$

(The human shout has a PWL of 70 dB and the large rocket motor 190 dB.)

As a sound wave propagates it disturbs the fluid through which it travels from its mean state. These disturbances are usually small. If we consider departures from a state in which the fluid is at rest with a uniform pressure p_o and density d_o. When this is perturbed by a sound wave, the pressure at position **x** and time t changes to $p_o + p'(\mathbf{x},t)$ the density to $d_o + d'(\mathbf{x},t)$ and the fluid particles move very slowly with a velocity $v(\mathbf{x},t)$.

As mentioned above the range of amplitudes usually experienced in sound waves is very great, hence the perturbation is commonly expressed on a logarithmic scale also. The sound pressure level (SPL) is a measure of the mean square level of fluctuation and is by convention defined as

$$\text{SPL in dB} = 20.\log_{10}\left(\frac{p'_{rms}}{0.0002\mu\text{bar}}\right) \qquad (2.5.2)$$

$$= 20.\log_{10}\left(\frac{p'_{rms}}{2.10^{-5}\ \text{N/m}^2}\right) \qquad (2.5.3)$$

where $p'^2_{rms} = \overline{p'^2}$.

On this scale the fluctuation of one atmosphere in pressure corresponds to 194 dB. (The threshold of pain is between 130 and 140 dB corresponding to a pressure variation of only one thousandth of an atmosphere.)

2.5.2 Sound and Welding

Microphones measure airborne sound. It is well known that welding processes supply useful information not only in the audible range (20 to 20,000 Hz) but also in the high frequency range. To obtain useful information from acoustic measurement, some minimum prerequisites must be set in order to reduce the number of variables to consider. These may be summarised as follows:

(a) The process sound shall exhibit a high sound pressure value and a good signal to noise ratio.

(b) The signal to noise ratio should be greater than 10 dB.

(c) The amplitude of the sound signal should be greater than the accuracy of sound measurement.

(d) The important details regarding process information should give rise to significant changes in either the SPL or frequency spectrum.

It is already known that every welding or cutting process has its own specific sound pattern. The skilled welder can judge the welding process from the welding sound. The instructor can distinguish welding performed by a beginner or an advanced welder. The sound supplies directly useful information on the process performance but it has been recognised that it is a major task to evaluate this information and to use it for process development and quality control.

Egon Schlebeck (1982) used a microphone, a sound level meter and spectrum analyzers to investigate the arc sound. A magnetically moved arc pipe welding system was studied with the microphone placed 1 m from the pipe axis. The following observations were made:

(1) During the preheating phase an obvious relationship between the sound energy and the electrical energy was observed.

(2) The axial and radial magnetic field components influence the sound energy.

(3) Factors such as poor edge preparation or contamination were observed in the sound pressure/time curve.

(4) Stable and non-stable were identified in the sound pressure/time curve as well as by statistical methods.

Schlebeck concluded that the study of acoustics can benefit development of welding processes and the perfection of cutting nozzles and eventually use the experience for acoustical control or monitoring of welding and cutting processes.

Prof.Dr. I. P. Erdmann-Jesnitzer et al investigated the acoustic emissions from a welding arc. Earlier work by Jesnitzer and collaborators revealed that the transition point from a globular to spray transfer is accompanied by a hissing sound. The investigation used a microphone amplifier system with the signal output calibrated in sound pressure units.

The sound from the arc was attributed to the following causes:

(a) Movement of the anode and cathode spots.

(b) acoustic resonance phenomena throughout the system eg. arc, electrode, electrode holder.

(c) noises caused by the power source.

(d) discharge noise of the discharge gas flowing through the nozzle.

(e) transfer of metal.

The investigation looked at the above factors as well as the arc voltage, the arc length and the welding current. Increases in arc voltage caused corresponding changes in arc sound and this was attributed to an increase of pressure in the plasma. It was also found that the sound pressure rises with increase in arc length (as the voltage rises). Although it was believed that the frequency also depends on the arc length, these workers could not produce a specific relationship between frequency and arc length.

Prof.Dr. I. P. Erdmann-Jesnitzer et al concluded that drop transfer and burn off characteristics could be detected if more subtle and precise equipment were available.

An investigation into the characteristics of welding arc sound was carried out by Yoshiaki Arata et al (1978) as a basis for welding process control. The sound waveform, the sound pressure level and the frequency spectrum were measured and the behaviour of the arc was observed by means of a high speed camera.

The study covered both GMA and TIG arc welding. The welding arc sound was measured by means of a condenser microphone. With the GMA welding process, bead on plate was carried out using CO_2 gas. It was assumed that the source of welding arc sound was a point on the basis that the distance (r) between the measurement point and the sound source is great compared to the size of the sound source. If the source exists on a rigid wall of infinite size, the sound wave is emitted to the surrounding space as ½ spherical wave. In this case the sound pressure level can be expressed by:

$$SPL = PWL + 10.\log_{10}(Q/4\pi r^2 + 1/R) \qquad (2.5.4)$$

where Q is directivity factor
R is room constant

This relationship was confirmed by experimentation. Using this relationship, the welding arc sound was analyzed. It was found that sound signal could be synchronised with the short circuiting in dip process. In the case of the spray GMA and TIG processes the patterns of the sound signal were dependant on the inherent current ripple of the welding power source.

Arata et al plotted various parameters against SPL. The input power I.V was plotted against SPL and an inverted 's' shape was observed. The effect of arc voltage on SPL was more dominant in dip and globular welding. Changes in wire feed speed below 200 A had little effect on SPL, but were found to be considerably large above 300 A. The SPL became constant if a shielding gas was not used. The SPL decreased slightly as gas flow rate was increased. It was concluded that welding arc sound provides useful information on the welding process and could be correlated to most of the common welding parameters known.

In their second report Arata et al (1979) used the arc sound to locate the optimum point in the arc V/I characteristic. The objective was to evaluate the hearing acuity of arc sound. Arata et al studied the SPL and frequency at various conditions using the GMAW process. Although the work was involved with establishing the criteria for safety from the arc sound, some useful information was obtained with regards to arc sound characteristics. When changing from dip to globular to spray transfer mode, it was established that there is a significant change in arc sound at the transition point at which the droplet is being transferred. It was also found that arc sound was much more sensitive to variations in arc voltage.

Arata et al (1980) also looked at the effects of current waveforms on TIG welding arc sound. Arata studied the effects of pulsing the current and compared them to other forms of current waveform. These were rectangular, sawtooth, triangular and sine wave. A DC transistor power source was used for the experiments which were carried out in similar manner to the earlier work.

The study looked at varying the frequency and amplitude of the pulse with all waveforms. The SPL was plotted against pulse frequency and pulse amplitude. It was found that the SPL was nearly proportional to the logarithm of the pulse frequency, the slope being maximum for the rectangular waveform reducing for sawtooth, triangular and sine waveform in order. Arata obtained a very similar result for pulse amplitude. That is, the SPL was proportional to the logarithm of the pulse current amplitude in the same order as mentioned for the frequency. Arata et al concluded that the sound pressure waveform is dependant on the current waveform.

Arata et al (1981) also investigated vibration analysis of base metal during welding using a study of the arc sound. Bead on plate welding was applied to SM41B steel plate using CO_2 shielded dip transfer welding. A piezoelectric accelerometer was used to measure welding vibration.

The frequency spectrum of vibration up to 3 KHz was analyzed by studying the arc sound. By measuring the vibration of the welding bench when white noise was produced from a speaker, it was shown that the vibration acceleration level (VAL) is proportional to the SPL. This correlation was studied for CO_2 arc welding for current settings of 200 A and 400 A. They concluded that SPL and VAL were proportional so long as the arc voltage was not excessive. They also found that the short circuit re-ignition frequency and the droplet separation could be detected similarly in both the VAL and SPL signals.

Zhang JiuHai et al studied the arc sound in TIG and Plasma welding and the possibility of its application in practice. They state that although some work has been done to analyses the characteristics of arc sound, limited work has been carried out to relate arc behaviour to the sound.

The objective of their work was to optimise the detection of arc sound, relate the arc sound to arc behaviour and explore methods of controlling the arc from the sound information. A high speed camera was used to monitor the arc, and the current, voltage and wire feed rate were also measured. A filter system was developed to remove the ambient noise from the signal.

From the study of AC TIG welding of aluminium Zhang JiuHai et al found that there was significant sound signal during the workpiece negative half cycle, but during the other half cycle hardly any arc sound signal appears. This phenomena was confirmed by separating the frequency spectrum of DCSP and DCRP TIG welding separately.

The arc sound caused by arc extinguishing and re-ignition was investigated separately in order to avoid the influences of other factors. They found that both arc extinguishing and arc re-ignition produce strong sound signals and can be detected repeatedly. In the case of the arc sound produced in dc plasma welding, it was found that the arc sound was stronger when there was a keyhole present. This result was used to develop a control system for keyhole plasma welding and to start and stop the welding carriage.

G Cook et al (1989) reported that Kaskinen and Mueller (1986) have utilised acoustical sensing for arc length control in GTA welding. It is also reported that the Idaho National Engineering laboratories (1989) and David Taylor Research Centre (1989) are studying the acoustical signals for detection of metal transfer mode. Lewis and Dixon (1985) are reported to be studying a method to use acoustical emission as a means to plasma monitoring in Laser Beam Welding. A similar study is being undertaken by Jon (1989).

The available literature for the analysis of the arc sound signal described above indicates that there are definite correlations between with the transfer and arc length characteristics. However, most of this work has provided only limited theoretical possibilities for utilising the sound signal. Although Zhang JiuHai did develop a control system for keyhole plasma welding, there have been minimal attempts by other researchers to correlate the sound from a quality monitoring point of view.

2.6 Arc Monitoring

D K Feder (1988) listed the applications of computers in welding technology. The author describes the functions of computers and their uses in information technology. The application given describes the use of computers from software packages such as finite analysis to calculate stresses involved; CAD packages for drawing; job scheduling and process selection for optimum economics; expert systems for optimum procedural selection; for process control and welding robots to optimise welding processes in real time; for quality assurance and inspection by utilising computer aided testing techniques such as holographic imaging and acoustic emission testing. The author suggests that most of the technology is already available and with development of smaller and faster computers there is plenty that can be improved upon.

The role of computers for monitoring and control has been demonstrated with respect to resistance welding. Several researches have studied the physical characteristics of the process to produce real time quality assurance measurement techniques. Broomhead and Dony (1990) utilised the real time measurement of dynamic resistance for quality monitoring of mass production resistance spot welds. A similar approach by Welserveco (1990) monitors the real time changes in voltage and current. The system uses the principle that any change in quality will be reflected in either the voltage or current signal.

G Blackenship (1990) described the use of a Personal Computer (PC) based control system for monitoring voltage fluctuations. Yihong and Chunqing (1988) described a microprocessor based control technique that uses electrode displacement due to thermal expansion of the workpiece as the control parameter. The system monitors the electrode displacement during the welding cycle and deviations are compensated by altering the current.

Eichhorn et al (1988) developed an automatic system to check every welded spot. The system comprised a database of stored parameters and predictors and monitors the tension strength, welding spatter and ware by incorporating transducers such as quartz crystal acceleration pick up to measure structure borne sound. The system gives a full report for each weld. A method for improving the measurement errors of the process parameters by using different types of sensors was described by Gedeon et al (1987). They describe the development of adaptive control units based on measurement of the voltage at the electrode tip.

Another example of computer based quality monitoring system was developed by Ruge and Eckel (1988) for Friction Welding. A computer controlled friction welding system was produced which comprised various sensors to sense the process parameters that affect the overall quality of the welded joint. In this case they measured the axial force, the axial movement, the torque and speed of rotation. The system comprised a database of process parameters and tolerance bands which were used as quality indicators for the specific conditions.

A more specific example of a welding QA system was demonstrated by Thiele and Lorenz (1988). They describe the possibilities of computer assistance to QA activities in conventional welding technology. They suggest the use of the computer from design stages to documentation of the NDE results. The authors give an example of a boiler and vessel manufacturing company to highlight the possibilities. One important point highlighted is that the data must be transferrable from one department to another to produce an efficient system.

G R Blakemore (1992) et al have developed a computerised system for control of a portable friction welding machine. A Motorola 68332 based control hardware was produced to provide in-process monitoring, analysis, control and QC/QA traceability. The techniques developed have allowed for the welding of much larger studs than was previously possible with small motors because of the precision of the control system.

Although there has been much research in the arc welding area, the application of the techniques developed has been less common.

Philpott (1986) developed a microprocessor based weld quality monitoring system for robotic GMA welding. The system used conventional and novel methods to monitor the process variables. As well as monitoring the conventional voltage, current, wire feed signals etc., the author also utilised the RF signal from the arc to assist in the decision making. It was found that by spectral analysis of the RF waveform, it was possible to detect both arc stability and gas shield breakdown. Philpott also developed a 'dip resistance monitoring' method for seam tracking. An analysis of the combination of the monitored process variables allowed development of an effective weld quality monitor. The final system also reported to a central management system connected to several robots. This allowed for a more effective Computer Integrated Management (CIM) system. Armatige (1986) later used the instrument to develop a data acquisition package to monitor the GMAW process.

General Dynamics Landsystems, USA (1991) produced an automated Weld Quality Monitoring System (WQMS) that is capable of locating a weldment in space, adjusting the weld path, measuring the joint volume and calculating the number of weld passes required. The system is capable of preheating, measuring the temperature of the preheat and performing interpass cleaning if required. The monitoring system comprises a Macintosh IIx computer system interfaced to an acoustics emission monitor and a welding signal isolation conditioning panel. This has inputs for a voltage sensor, a current sensor, a wire feed rate sensor, a hydrogen monitor, a gas flow sensor, a temperature sensor and a travel speed sensor. The authors hope that the implementation of WQM system will allow quality verification of the total weld length and also allow discontinuities and defects to be traced to their origins.

Drews and Fuchs (1989) outlined the development of a robot welding system and proposed an approach to the automation of the welding process and its integration into CIM. They demonstrated the modularity of the total system, incorporating sensor systems, welding equipment, CAD/CAM, data systems and robots.

Adam and Siewart (1989) utilised a 16 MHz microcomputer with a fast analogue to digital conversion board to develop an arc monitoring system to predict the transfer mode in Gas Metal Arc welding. The software utilised fast fourier analysis and amplitude and frequency histograms to distinguish the differences between the modes. The authors found that for globular transfer, the fourier transform exhibits a well defined peak at about 80 Hz, which suggests 80 metal droplets per second in this mode. It was found that the transition from short circuit to globular mode could also be detected with the spectrum.

The spray mode was difficult to measure in the frequency domain. With the use of amplitude-frequency histograms, the authors found that the short circuit mode produced two main peaks because the voltage remains in two distinct ranges (short and open circuit) during most of the time. The globular mode histogram presented one main peak at the average voltage and two smaller ones (above and below the average value) associated with the droplet transfer.

In spray mode the authors found that the voltage variations are very small (about 0.5V), the amplitude frequency histogram was characterised by a single sharp peak centred around the average value. By plotting the ratio of the highest peaks in the voltage amplitude frequency histograms as a function of the power supply voltage a clearer technique for detecting the mode was found. This ratio ranged from 1 for the short circuit mode to zero for the spray mode. Adam and Siewart also plotted the Integral of the a-f histogram and found that the relative value was minimal in the globular mode. It was suggested that these parameters could be used for on-line control.

G Cook et al (1989) discussed the issues of feedback and adaptive control for the fusion welding process in terms of sensing, modelling and control. They suggest that variables of the welding process can be divided into direct weld parameters (DWP) and indirect weld parameters (IWP). The direct weld parameters include weld reinforcement, weld geometry, fusion geometry, mechanical properties etc. Whilst, indirect weld parameters are those input variables that control the direct weld parameters. These include voltage, current, travel speed, electrode extension etc. The authors describe the implementation of multi-variable weld process control in terms of sensing, modelling and control.

It is suggested by the authors that in recent years, great strides have been made in sensor technology, particularly in the areas of optical sensors, arc sensing, infrared, acoustics and ultrasonic sensing. Optical sensing has been developed and used for a number of applications, including joint tracking and fill control, molten pool width, weld bead profile, arc length control and penetration control. Arc sensing has many applications such as automatic voltage control, tracking and width control and detection of metal transfer mode. Infrared sensing has potential applications ranging from sensing of discontinuities to cooling rate measurement.

Acoustical signals generated by the welding arc are thought to be the principle source of feedback for manual welders and several researchers have studied the relationships between acoustic signal and welding properties (see section 2.3). G Cook et al concluded that there have been several advances in both sensor technology and steady state and dynamic control models. They suggest that long term efforts will focus on combining process modelling and microstructural evolution modelling for eventual control of both macro and micro parameters.

Xie and Bolmsjo (1991) have studied the functions of a human welder and the relationships with the electrical signals and arc stability. A system was produced for monitoring the stability of the GMA short arc process. A model of the process was developed as a total quality monitor for robotized welding. In terms of monitoring they have produced a monitoring system capable of acquiring the electrical signals at 70 kHz, although most the work was done with a sample rate of 4 kHz. A Pascal program was developed to measure the important parameters.

Rehfeldt et al (1991) described the use of a microprocessor based analyzing and evaluating system, the 'ANALYSATOR HANOVER 10.1' for examining various arc welding processes. The system can sample up to 1 MHz and can calculate several useful statistical functions with the data. One of these, the Probability Density Distribution (PDD) was shown to be a very useful method to improve the welding process.

J P Boillot et al (1992) have recently described further advances in adaptive robotic welding. They have utilised the latest sensor technology to monitor, measure and control the welding parameters, and provide seam tracking facilities with a laser based real time image processing system. The process models have been developed, together with several look up tables for process selection.

C Hsu et al (1992) have utilised a VME bus based computer control system for electron beam welding. The VME bus hardware uses multiple processors in order to achieve the data acquisition and control functions. The human interface, includes an embedded PC as most people are familiar with them. The system incorporates a multi-tasking operating system called (VRTX) which optimises the speed requirements. The system includes a resident 'expert' system and databases to allow the welding engineer to meet the goals of their application more easily.

H Smartt et al (1989) sensed the current to monitor and control the heat and mass transfer of the base metal via a developed PID (Proportional Integral Differential) control model. They also studied droplet transfer by traditional signal analysis techniques such as Fast Fourier Transforms (FFT) and suggest that it is locally chaotic.

Vegaki et al (1984) produced a quality control system to improve the quality control of welding in the manufacture of large diameter pipes. The system comprised a business computer as the central control, a process computer to control all of the operations in the plant and several micro-computers for individual control of process parameters, seam tracking, feedback control etc.

The use of computers in welding, has become much more apparent in recent years. There have been several recent publications and conferences concentrating in this area (eg. Computer Technology in Welding, Cambridge 1992). Several authors have described the utilisation of computers for expert systems and welding orientated databases Such publications describe slightly differing methods of utilising expert systems for various welding defect prediction and optimal parameter selection, eg. G J Curtis et al, A J Dewhurst, J Crouch et al, Szu-Yuan Sun, S C Costa and J Norrish (all 1992).

Other authors have described various software packages to assist in parameter selection and welding procedure development (B Palatos (1992), L M Anisdahl et al (1992), S Anik et al (1992), H F Shaw (1992) etc.). Recent advances in this area also include the development of Robot simulation packages such as Grasp (J Weston 1992) for 3 Dimensional simulation of a robotic welding system.

Several researchers have attempted to study the arc stability of metal transfer during the last decade. The approach used for the investigation has ranged from general statistical investigations (eg. J Nunes 1982) to mathematical modelling based on basic arc physics (eg. P Kapadia 1991).

The review of the work that has been done in this area has shown that the techniques used for arc monitoring have evolved enormously in the last decade. At present, because of the cost of development and capital, it is the large manufacturers and fabricators that are benefiting from the progress made. However, as costs fall and techniques become established it is expected that cheaper quality monitoring methods will be produced.

The published research data described utilise either statistical or spectral analysis techniques in order to analyze the monitored data. In order to complete the objective of this thesis, it was necessary to investigate, understand and review several of the statistical and spectral techniques available to obtain the optimal method for quality assessment. The theoretical implications and the some of the applications of the techniques will be described.

2.7 The Fast Fourier Transform (FFT)

One of techniques used in the present work to analyze the quality performance of welding process was FFT analysis. Hence a basic introduction to the technique is appropriate. Fourier Analysis is a well known theorem which says that any periodic waveform can be represented by a series of sine and cosine waves. Hence, if a Fourier series can be written for a waveform, then the components of the series completely describe the frequency content of the waveform (Ramirez 1985). The general form of the Fourier series is commonly written as,

$$x(t) = a_0 + \sum_{n=1}^{\infty}(a_n \cos n\omega_0 t + b_n \sin n\omega_0 t) \qquad (2.7.1)$$

The Fourier series is a useful tool for investigating the spectra of periodic waveforms. A physical process can be periodic or non-periodic. When dealing with non-periodic waveforms the Fourier Integral is used. The Fourier Integral can be derived form the Fourier Series by allowing the period to approach infinity. A physical process can be either described in the time domain, by values of some quantity y as a function of time t, eg. y(t), or else in the frequency domain where the process is specified by giving its amplitude Y (generally a complex number including phase) as a function of frequency f, eg. Y(f). For many purposes it is useful to think of y(t) and Y(f) as two different representations of the same function. The movement between the two domains is achieved by means of the Fourier Transform equations,

$$Y(f) = \int_{-\infty}^{\infty} y(t)e^{2\pi ift}dt \qquad (2.7.2)$$

$$y(t) = \int_{-\infty}^{\infty} Y(f)e^{-2\pi ift}df \qquad (2.7.3)$$

If t is measured in seconds, then f in the above equation is in cycles per second, or Hertz. However, the equations work with other units. For example, if y is a function of position x (in metres), Y will be a function of inverse wavelength (cycles per metre), and so on.

For many common waveforms, the Fourier transforms can be obtained by referring to tables and charts in engineering handbooks. But in most practical cases, the real waveforms rarely match the idealised description in tables. For this purpose, a digital method was developed, whereby the waveform is digitised and the Discrete Fourier Transform is evaluated (DFT). A digitised waveform can be transformed to the frequency domain by applying the fourier integral over the window interval. By doing this, the following expression is obtained from the DFT,

$$X_d(k\Delta f) = \Delta t\sum_{n=0}^{N-1} x(n\Delta t)e^{-j2\pi k\Delta f n\Delta t} \qquad (2.7.4)$$

By performing additional manipulations the inverse DFT can be calculated,

$$X_d(n\Delta t) = \Delta t\sum_{k=0} x(k\Delta f)e^{j2\pi k\Delta f n\Delta t} \qquad (2.7.5)$$

The Discrete Fourier Transform (DFT) allows time series of samples to be transformed to a series of frequency domain samples and the Inverse DFT allows you to transform a series of frequency domain samples back to a series of time domain samples.

The (DFT) algorithm shows that the number of major calculations required to evaluate the DFT of n points is n x n. When calculating these on a computer when n is small the time taken to evaluate the DFT is not noticeable. However, as n increases above 16 say, even the faster computers can take several seconds for the calculations. Hence a faster method for evaluating the DFT is required. The Fast Fourier Transform (FFT) is a more efficient method of evaluating the DFT of a number of digital samples.

It is not necessary to describe how the method works since it would take several pages and is already printed in several books. It is only important to know that the Fast Fourier Transform is simply an efficient computational tool for accomplishing certain common manipulations of data (Flannary 1988).

Because of the complexities of the FFT algorithm, it is not generally used for more than 2048 data points. In practice, to evaluate the spectrum of an unknown waveform of high frequency, significantly more points are collected. Hence, as a signal processing technique, the FFT is not very useful for on-line measurement. However, it can be a valuable tool for pin-pointing desirable and undesirable frequencies, prior to hardware filtering.

2.8 Statistics and Modelling

2.8.1 Introduction

The development of faster processing speeds and high storage capacity in computers has meant that complex statistical algorithms can be included in the testing loop of a control system. This has led several researchers to attempt to develop optimised 'quality' models for the welding process. This section gives a brief description of the modelling techniques used with some examples of the current activity within welding circles.

A mathematical model represents a process or some aspect of a process by a set of deterministic or probabilistic equations providing quantitative relationships between the key process parameters and responses (Scotti 1991). A model is based on past variations in behaviour and has the ability to predict future events if applied correctly. Experimental Statistical Analysis, therefore, is an instrument to reach a mathematical model.

Recent work at Cranfield Institute of Technology (Modenesi (1990), Alfaro (1989), Scotti (1991), Paranhos (1990) etc.) have covered the subject of statistical modelling in welding in great detail. However, some specific concepts and weaknesses of statistical techniques must be introduced since they are necessary for a full understanding of this work. Thus, the following sections describe the various experimental statistical analysis techniques used.

Modelling involves creating an idealised understanding of a real world situation or system to help to understand its behaviour (Modenesi 1990). A model does not replicate a system, but contains the elements that the modeller considered important and was able to implement. Therefore there is not a unique model for a system, but several different models can be developed by using different interpretations of the system. It is important to emphasise that a model, whether physical or mathematical, should be based on physical principles, not simply chosen (Alfaro 1989). Modelling is a fundamental tool for knowledge formation. However, a model must not be confused with reality as this can lead to the inhibition of new ideas.

Three basic steps are required to produce a final model for a system.

a) **Model Formulation**

This is the most important phase because a badly formulated model cannot accurately provide the required response to the input variables. To formulate a model properly three important factors must be identified,

i. the most significant variables and processes
ii. the correct structure to represent the system
iii. the degree of interaction between variables.

These three factors may or may not be obvious depending the on the existing knowledge available for the process. If the theoretical principles governing the system are not all known then statistical and curve fitting techniques may have to be used. This phase involves the careful design of the required experiments.

b) **Model Calibration**

This is the fitting process. The measured data is used to optimise the model variables to give a best fit for the data. This may be done using both analytical and numerical methods such as multiple regression or finite differences.

c) **Model Verification**

This involves an analysis of the response of the model to various input conditions to make sure that the model output is rational. The model should be ideally tested with data that was not used for the calibration.

The following sections describe the various techniques required to obtain an optimal model.

2.8.2 Experimental Design

Scotti (1991) reported Galopin and Boridy as defining statistical experimental design as method of planning an experiment so that appropriate data can be collected and analyzed by statistical methods resulting in valid and objective conclusions. Whatever the objectives of an experiment are, no method of data analysis can ever overcome the handicap of poorly designed experiments.

The ideal design uses the smallest number of experiments, although they are significantly and equally distributed within the defined phenomenon contour. Recognition and statement of the problem are very important steps since they enable the choice of the significant variables and define responses and operational limits.

In applied statistics, the independent variables, or inputs, of a model are normally referred to as factors, or controlling parameters. The different values specified for the same independent variable in an experimental design are called levels (e.g., levels of factors). The output (dependent variable) is denoted as effect or response. The terms factors and responses will be used for this work.

The first stage of any statistical design programme is the selection of the factors and levels. To select them, it is important to keep in mind the experimental objectives. If the operational field is known and the objective is, for instance, to find the optimum working point, the extreme factors are automatically defined. However, if the objective is to find an operational field or to predict the effect of the variables, more practical investigations are usually necessary.

The second step is to choose the number of levels ie.,

(i) The number of levels for each factor to be considered.
(ii) The level range.
(iii) The spacing of each level.
(iv) The number of observations for each level.

These choices will differ for each situation, however, the decisions made at this stage may have a significant effect on the final outcome.

The definition of the level range to be used is also critical. If the range is too wide, the normal supposition of linearity may be invalidated. Whereas, a very short range can lead to errors due to the variance of the parameters. In addition, in many welding processes some parameters are closely related to others, due to either limitation of equipment and/or physical constraints of the system. This may obstruct ideal design strategies and cause complications during further data analysis.

A number of observations of the same factor and level (defined as replicates) is essential in order to estimate the experimental error. This will improve the confidence factor of the final model and avoid errors caused by a spurious event caused during a particular set of observations.

The Single Factor method is a very common technique in designing of experiments. The level of the factors is varied one at a time while the remaining factors are held constant, However, this technique does not cover all possible combinations, but this approach is very useful in the early stages of an experimental program. It is very suitable for exploratory trials to define the range and number of levels necessary for a final design.

One of the most suitable techniques for designing experiments in welding applications is Factorial Design. In this approach all possible combinations of the factor (parameter) levels are investigated, providing the smallest number of trials with which k factors can be studied. Single Factor design requires at least $(k + 1)/2$ times as many runs as the factorial technique to secure the same precision for the estimate (Box et al., 1978).

Factorial design also allows the detection of the effects of interactions at several levels, yielding conclusions that are valid over a range of the experimental conditions. Interactions can be illustrated, for instance, by the effect of a cross-product of two or more factors (Scotti 1991).

The simplest factorial design is the 2^k Factorial Design technique. Each of the k factors is used at only two levels, i.e., a "high" and a "low" level. A complete experiment of this kind requires 2^k trials. If a linear relationship among the factors cannot reasonably describe the phenomenon, more than two levels are required and the number of experiments rises. When the number of factors is high and high-order interactions can be neglected, fractional factorial designs can be used as a means of reducing the number of runs. Half factorial and a quarter factorial designs are most commonly used. The use a slightly modified factorial design approach for scheming the experiment, such as including a central point, may enhance the design concerning the ability to identify no-linearity in the response curve. However, it is advisable to use more than two levels as a means of dealing with this situation.

2.8.3 Regression Analysis

It is natural to investigate the extent to which one variable is related to another and to require some numerical representation of the relationship (Dolton 1989). Regression and correlation provide a set of techniques for dealing with these issues. The progress in computer technology during the last two decades has brought about significant changes in the analyses of complex experimental data. Regression Analysis has become much more accessible for more complex models and increasing number of variables. In addition the output from regression equations is more useful in control applications.

Regression Analysis techniques fit models relating one dependent variable, known as the response, to independent variables, known as the factors, by minimizing the sum of the residuals for the fitted line. This technique allows a more quantified study of the variables. Regression Analysis can also be used to predict new values of the dependent variables based on observed relationship.

The number of factors involved describes the type of regression technique to be used. Simple Regression relates the response to only one factor. Whereas, for multiple Regression the relation is widened to many factors. The fitting technique can produce both linear and non-linear relationships between the dependant and independent variables.

Each procedure has its own features and uses. Multiple (linear) Regression Analysis seems, however, to be appropriate for most practical welding situations.

Simple Regression

The basic regression model assumes that the values of one variable Y, are linearly related to the values of another variable X, but that the relationship is not exact. This may be written as,

$$Y = a + bX + \text{an error} \qquad (2.8.1)$$

The most common procedure for computing a, the intercept, and b, the slope coefficient, is the least squares method. Once values for a and b have been obtained, a predicted value of Y based on a given value of X can be computed. The least squares method involves choosing a and b so that the sum of the squared deviations

$$\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2 \quad \text{is minimised} \qquad (2.8.2)$$

where $\hat{Y}_i$ is the deviation of any point from the regression line.

Graphically, this means that a straight line is chosen that minimises the squared vertical distances between the line and the dots in the scatter diagram. Hence,

$$\text{since } \hat{Y}_i = a + bX_i \qquad (2.8.3)$$

$$\text{we minimise } \Sigma(Y_i - a - bX_i)^2 \qquad (2.8.4)$$

Taking partial derivatives of this function with respect to A and B, and then setting resulting equation to zero:

$$\frac{\delta\Sigma(Y_i - a - bX_i)^2}{\delta a} = -2\Sigma(Y_i - a - bX_i) = 0 \qquad (2.8.5)$$

$$\frac{\delta\Sigma(Y_i - a - bX_i)2}{\delta b} = -2X_i(Y_i - a - bX_i) = 0 \qquad (2.8.6)$$

Simplifying the two equations with two unknowns,

$$\Sigma Y_i - \Sigma a - b\Sigma X_i = 0 \qquad (2.8.7)$$

$$\Sigma X_iY_i - a\Sigma X_i - b\Sigma X_i^2 = 0 \qquad (2.8.8)$$

or

$$\Sigma Y_i = na + b\Sigma X_i \qquad (2.8.9)$$

$$\Sigma X_iY_i = a\Sigma X_i + b\Sigma X_i^2 \qquad (2.8.10)$$

and solving for a and b we obtain

$$b = \frac{\Sigma X_i Y_i - (\Sigma X_{i\Sigma} Y_i)/n}{\Sigma X_{i2} - (X_{i2})/n} \qquad (2.8.11)$$

$$a = (\ \Sigma Yi - b\Sigma Xi\ )/n \qquad (2.8.12)$$

where n is the number of points.

Goodness of Fit

The usefulness of the mean as a summary statistic depends on the degree of dispersion in the data (Wittink 1988). In the same way, the usefulness of the regression line as a summary of the relationship between two variables also depends on the degree of dispersion in the data.

Using the equations above, the best fit line between a set of points can be plotted. The difference between an actual value (Y_i) in the sample and a fitted value ($\hat{Y}_i$) is called a *residual* (u_i). Note that the sum of the residuals should equal or approach zero. One method of testing the goodness of fit is to calculate the sum of the squared residuals (Σu_i^2). However, it is difficult to use only this quantity as it depends on the unit of measurement of the variable being considered. One way to overcome this problem is to compare the sum of the squared residuals with the sum of the squared deviations from the sample mean (u_i^2)/(Y_i - Ym).

If we separate the total amount of variation in the criterion variable into two parts, explained (accounted for) and unexplained (not accounted for) a relative measure of goodness of fit is obtained by taking the ratio of the explained variation over the total variation.

$$R^2 = 1 - \frac{\text{(Unexplained variation in Y)}}{\text{Total variation in Y}} \qquad (2.8.13)$$

since the unexplained variation equals the total variation minus the explained variation.

R^2 is often referred to as the coefficient of determination. Formally in equation form we have

$$(Y_i - Y_m)^2 = (\hat{Y}_i - Y_m)^2 + (Y_i - \hat{Y}_i)^2 \qquad (2.8.14)$$

Total amount of variation	Explained amount of variation	Unexplained amount of variation

Hence R^2 may be expressed as:

$$R^2 = 1 - \frac{(Y_i - \hat{Y}_i)^2}{(Y_i - Y_m)^2} \qquad (2.8.15)$$

For the simple linear model, the largest possible value is $R^2 = 1$, and the smallest is $R^2 = 0$. These indicate perfect fit and complete lack of fit respectively.

The Correlation Coefficient

The correlation coefficient measures the degree of linear association between two variables, X and Y. Correlation analysis is used to test the strength of relationship without calculating its coefficients. The correlation coefficient is the square root of R^2 (r). A positive correlation coefficient indicates that as one variable increases in magnitude, the other variable also tends to go up. Conversely, a negative correlation coefficient indicates that as variable increases in magnitude, the other variable decreases in magnitude. If the correlation coefficient is zero, there is no linear relationship between the two variables. It can be shown that the correlation coefficient is also related to the slope coefficient in simple regression. Specifically, it can be shown (Wittink 1988) that

$$r = b \frac{Sx}{Sy} \qquad (2.8.16)$$

where Sx is the standard deviation of X.
Sy is the standard deviation of Y.
r is the corellation coefficient.
b is a constant.

Multiple Regression

Multiple Regression Analysis is widely used in experimental situations where the experimenter can control the independent variables (more than one key independent variable almost always influences the response) (Scotti 1990). It is based on the assumption that a certain response Yi is adequately described by a first-order linear model (linear in the parameters and linear in the independent variables) with k factors (xi), i.e.,

$$y = \alpha + \sum_{i=1}^{k} \beta_i x_i + u_i \qquad (2.8.17)$$

where α and β_i are unknown parameters and u_i is the experimental error.

A first-order model with more than two factors works in exactly the same way as for two, but as the regression response is a hyperplane, it is no longer possible to visualise it in simple geometrical terms. Whatever the order of the model, the major assumptions made in regression analysis are:

(a) the errors (u_i) are assumed to have mean zero and constant variance σ^2

(b) the errors (and consequently the dependent variables) are non-correlated (do not depend on the value of any other error) and normally distributed.

Regression analysis is based on the calculation of the sum of squares of the residuals. The technique used to obtain the regression coefficients is described in many books about the subject (eg. 'The application of Regression analysis by D Wittink, 1989). There are also now several computer packages (eg STATGRAPHICS, SPSS) which allow the use of the technique without much theoretical knowledge from the experimenter.

One of the most difficult problems in regression is often the selection of the independent variables (factors) to be employed in the model (Scotti 1990). The Stepwise Regression methods are probably the most widely used amongst the automatic search methods (Neter et al, 1983). Primarily, this search approach develops a sequence of regression models, at each step adding or deleting an x variable. The criterion for adding or deleting the variables can be stated equivalently in terms of error sum of squares reduction, coefficient of partial correlation or F* statistic, as defined by the routine or experimenter. The **F^*** statistic is the most common. The Forward Selection procedure begins with no variable in the model and adds one at a time provided that the new variable adds significantly to the model. It also checks at each stage whether the previously selected variables are still significant, variables that become insignificant are removed. The Backward Selection procedure is the opposite of forward selection. It begins with the model containing all potential x variables and identifies the ones with the smallest **F*** value to be dropped. Some stepwise routines have, in addition, options for forcing or removing variables into the model.

It is important to point out that stepwise regression procedures do not guarantee that the best subset model will be identified. Furthermore since all stepwise-type procedures terminate with one final equation, an unskilled analyst may incorrectly conclude that an optimal model has been found.

Model Adequacy Checking

Once the dependent variables have been chosen and the regression coefficient calculated, the next step is to assess the adequacy of the model, when the suitability of the model is studied and the quality of the fit determined. The quality of the fit is analyzed and if necessary further modification of the model takes place. There are numerous statistical techniques for this type of analysis and the most important ones are always available after computation.

The **F*** statistic is a common parameter for testing significance in the selection of the independent variables. The object of this test is to determine whether there is a linear relationship between the response Y and any variables X. Significance does not imply importance but describes real effects that are not due to random fluctuations (noise) of the process.

Summarizing the range of useful techniques mentioned:

(i) The coefficient of determination (R^2) may be interpreted as the relative reduction in the total variation associated with the use of the independent variable in a simple regression model. Thus, the greater is the value of r^2, the more is the total variation of y reduced by introducing the independent variable x.

(ii) The coefficient of correlation (r)

(iii) F-Ratio is the ratio of the model mean square to the residual mean square (MS_R/MS_E).

Collinearity

For many experimental situations the independent variables may tend to be correlated among themselves and with other variables that are related to the dependent variable, but not included in the model. This type of correlation, known as collinearity, can induce many problems in regression modelling, such as to exaggerate or change the sign of the coefficients estimates or prediction of unrealistic values. However, this does not curb the ability to obtain a good fit to the data. It is strongly recommended that tight experimental supervision is kept in order to avoid correlated independent variables whenever possible. Where this practice is not feasible, the methods for detecting multicollinearity are advisable. A variety of such methods can be utilised.

Qualitative Diagnostic techniques that Indicate if Collinearity exists

(i) The appearance of large coefficients of correlation between pairs of independent variables in the correlation matrix (Correlation Analysis).

(ii) The evaluation of large changes in the estimated regression coefficients when a variable is added or deleted, or when an observation is altered or deleted.

(iii) The appearance of estimated regression coefficients with an algebraic sign that are opposite to those expected.

These qualitative methods have significant limitations. They do not provide quantitative measurements of the effect and the characteristics of multicollinearity. Another limitation of such methods is that sometimes the observed behaviour may occur without multicollinearity being present. The presence of serious multicollinearity often does not affect the usefulness of the fitted model provided that the values of the independent variables for which deductions are to be made follow the same pattern as the data on which the regression model is based.

The presence of multicollinearity may be tackled in many ways, such as expressing the independent variables in form of deviation from the mean in polynomial regression models. However, the problem can be statistically treated by modifying the method of least square to allow biased estimation of the regression coefficients. When an estimator has only a small bias and is substantially more precise than an unbiased factor, it may well be the preferred estimator since it will have a larger probability of being close to the true parameter value.

The 'Ridge Regression' analysis (Scotti 1990) technique provides estimators by introducing into the least square normal equations a constant (ridge parameter) $\theta \geq 0$. This constant reflects the amount of bias in the estimators (when $\theta = 0$, the equation reduces to the ordinary least squares regression coefficients). A commonly used method of determining the biasing constant θ is based on the ridge trace (a simultaneous plot of the values of the estimated standardised regression coefficients for different values of θ). The choice of the value to be used is subjective. As a guide, the smallest value of θ is used where it is deemed that the regression coefficients first become stable in the ridge trace.

In addition to the 'Ridge Regression' technique, there are other remedial measures for multicollinearity. These include 'Regression with Principal Components', where the independent variables are converted into a linear combination of the original independent variables and 'Bayesian Regression', where known information about the regression coefficients is included into the estimation procedure.

Weighted Regression

The least squares technique emphasises each observation equally. However, there are occasionally cases when some observations require greater emphasis than others. For such occasions a 'Weighted Least Square' technique can be carried out during the multiple regression analysis. This special case should be used when the error term variance is not constant for all observations. Observations with error terms that are subject to large variance should receive less emphasis.

Dummy Variables

For occasions when the variables of interest are not quantitative but are qualitative eg., investigation of consumables, quantitative indicators for the category of the qualitative variables can be used during the regression analysis. Such indicators are known as 'dummy variables' and can be selected in order to describe particular classes of qualitative information.

2.8.4 Model Validation

The previous sections describe the various methods of designing the optimal data collection and data analysis techniques. Once a model has been developed the next step is to validate this model.

Model validation is different from Model Adequacy Checking. Influential factors not known during the model building stage may significantly affect new observations. Proper validation of a model should involve testing the model in the environment before it is released to a user.

Scotti (1990) and Montgomery and Peck (1982) suggests that three techniques are useful for model validation:

(i) Analysis of the model coefficients and predicted values including comparison with prior experience, physical theory and other analytical models or simulation results.

(ii) Collection of fresh data with which to investigate the model performance.

(iii) Data splitting - excluding some of the original data and using these observations to investigate the model's predictive performance.

The authors suggest that validation techniques should concentrate on the type of end use required, eg. validation of a model intended for use as a predictive equation should concentrate on determining the model prediction accuracy. However, since the analyst often does not necessarily control the use of the model, it is recommended that whenever possible, all available validation methods above should be employed.

2.8.5 Modelling and Welding

Several researchers have worked on the modelling of welding processes. These studies range from modelling of the weld bead geometry (eg. Modenesi (1990), Alfaro (1989), Scotti (1991), Andersen (1989) etc.) or modelling the weld reinforcement (Nishiguchi et al, 1977) to modelling the arc itself Kapadia and Dowden (1991). Weld Modelling is important for advancing the knowledge on the mechanics of weld processes and how they can be best controlled and utilised (Andersen et al, 1989).

Several researchers have attempted to model the weld bead geometry using different approaches. A review of the work carried out in this area was given by Shinoda and Doherty (1978) and by McGlone (1982). However, the researchers have adopted different approaches to tackle the problem. Alfaro (1989) , Modenesi (1990) and Scotti (1991) have all attempted to solve the problem by using traditional design methods and factorial design techniques together with stepwise multi-variable linear regression methods to determine the variable constants.

S D Smith (1992) produced a review of various weld modelling techniques for the prediction of residual stresses and distortion due to fusion welding. Several thermal and mechanical modelling techniques are described including finite element analysis methods. It is suggested that weld modelling techniques are dependant upon data from the experimental welds which can limit the effectiveness of modelling in many applications.

Galopin et al (1992) have produced software to optimise the modelling methods for procedure and process optimisation. The operating field of the welding process is defined as a multi-dimensional ellipsoid which discriminates between accepted and rejected experimental tests. The unique strategy then utilises regression techniques to optimise the models. The authors claim successful modelling of several welding situations.

Andersen et al (1989) and Stroud et al (1991,1992) have opted for a more novel approach by using artificial neural networks. The former method requires obtaining the data in a controlled manner and fine tuning the model by testing it with further experiments. Whereas, the latter technique involves the 'training' of artificial neural networks to automatically learn the required model by setting the output requirements. The traditional methods require some understanding of the physical process which means that the model is more useful in understanding the process. By using neural networks, the system will automatically calculate control gains for the output and these will only relate to the output conditions set by the user. On the other hand, neural networks have the advantage that the experiments required to attain the required welding specifications can be minimised.

From the review of the present research in modelling of the welding process, it is apparent that as the requirements for greater quality and efficiency increase, the quest to optimise the models for quality will be enhanced.

2.9 The Quality Assessment of Welding Wires

2.9.1 Introduction

The British standard relevant for solid GMAW welding wires is BS2901, (BS2901 1983). This standard gives quality control standards in terms of chemical composition limits, diameter, tolerances, spool sizes and weights. The chemical composition limits are fairly loose allowing a considerable variation in important elements which may effect both strength and wire strength. The standard makes no reference to the internal condition of the wire, the surface condition or temper. In the case of solid and flux cored wires the composition and dimensions of the consumable may fall within the limits defined in the standards. A similar (BS 7084) standard defines requirements for flux cored wires for Carbon/Manganese steels.

Several researchers have studied the factors that determine good weld quality and how to control it (see section 2.3). One of the factors controlling weld quality is the quality of the welding consumable. However there is little published work on the best methods of assessing the quality of welding wires.

The effects of the quality of aluminium welding wire have been investigated by some authors. I F Scott (1983) studied various parameters as a part of a major research programme for the specification of aluminium welding wire. Wires of known quality were compared to observe their consequence on soundness (porosity etc), wire feed rate consistency, penetration, bead shape and electrical signals were all studied in turn, together with welder skills.

The work demonstrated that wire quality can have major effects on weld quality. It was shown that both penetration and bead shape were affected. In some cases the bead width was also different at the same welding conditions. In other cases, the current required to weld at a set wire feed rate was higher for low quality wires. Spatter was also increased in such cases. In terms of the electrical characteristics, the researcher observed a greater 'spread' in the voltage and current signals for 'bad' wires even when metal transfer was good. It was suggested that the largest differences were observed in the porosity analysis.

In the case of solid steel wires for GMA welding variations in operating performance have been noted with consumables of nominally the same composition. This has been explained by minor changes in REM content and surface conditions (J Norrish 1992). These variations have not, however, been easy to correlate with specific wire analyses and in practice are often only detected by manual welding trials.

The use of sensors and computer control in production allows a more stringent control on the flux composition. Fluxes and wires created for use with microprocessor controlled automatic welding processes do need to be compositionally consistent and homogeneous. The welding consumable plays a very complex role in the welding process. Components of these consumable must protect the weld deposit, generate acceptable plasma, stabilise the arc, influence the bead morphology and promote the ability to weld out of position.

D L Olson (1989) described the technological advances and needs for future welding consumable. The advances are described in terms of either chemical or physical behaviour of the welding flux. Olson summarised the following consumable research requirements and noted in particular the need to:

> "Develop consumable for microprocessor controlled welding processes via research such as developing methodology to produce consistent and homogeneous welding fluxes or determining the physical behaviours of welding flux that can be sensed to control consumable welding process behaviour".

Some of Olson's suggestions are already being investigated by consumable manufacturers. Whilst the improvements in automation technology will force others to produce more consistent products. The work carried out for this thesis involves determination of operating performance in the GMAW process with flux cored wires and a brief description of tubular cored welding wires used for the GMAW process is appropriate.

2.9.2 Tubular Cored Wires

Cored wires are typically manufactured from a continuous flat steel strip, formed into a U shape and filled with flux powder (Widgery 1989) The exact composition and mixture of the constituents is often computer controlled. Once mixed, the flux powder is fed into the U shaped wire. (This stage can also be computer monitored). The steel strip is then drawn down through a series of reducing dies to a diameter of 1.6 mm, often using a Calcium drawing soap. After drawing is completed the wire is wet washed with detergent to remove the drawing soap prior to winding onto a drum for baking. Baking is carried out for 12 hrs at 300°C, after which the wire is lubricated with lanolin and graphite before being wound onto individual reels.

Alternative production processes involve either filling a preformed tube which is subsequentially drawn down to size, roller reduction or dry drawing though diamond dies. Each process leaves scope for variation in flux composition, fill rate, flux homogeneity and surface condition; all of which may affect subsequent welding performance.

The flux provides protection from atmospheric contamination, de-oxidation, arc stabilisation and alloy addition. The composition can be varied in order to give different weld metal properties. Tubular wires can be classified into three groups according to the composition of the core materials, ie ***Gas Shielded Flux Cored Wires*, *Metal Cored Wires* and *Self Shielded Flux Cored Wires*.**

Gas Shielded Flux Cored Wires may be used with either Carbon Dioxide or Argon rich shielding gases. These can be either of the basic or rutile type. The basic welding wires contain basic slag forming properties and deposit metal with good mechanical properties and can deposit hydrogen controlled weld metal. The rutile welding wires have spray arc smoothness even at low current settings. The special slag formulation of the rutile wires enhance their positional welding capabilities.

Metal Cored Wires contain mainly metal powder with small amounts of de-oxidants and arc stabilisers added. They have a high recovery rate with minimal interpass slag. This makes them especially suited for robotic welding and applications with multi pass welds. They have high deposition rates in the flat position, excellent quality and weld appearance and high travel speeds because of their stable arc characteristics.

Self Shielded Flux Cored Wires are used without an additional shielding gas and are useful in situations where draughts make the gas shield ineffective. The core contains slag forming constituents, materials which release shielding vapours and de-oxidisers and de-nitrifiers to remove Oxygen and Nitrogen from the liquid metal.

Some researchers have investigated the burn off characteristics of cored wires. Ter Haar (1974) developed a relationship between the melting rate of the sheath to the current, electrical stick-out and cross sectional area,

$$M_s = a + b.I + c.s.I^2/A \qquad (2.9.1)$$

where
M_s is the melting rate of the sheath in g/min
I is the current in amps
s is the stick-out length in mm
A is the cross sectional area in mm^2
a,b,c are constants dependant on shielding gas and wire type

Flux cored wires have greater burn off rates than solid wires. This can be attributed to the small cross sectional area producing high current densities. The flux fill is a poor conductor hence most of the current passes through the sheath (1979). With metal cored wires some of the current is carried by the core. Further studies by Matsuda et al (1980) have shown that the melting rate of rutile flux cored wires decreased with increasing iron powder in the core. This is attributed to a decrease in electrical resistance of the core, thereby reducing the current density in the sheath.

2.9.3 Wire Quality Control Testing

A welding consumable must be able to deposit sound weld metal in a reliable and consistent manner (1989). To achieve this there must be a stable metal transfer across the arc. The standards relating to tubular wires (BS 7084 & AWS AS.20) do not mention this and the 'weldability' of a wire is determined by the manufacturer.

The quality of the welding wires are usually determined by a manual welding test run to an established welding procedure (ESAB 1990). The welding performance of the wire is judged subjectively by a trained welder on the basis of observations described in the welding procedure. This subjective judgement is heavily dependant on the welder's level of training, skill and experience.

The surface condition of the wire can be tested by a 'shorting test'. This is done by feeding out 2m of wire and shorting it to earth. The level and type of fume evolved indicates the amount of soap and lubricants present on the surface. Finally, a test is performed to assess how easily the wire feeds through a conduit. This is done by monitoring the current that the wire feeder draws during welding.

On the basis of these tests, the wires are typically graded either 'A', 'B' or 'C'. A wire that is graded 'C' is considered a failure. Wire production is halted and further testing is carried out to confirm the results of the welding tests. If the results are confirmed, the source of the problem must be discovered before production can continue.

The source of failure is difficult to locate using these techniques as it is dependant on welding skills and observed assessments such as 'didn't sound right' or 'too much wire'. Such assessments although useful cannot quantify the weld results in a manner that would aid in the continuation and improvements of the wire quality.

It is apparent from the literature, that many researchers are aiming to incorporate microprocessor based monitoring systems into their systems with a view to reduce the 'human factor' to a minimum. With increasing automation the desire for optimising the quality of manufacture with minimum costs is a priority. The object of this work was to monitor the electrical properties of the arc with an aim to produce a repeatable technique to aid in the objective assessment of wire quality.

3. PRELIMINARY EXPERIMENTAL WORK

3. PRELIMINARY EXPERIMENTAL WORK

3.1 Introduction

The objective of the research was to study the electrical properties of the arc with an aim of producing a tool to aid in the performance assessment of wire quality. The previous method of wire quality testing was performed by an experienced welder with a preset welding procedure (Appendix A). It was known that the welder subjectively grades the wires by 'watching' and 'listening' to the arc for stability and consistency during the welding test. Hence, any objective technique established, must agree with the welder's assessment.

3.2 Experimental Procedure

Welding Equipment

Power Source

All of the preliminary work was carried out using a GEC Control Arc 500 Power Source. This was a multi-process inverter based power source, capable of producing synergic control of spray, pulsed and dip transfer GMA welding conditions as well as the TIG and MMA processes. It can produce either a constant current output or a constant voltage output.

Wire Feeder

A GEC '2D' wire feeder was used to drive the wires through the torch. This wire feeder receives its demand signal directly from the power source and has a built in optical encoder to control the output. The wire feeder also has gas solenoid and pre/post purge controls via the power source.

Welding Torch and Table

A LINDE ST-5M water cooled welding torch was positioned vertically above a moving table to produce automatic 'bead on plate' down hand welds. The table travel speed was continuously variable and calibrated on mm/sec.

Monitoring Equipment

In order to monitor and collect the transient changes in the welding signals the DATA HARVEST Databox was used. This can monitor up to eight analogue channels at a maximum sample rate of 4 kHz per channel with eight bit resolution and no isolation. However, this was a general purpose data logging unit, which expects a 0 to 2.55V input to give 256 digital levels. In order to monitor the welding signals, a general purpose signal conditioning unit was designed and built. This comprised four analogue channels with an input range of 0 to 10 V, plus four different gain settings and offset settings so that the transient could be digitised optimally.

Since one of the methods used by the experienced welder to assess the welding is to 'listen' to the arc, it was thought that it may be possible to utilise the sound from the arc measured via a microphone. However, since the microphone produces a small amplitude ac signal, a high gain amplifier circuit was designed and built to plug into another channel in order to amplify the output from a microphone.

The light emission from the arc was measured by using a RS general purpose photodiode (RS No. 305-462). This was placed in a protective metallic tube and insulated from the surrounding steelwork. Neutral density filters were placed in front of the sensor to regulate the incident light.

The wire feed rate was initially measured by connecting a DVM to the output terminals of the wire feed unit (the drive signal to the motor) and later by using a Data Harvest Wire feed sensor which was calibrated to give a 0.08V/m/min output.

The mean current and voltage were initially measured using a MONARC 5000 Data Logger. The mean current was measured by using a RS Hall Effect probe connected to the positive welding cable. The mean voltage was measured directly between the contact tip and the work piece.

Arc Length Measurement

The arc length was measured by using a video camera aimed at the arc via a filter. The system was calibrated by attaching a clear plastic film in front of the visual display and aiming the camera at a ruler next to the welding torch. Parallel horizontal lines were drawn across the film from which the measurements of arc length could be made. (Fig 3.1).

Welding Consumables

All welds were bead on plate deposited in the down hand position. The base material was 6 mm thick mild steel for the dip transfer experiments and 12 mm thick mild steel for pulsed and spray transfer experiments. The gas used was initially ArgoShield 5 (ie. 93% Ar, 2% 0_2, 5% CO_2).

Seven different rolls of tubular cored wires were provided by ESAB Ltd to for the investigation. All of the wires were 1.6 mm diameter and nominally of the same composition. However, only one (Coromig 57) was classified as an 'A' wire according to the manufacturers' own quality test and was used as the reference wire for the purposes of this project. It was drawn using Ca 'Steel Skin' soap and baked at 300 C for 12 hours. The remaining six wires were considered to have failed the test and could be placed into two groups as follows:

Group I:

These wires were of the same chemical composition as the reference wire but had different Oxygen levels in the iron powder fill.:

1. **GM10** - 344 ppm Oxygen
2. **GM11** - 498 ppm Oxygen
3. **G12** - 72 ppm Oxygen

The oxygen level in the GM11 wire was considered the standard for cored wires prior to baking. This group of wires were drawn using the same soap as the reference wire but were not baked. The soap was clearly visible on the surface of the wire as a white powder.

Group II

This group of wires had the same chemical composition and Oxygen levels of fill (498 ppm) as the reference wire but were drawn using different soaps:

1. **TF44** Ca Soap but of different composition
2. **5.2.1** Na Soap, considered to be equivalent to Ca Soap used for the reference wire.
3. **5332** Production CoroMIG 57 drawn using a Ca soap of unknown origin.

Procedure

The microphone was positioned 1 m from the welding arc at an angle of 45 degrees to the horizontal. The light sensor was positioned 60 cm from the welding arc in the same plane (Fig 3.2).

The Databox was programmed to acquire data at its fastest rate (4 kHz) to monitor the voltage, current, sound and light giving an inter-sample time of 1 msec. The Databox has a memory of 32768 samples which meant that 8.192 seconds of welding could be logged at a time. All of the data acquisition (with the Databox) took place during the most stable region of the continuous welding once the arc had been established.

Bead on plate welds were carried out using the dip transfer, pulsed and spray GMA Welding processes. The optimum welding parameters for each process condition were established and set up from experience and trial and error basis with the reference wire. The experiments were then repeated using the same parameters with the 'bad' wires.

Process Parameters

Dip Transfer Experiments

The optimum welding conditions for 'good' welding were found at wire feed rates of 2.5 m/min and 3 m/min at a stand-off of 15 mm, using the reference wire. The experiments were repeated for the other test wires, keeping all of the parameters constant. Only, the wire feed trim was adjusted to prevent stubbing.

Pulse Transfer Experiments

In this mode, the power source maintains the peak current (Ip) and the peak time (Tp) and varies the background time (Tb) and the background current (Ib) in response to fluctuations in arc length. The optimum welding conditions for 'good' welding were found at wire feed rates of 3 m/min and 4.5 m/min at a stand-off of 20 mm, using the reference wire. The experiments were repeated for the other test wires, keeping all of the parameters constant. Only, the voltage trim was adjusted to set the arc length. A nominal arc length of 6 mm was used for the experiments.

Spray Transfer Experiments

The optimum welding conditions for 'good' welding were found at currents of 280 A and 300 A at a stand-off of 25 mm, using the reference wire. The experiments were repeated for the other test wires, keeping all of the parameters constant. Only the Voltage Trim control (Wire Feed Rate Adjust) was adjusted to set the arc length. A nominal arc length of 6 mm was used for the experiments.

3.3 Data Analysis

In order to utilise the data captured with the Databox, a general purpose software program was written in 'C' which converted the data files from the databox to ASCII format and also truncated the data from 8192 samples per channel to 1024 samples per channel. This was done so that standard mathematical and statistical packages such as MATHCAD could be used for analysis.

For the analysis of dip transfer, another software program was written in TURBO BASIC to separate the data into the arcing period and the short circuiting period. This program also plotted the best fit lines for voltage and current characteristics in either period.

For statistical processing, another program was written (in Microsoft 'C' V5.1). This program calculated the following values for each experiment:

i. The mean value of each signal.

ii. The standard deviation of each signal.

iii. The standard deviation of cycle time and the ratio of arcing time to short circuit time (only for dip transfer mode)

iv. Peak and mean background values for each signal and their associated standard deviations.

v. The standard deviation of cycle time for pulse mode.

The FFT of the light signal was also plotted for each experiment using the standard data analysis package MATHCAD. However, due to memory and speed limitations of the computer, the data had to be truncated further to 256 points.

3.4 Summary of Results of Preliminary Experimentation

Experiments	Reference Wire	'Bad' Wires
Arc Sound	It was found that the microphone used for monitoring the sound signal and also the associated signal conditioning was not suitable for the experiments due to an over sensitivity to noise. Hence, the preliminary investigation of the sound signal was abandoned.	
Spray Transfer	* True spray transfer. * Very stable metal transfer. * Weld bead shape good. * Very little spatter. * Stable arc length * V/I characteristics similar for all current settings.	* Marginal globular/spray transfer observed at 280A. * True spray transfer at 320A. * Higher arc length fluctuations * Increased spatter at 280A. * V/I characteristics data more spread at 280A. * Higher Std.dev. of arc voltage than reference at 280A. * Higher Std.dev. of arc light than reference. * Mean wire feed rates higher for 'Group II' wires.
Pulsed	* Good Weldability * Good bead appearance * Virtually no spatter * Light signal closely follows voltage. * V/I Characteristics similar for both 'Good' and 'Bad' wires.	* Good Weldability * Good bead appearance * Slight spatter in 'Group I' wires * Higher wire feed rates * Background amplitude higher * Background period shorter than reference.
Dip Transfer	* Most stable 'sounding' arc. * Good weld bead shape. * Good wetting angle. * Low spatter.	* Very unstable arc * High spatter * 'Group I' wires more stable than 'Group II' wires. * 'Group II' wires produced better wetting angles and bead shapes than 'Group I' wires. * No correlation to Light data observed.

3.5 Discussion of Preliminary Work

The main factors that contribute to the weld quality are arc stability, spatter levels, bead shape, positional capabilities etc. These in turn are directly related to metal transfer, therefore in assessing the quality of a consumable, the stability of the metal transfer is of prime importance. In order to achieve stable welding conditions, the metal transfer must be regular, giving acceptable weld deposits which can be related to wire quality.

For optimum stability with flux cored wire welding the droplet melting must be balanced with the droplet transfer rate. The droplet transfer rate (burn off rate) influences the droplet size and droplet frequency and these are the main parameters that relate to the stability of the process.

Spray Transfer Experiments

This mode of transfer is characterised by a continuous arc between the consumable wire and the workpiece and the metal is transferred across the arc in discrete droplets. The droplet size and transfer frequency depend on the arc current and the welding voltage. At low currents, transfer is globular, with droplets larger than the wire diameter, metal transfer is largely due to gravitational forces and this causes undesirable instabilities and spatter.

As the current is increased, the size of the droplets decrease and the droplet frequency increases. At a particular droplet size and frequency, the droplet size becomes minimum and the droplet transfer frequency is at its maximum. The current at which this occurs is known as the spray transition current. The electromagnetic force dominates the metal transfer.

It was found that only the reference wire gave spray transfer at 280A at the desired arc length. The burn off rate for steady state open arc welding is given by the expression (Halmoy 1976),

$$w = \alpha . I + \beta . L . I^2 \qquad (3.5.1)$$

where α is the arc heating constant
β is the resistance heating constant
L is the electrical stick out
I is the arc current

Variations in the burn off rate of different wires can therefore be related to differences in either of the two heating constants, α and β. The α term is dependant on the polarity and the composition of the electrode. This implies that the presence of soap on the surface of the wire has little affect on the α term. The β term is dependant on the resistivity of the wire.

Matsuda (1979) suggested that the resistance of the wire is influenced by the ratio of iron powder in the core. The spray experiments indicated that the 'Group I' wires which had differing oxygen levels and were unbaked. This suggests that they have differing core resistances (β values) thus causing different melting rates. The 'Group II' and reference wires have similar oxygen content and baking procedure. The type of soap being the only difference. The type of soap must therefore have a direct influence on the resistive component.

Variations in arc length can be attributed to changes in arc voltage. Variations in arc voltage may be caused by either changes in stick out or changes in the length of the arc column. Since the stick out was nominally kept constant in these experiments, fluctuations in the arc voltage may be directly related to variations in the arc length.

At 280 Amps, the standard deviations of the arc voltage indicated that the 'GM12' provided lower variations in arc length than even the reference wire. However, this did not agree with the observed behaviour. Whilst, other wires such as GM10 gave low standard deviations even though some short circuiting was observed. This work suggested that the standard deviation of arc voltage was not a very reliable indicator of performance at currents below the spray transition current. Conversely, at 320 Amps a definite correlation was observed between the observed arc length variations and the standard deviation of the arc voltage.

The slope of the V/I characteristics did seem to give the best indications of the wire quality, although there were differences in the relationship between the observed stability and the calculated slope for the wires which did not agree.

A study of the transient waveforms plotted from the acquired digital data, showed that although variations in the arc voltage and current were clearly observed, there was no clear indication of droplet detachment in the waveform. This may explain why the FFT calculations of the light signal data did not give any useful indication of droplet detachment stability. (This problem was believed to be due to the inadequate speed of the logging system). A quality index based on measurement of the droplet detachment frequency would be an acceptable technique if it could be detected easily, but limitations of the initial data collection system prevented observation of a clear peak on the FFT plot.

Dip Transfer Experiments

The stability of a dip transfer process can be detected by monitoring the frequency and regularity of the electrode short circuits in the weld pool. However, even with optimised welding conditions dip transfer is a statistically variable process. The welding parameters are interactive and difficult to set. Therefore variations in any one parameter will have a direct influence on the stability of the process.

In dip transfer, the burn off rate is made up of two components, the melting rate and the detachment rate, and these must balance to obtain a stable metal transfer. Wire melting is due to a combination of resistance heating during the short circuit period and resistance and arc heating during the arcing period. The length of wire melted per cycle may therefore be expressed as,

$$WT = \beta.s.(I_{sc})^2.t_{sc} + \beta.s.(I_a)^2.t_a + \alpha.I_a.t_a \qquad (3.5.2)$$

where	β	is the resistive heating factor
	α	is the arc heating constant
	s	is the electrical stick out
	I_{sc}	is the short-circuit current
	I_a	is the arc current
	t_{sc}	is the short-circuit period
	t_a	is the arc period
	T	is the cycle period

Ideally, the length of wire melted per short-circuit should be constant. However, in practice this is difficult to achieve absolutely.

The standard deviation of the cycle time sd(t) is one of the factors which may be used to assess stability variations. This should indicate the stability of the process in terms of the amount of fluctuation in the length of wire melted each cycle, although this factor is sensitive to wire feed rate, and in the present work the ratio of the standard deviation of cycle time to the short circuit time was used to overcome this sensitivity. Comparing wires, these factors suggested that the 'Group II' wires correlated well with the subjective assessment of the wires' performance, whilst the 'Group I' wires gave values contradictory to those observed.

Lucas and Butler (1980) suggested that the standard deviation of the short circuit peak current level is a suitable method for assessment of process stability. Using this factor, the results seemed to correlate better with the

'Group I' wires. However, in the case of the 'Group II' wires, the stability factor contradicted the subjective assessment.

The subjective assessment of the process also included the spatter levels and bead shape. However, it is possible that the spatter generation may be directly related to the chemical reactions due to the composition of the flux constituents. In the experimental work, it was observed that the 'Group II' wires generated less spatter than the 'Group I' wires. This would suggest that the amount of spatter generated was related to the oxygen content in the wire. The bead shape is a function of the amount of plate melted in the arcing period and the burn off rate. The volume of plate melted for the 'Group I' wires was lower than that for the reference wire.

No single method was established in these initial experiments for indexing the stability for the dip transfer process. However, a combination of the statistical techniques used may be appropriately interpreted. The wire used for these experiments was 1.6 mm which is not usually used for the dip process. Therefore, the optimum settings used may not be good enough to base any assumptions on. Further work in this area was required to confirm the results.

Pulse Transfer Experiments

The pulse transfer process is inherently a more stable process. The process enables spray type transfer to be achieved at low mean currents. Droplet detachment occurs during a high current (higher than the spray transition current) for a short duration pulse, whilst the arc is maintained by a low current background period. Spatter is minimal.

The pulsed transfer experiments were performed using the frequency modulated arc length control within the power source. This method varies the background amplitude and period with a constant $I_b.T_b$ product to control the mean arc voltage. Hence, the degree of variation in these parameters for the different wires may indicate the differences in their controllability which may be a factor to assess wire quality.

The transient plots indicated that the 'Group I' wires provided a larger variation in the background parameters, whilst observation and the standard deviations of these parameters suggests that the 'Group II' wires are more stable. Since the power source uses the peak voltage as the control signal to the feedback loop, the fluctuations in this signal may also indicate the transfer stability of the wire, however, in these experiments, no conclusive relationship was found.

The V/I characteristics suggested that the 'Group I' wires were less stable than the 'Group II' wires. These results agreed with the subjective assessments made during welding. However, since the manufacturers' own tests are done near spray transition current, better correlation may be obtained if the peak current was set at this level.

3.6 Conclusions - Preliminary Work

All of the statistical information calculated at this stage was based on 1024 data points obtained from the most stable segment of a welding trial. This represents only a short length of weld and does not allow for more violent fluctuations in the welding behaviour. Hence, although some useful information may be obtained from these experiments, the information may not be representative of the total welding process. To obtain a more accurate picture a longer welding run must be measured and a higher sample rate used to measure both transient and slow variations in the welding signals.

The measurement of the observed light signal suggested that it closely follows the voltage signal and since a welder cannot 'see' variations in the light that are not reflected in the voltage signal, this signal may not provide any extra information from which to use for quality assessment. The transient waveforms in fact suggested less information was observed which may be due to positioning and type of light sensor used. Further work in this area is required.

The measurement of the sound signal was not successful at this stage but it is clear that an experienced welder can detect 'good' and 'bad' welding from the audible sound. Hence, it was decided that further investigation of the arc sound must be carried out.

The statistical analysis of the electrical signals was the most successful in detecting variations in the arc stability for all of the modes. Further work was required to obtain a useable method to assess the quality.

The experimental work done at this stage was used to assess the feasibility of achieving a method to quantify the quality of flux cored wires. Although, no obvious method was immediately highlighted, some definite possibilities were identified. However, in order to achieve the analysis a more 'flexible' monitoring instrument was required with a faster sample rate and more data acquisition and analysis tools available. Although there are several instruments available that can acquire and analyze the data, none could analyze the data without the assistance of additional software packages. Since one the objectives of the project was to produce an on-line instrument to output indexes of wire quality a fully self contained system was required.

To obtain on-line data and analysis a proprietary instrument was built. This was comprised of a STE based PC compatible computer plus an analogue data acquisition board built into an industrial case. Special software was written in 'C' to calculate all of the required statistics and FFT analysis techniques.

4. EXPERIMENTATION USING THE STE PC MONITORING SYSTEM

4. EXPERIMENTATION USING THE STE PC MONITORING SYSTEM

4.1 Introduction

The preliminary investigation concluded that a PC based monitoring system should be built to provide faster sample rates, greater data collection plus statistical and FFT analysis routines for the captured data. For the remainder of this work an industrialised system was obtained. This incorporated a 8088 PC XT compatible computer on STE BUS, a built-in 5 inch monochrome monitor, a 3.5 inch double density disk drive together with an 8 channel multiplexed 8-bit Analogue to Digital conversion board.

One of the problems highlighted by the early experimentation was that the captured data did not represent an acceptable length of welding at the high sample rate. This meant that statistical results were based on a small length of weld. The first solution to this problem was to increase the size of data captured. This solution however had the obvious problems of data management and also the difficulty of exporting the data to other packages for specialist analysis. To overcome this problem, the 'windowing' strategy (described later) was conceived (Fig 4.1).

Since the welding signals were at different amplitude levels, the signal conditioning unit built for the early work was adapted for use with the new system. The electronic circuitry was modified to incorporate increased amplification for the audio signals and to provide isolation from the arc voltage signal. Also the signal conditioning unit was set up to monitor the wire feed signal directly. With this new experimental configuration, the arc voltage, the arc current, the wire feed rate and the arc sound could be monitored all together if required.

Since this system was required to be flexible, a special software program called 'qsab' was written using Microsoft 'C' V5.1. This could monitor, display and analyze the welding signals in the most efficient manner. The design and operation of this software is described in the next section.

4.2 Description of the Software

In order to provide the maximum flexibility for the monitoring system, the software was designed in a structured manner with each procedure callable via a particular key press. Before the software code could be written and compiled, an initial specification was developed to which additional routines could be added easily.

The initial specification for the flexible monitoring system was as follows,

Data Logging

The system was required to capture up to 48 kB of data with variable settings for channels, sample rate and trigger facilities.

Data Display

The system was required to display the captured data both graphically and numerically.

Data Storage

The system was required to be able to save the captured data to disk for later analysis and provide the facility to export data to other analysis packages.

Data Retrieval

The system was required to be able to retrieve data captured and saved to disk in earlier experiments.

Statistical Analysis

The system was required to be able to calculate and display the means, standard deviations, peak and background amplitudes and periods for each channel. The system was also required to be able to save these statistics in ASCII format for use with other useful software packages.

FFT Analysis

The system was required to be able to calculate the FFT spectrum of any block or channel of captured data.

Once this specification was written, a flowchart of the system was drawn from which the code could be written (Fig 4.2). It can be seen that if any other calculation was required, the new routine could easily be added. The software menu screens are shown in Fig 4.3 and Fig 4.4. It can be seen that each procedure is called by a function key press and the actions assigned to each key are described in Appendix B.

Channels to Log

Four channels were available and these were used for Sound, Wire Feed, Voltage and Current. Since the total amount of data memory was 48 kB, the amount of data captured for each channel depends on the number of channels logged.

Window Interval

To obtain high speed transient data over a long length of weld, it was decided that the samples would be captured at the maximum sample rate (65 μs per sample) in blocks of 512 samples per channel and then have a user selected interval before another block is collected. By this method, each block or 'window' of data can be individually statistically analyzed and compared to other 'windows'. Hence, both transient and slow inconsistencies may be detected.

The window interval sets the time duration between capturing the blocks of data samples. This may be set from 0 (continuous logging) to 64 seconds. The length of welding monitored depends on this value.

Trigger Channel

Before each window of data is stored, the trigger channel is monitored to see if the trigger conditions have been achieved.

Trigger Level

The trigger channel is monitored for achievement of the level setting before storing.

Trigger Direction

Similar to an oscilloscope, the data is only stored if the trigger channel data is in the required direction High or Low.

Sample Rate

For the STE based PC, the sample rate was set by incorporating a delay between acquiring samples as the A/D board did not have a variable sample rate. The delay was created by running a dummy software loop and the number of times this loop was run determined the sample rate. It was calibrated by using a signal generator to determine the required count for a correct sample rate.

Channel Gains

Since the A/D board had 8 bit resolution for a 0 to 5V input signal, the actual signal range at the maximum value must be used to calibrate each channel. The required calibration can be saved to disk once set, and the program automatically reads this value in, each time it is run.

Statistics

When the 'F7' key is pressed, a new menu appears which allows the operator to calculate and display the statistical data. When the program was first written this only calculated the means, standard deviations, peak, background, peak time and background time for each channel. However, as will be described later, during the research other statistical parameters became important and these were added to the menu as and when required.

Once the initial software was written and tested using a signal generator, it was applied to welding monitoring. When a useful calculation became apparent, the algorithm was added into the statistical menu with its own 'key'. These were then displayed as required.

4.3 Experimental Set up

As a result of the early work, it was apparent that a new multi-variate approach was required. Hence, a mathematical modelling technique was incorporated. This technique involves designing factorial experiments and using multiple regression analysis. A statistical software package called STATGRAPHICS was used throughout this work. This package includes several special functions to aid in the experimental design, the correlation analysis as well the regression techniques.

The existing manual technique used for wire quality assessment is performed at above 300 A (spray transfer welding) (Appendix A) using a fixed procedure. At this stage it was decided to produce a method that was centred at the same settings.

The experimental set up is shown in Fig 4.5. The system comprised the PC based monitoring system incorporating the software described above, a moving table with a fixed water-cooled welding torch, a GEC Control Arc 500 power source, a GEC 4D wire feed unit, a Panasonic High Resolution Video Camera aimed at the arc through appropriate filtering and a 20in graduated monitor.

A Data Harvest wire feed tacho unit was fixed to the wire at the wire feed unit. The current was measured using a HEME current transducer, the arc voltage was monitored directly across the torch and the arc sound was monitored by a microphone as described in the early work. However, the arc sound signal was connected to a separate audio amplifier circuit prior to connection to the signal conditioning unit.

4.4 Design of the Experiments

The experimental programme was intended to produce data for statistical modelling of the GMAW process. Theoretical model building is based mainly on considerations about basic physical and chemical principles whilst statistical modelling depends purely on the collected experimental data it is being applied to. Hence it is essential that the experiments are designed properly and efficiently in order that the modelling exercise succeeds. The problem must be properly defined, the experiments must be set up accurately and their execution must be precise.

The existing manual method of performance assessment was accomplished by the assessment of a single bead on plate weld at a fixed current, voltage, wire feed rate, arc length and travel speed at a point above the spray transition point. From the early experimental work it was established that a visual assessment and audio assessment of the arc stability was the criterion used by the manual welder. This was confirmed by the subjective assessments made in the early experiments. In order to quantify a stability criteria, however, the term 'arc stability' must be defined prior to setting up an experimental procedure. The two main consequences of instability were seen to be:

(i) Variations in arc length
(ii) Variations in metal transfer -> droplet size

These variations led to the conclusion that a statistical modelling strategy concentrating on these areas may yield a more successful solution.

The spray transition current for the 1.6mm standard wire used occurs at a current of 300A. Hence a set of experiments were designed which were centred at the spray level. The centre point of the experimental range named the 'medium' level was set up at,

Current = 300 A
Stand Off = 20 mm
Arc Length = 5 mm

Initial trials were designed with the current, the stand off and the arc length as the controlled variables. The following tables show the minimised design of experiments that were used.

	Stand Off	Current	Arc Length
1	Low	Low	Low
2	Low	Low	Medium
3	Low	Low	High
4	Medium	Medium	Medium
5	Low	High	Low
6	Low	High	Medium
7	Low	High	High
8	High	Low	Low
9	High	Low	Medium
10	High	Low	High
11	Medium	Medium	Medium
12	High	High	Low
13	High	High	Medium
14	High	High	High

Since, the stand off and the current were reasonably accurate measurements, these variables were set to high and low settings only. However, the arc length measurement required some visual assessment, hence three settings of arc length were included.

Using this design strategy, several sets of experiments were carried out. The power source was set for constant current welding at the required settings.

The data acquisition system was set up to capture data for arc current, arc voltage, the wire feed rate and arc sound, at the fastest sample rate. The actual sample rate of the STE data acquisition hardware was determined by utilising the real time clock within the STE computer to calculate the difference in time before and after data acquisition. The result was divided by the number of samples acquired to give an average value. It was measured at 270 μs for obtaining the four channels of data (approx 65 μs per sample).

In order to obtain both useful transient and statistical information, the 'windowing' technique was used. This method functions by capturing a number of samples at a high sampling frequency and then waiting for a pre-set period. This process is repeated until the data buffer of the acquisition system is full. By using this method, a set number of 'windows' of data are captured, each containing enough transient information about the process characteristics, whilst allowing a statistical evaluation of the entire experiment to be carried out. For the purposes of the STE monitoring hardware, the monitoring parameters set up can be summarized as follows:

Channels Logged: Voltage, Current, Wire feed Rate, Sound.

Total Data Size: 49152 samples (8 bit resolution)

Window Size : 512 samples per channel
(2048 samples per window)

Window Interval: 0.25 secs per window

Sample Period : 270 μs for 4 samples

No. of Windows : 49152÷2048 = 24

The mean arc current was set up using the digital display on the power source. Whilst, the arc length was set up by welding several dummy runs and trimming the wire feed rate and measuring the length on the video monitor (calibrated in mm). Each run (including the dummy runs) was videoed for later analysis.

The stand off was initially set up by setting the torch to workpiece distance, and this was fined tuned later using an image processing system. This system allowed for the digitization of a video image (acquired via the video recorder) and provided facilities for calibrated length and area measurements taken from any part of the image. Hence, the torch to workpiece distance was re-measured by using the video recording taken during welding.

The sound signal was measured by placing a differential microphone 300 mm from and perpendicular to the arc. An improved amplification circuit was designed and built to ensure that a useful signal was obtained.

The STE data acquisition system provided a digitisation of the actual arc voltage, the arc current, the wire feed rate and the arc sound during the welding. The data capturing process was triggered manually, once the arc was initiated. This was done to ensure consistency of the technique.

Bead on plate welding trials were initially carried out on three separate occasions for confirmation purposes and correlation analysis. On each occasion, the experimental design procedure described above, was repeated. The following pre-weld settings were employed:

	Low	**Medium**	**High**
Arc Length	3 mm	5 mm	7 mm
Arc Current	270 A	300 A	330 A
Stand Off	17 mm	20 mm	23 mm

Following each welding trail, the video recording of the welding arc was replayed and the image processing system was employed to measure the actual arc length variations during the welding. In addition, the image processing system was to used to measure the size of the droplet length at equidistant points during the weld. All of the data was then analyzed for correlations and statistical trends between the variables. The analysis techniques used will be described in the next section.

4.5 Data Analysis

After each set of experiments, the data was statistically analyzed for useful information. Three different analysis procedures were employed:

(1) Special statistical and FFT routines were added to the monitoring system software. These routines performed the following calculations on each channel of data and on each window of data:

(a) **Window Mean** (M_w) is defined as,

$$M_w = \frac{(\Sigma d_n)}{W_n}$$

where

d_n are the sample values for the channel
W_n is the window size (512)

(b) **Window Standard Deviation** (SD_w) is defined as,

$$SD_w = \sqrt{\frac{(\Sigma(d_n - M_w)^2)}{W_n}}$$

(c) **Window Peak** (PK_w) is defined as,

$$PK_w = \frac{(\Sigma(d_p)}{W_p}$$

where

d_p are the sample values $> M_w$
W_p are the no. of samples $> M_w$

(d) **Window Bkgnd** (BK_w) is defined as,

$$BK_w = \frac{(\Sigma(d_b)}{W_b}$$

where

d_b are the sample values $< M_w$
W_b are the no. of samples $< M_w$

(e) **Window Maximum** (MAX_w) is defined as the highest value reached.

(f) **Window Minimum** (MIN_w) is defined as the lowest value reached.

(g) **Window Peak Time** (TP_w) is defined as,

$$TP_w = \frac{(\Sigma(t_p)}{tp_n}$$

where

t_p are the periods when the samples are > M_w
tp_n are the number of peak excursions

(h) **Window Bkgnd Time** (TB_w) is defined as,

$$TB_w = \frac{(\Sigma(t_b)}{tb_n}$$

where

t_b are the periods when the samples are < M_w
tb_n are the number of bkgnd excursions

(j) **FFT** are the Fast Fourier Transforms as defined and described in chapter 2.

(2) The data was converted into ascii format so that it could be analyzed using a graphical spreadsheet package called DADISP. This package allowed for overlaying the data and performing known mathematical functions on the data. The software provided a useful method of analyzing the data from the arc sound signal (see chapter 5).

(3) The data was thoroughly analyzed for correlation analysis and model building purposes (see chapter 5) using a statistical graphics package called STATGRAPHICS. This process was performed on each of the initial welding trials and as a consequence it was found that the stand-off variable should be removed from the experimental design (see chapter 6). As a result, a further set of experiments were designed and carried out with specific variation in the arc length and the arc current only. These experiments were repeated for all of the 'bad' wires to provide comparison data later.

5. DATA ANALYSIS AND MATHEMATICAL MODELLING

5. DATA ANALYSIS AND MATHEMATICAL MODELLING

5.1 Introduction

Stepwise regression analysis techniques were used for all of the modelling work. Since the arc sound was also logged during the experimentation work, the sound data was analyzed both together with and independent from the arc voltage, current and wire feed data. The sound data analysis and modelling is described in section 5.5.

The experimental work utilised the data windowing technique to capture data for a long length of weld. The data captured comprised 24 windows of transient data in blocks of 512 values per channel, each separated by a time interval. In order to obtain sufficient statistical information about the process, the mean parameters (as described in section 4.4 (1)) for each window were calculated and the overall mean for each run was evaluated by taking the mean of the 24 windows. In addition, the mean arc length, the mean stand-off and the mean droplet length for each run were measured using the video image processing system.

5.2 Model Building

After the average parameters for each run had been calculated for a set of experiments, the data was entered into a data file suitable for retrieval by the STATGRAPHICS software package (see Tables 5.1, 5.2). This data was initially analyzed for interactive correlation, prior to model building.

Before the regression process could commence, the data was plotted in several ways so that obvious relationships would become highlighted and unnecessary processing could be avoided.

A plot of arc length against arc voltage for the 'Good' and 'Bad' wires is shown in Fig 5.1. It was apparent that the arc voltage is not solely a function of the arc length. Plots of arc length against the other parameters independently similarly showed little correlation or obvious differences between the 'Good' and 'Bad' wires.

The voltage/current characteristics for 'Good' and 'Bad' wires showed a small difference in the slope of the characteristic (Fig 5.2). A small difference was also observed for the wire feed rate/current characteristic (Fig 5.3). A plot of droplet detachment length against voltage deviation (Vpk-Vbk) (Fig 5.4) showed that these parameters were directly proportional. Consequently, it was assumed that voltage deviation is also proportional to the variation in arc length.

A plot of wire feed rate against droplet detachment length (or arc voltage deviation) displayed a negative sloping linear relationship (Fig 5.10). It was observed that the slope of this curve was much higher for the 'Bad' wire than the reference wire.

The first correlation analysis produced by using the STATGRAPHICS software defined the following relationships:

Arc Length (Al) = f(V,I) (5.1)

Droplet Len. (D) = f(Al)= f(V,I) (5.2)

Droplet Len. (D) = 0.8 x Wire diameter (Wd) at spray transition (5.3)

Wire feed Rate (W) = $f(I, I^2 \,\&\, L)$ (5.4)

Wire feed Rate (W) $\propto$ Droplet Len. (D) (5.5)

Where

V = Mean Voltage; I = Mean Current; W = Mean Wire feed Rate;
L = Stick Out (Stand Off - Arc Length);

Relationship (5.1) above is affected by the welding mode of the process (ie Constant Current or Constant Voltage). Previously reported relationships for arc length have normally associated arc length as being proportional to the arc voltage. However, the results obtained for the present work showed that there is also some correlation with the current.

Relationship (5.2) above was further investigated and it was established that the droplet length is proportional to the change in arc length. For the case of constant current welding, the change in arc length is proportional to the change in arc voltage. Whilst, for constant voltage welding, the change in arc length is proportional to the change in arc current. Hence, the models for arc length and droplet length were investigated.

$$Al = K_v(V) + K_i(I) + K_c \qquad (5.6)$$

$$D = K_1(Vpk-Vbk) + K_2(Ipk-Ibk) \qquad (5.7)$$

After further data analysis it was established that the variables,

$K_1 = K_v$ and $K_2 = K_i$

Which means that equation (5.7) may be re-written as,

$$D = K_v(Vpk-Vbk) + K_i(Ipk-Ibk) \qquad (5.8)$$

The third relationship (eqn. 5.3) was determined by plotting the Current I against voltage deviation D (Figs 5.6. 5.7, 5.8). Since it was established that the arc voltage deviation is directly proportional to the detachment length, using the (Fig 5.4) plots of detachment length against current would yield the same results. A comparison histogram of the arc voltage deviations for 'Good' and the 'Bad' wire is shown in Fig 5.9. It was determined that for the reference 'Good' 1.6 mm wire, the droplet length was approximately 1.25 mm at the spray current level (300A) for all of the arc length settings. Whereas the 'Bad' wire was still welding in globular mode at this current with a detachment length closer to 2 mm. Previous published and unpublished works in this area have also reported a similar result.

The fourth relationship (eqn. 5.4) mentioned above provides an indication of the melting ability of the wire and is in fact a repeat of the Halmoy relationship (equation 2.1.3) as was described in chapter 2, based on

$$Wm = \alpha I + \beta L I^2 \qquad (5.9)$$

where
Wm is the wire electrode melting rate,
I is the arc current,
L is the stick out distance.

For a stable arc with spray conditions at a constant current and arc length, the melting rate should be equal to the wire feed rate (ie. equilibrium), hence for modelling purposes the wire feed rate was used as the independent variable in this case.

The last relationship described above (equation 5.5), suggested a linear relationship between the wire feed rate and the droplet length. This relationship is more distinctive for the 'bad' wire than it was for the reference wire (Fig 5.10). It was observed that above the spray transition level, the droplet length levels off and hence the relationship may not be valid in this area. This model was evaluated by a simple regression as:

$$D = K_4 + K_5 W \qquad (5.10)$$

where

D is the droplet detachment length (determined via eqn. 5.8)
W is the wire feed rate

Models for arc length, droplet length, melting rate and wire feed rate were produced by stepwise regression techniques as mentioned above, using the final mean values for each run of the experimental design. For each model the optimal R^2 and minimal error statistics were established before a model was accepted. The output R^2, F and other error statistics produced by the software during model building are shown in Tables 5.1c, 5.1d.

5.3 Sound Data Analysis

Since the sound signal is more difficult to measure (due to the small signal levels and the background noise problems) and acceptable models for quality assessment were eventually developed without including the sound data, it was decided that the sound data should be analyzed independently. The correlation analysis table showed that the sound data did have some relationship to both the arc voltage and current signals.

To analyze the correlation of the sound data more efficiently the data files produced by the STE monitoring system were converted to ASCII so that they were accessible by other software packages. The data for each experiment was then imported into the graphical spreadsheet package called DADISP. The DADISP software has facilities to manipulate the data of any graphical window by performing a choice of useful mathematical functions on the data.

The data for the sound signal was acquired at the same time as the electrical characteristics of the arc (voltage, current and wire feed). Hence, an initial point of investigation was to analyze the sound signal data for correlation to the electrical characteristics. To investigate such relationships, it was decided that in addition to the data already captured, a further set of experiments would be carried out, using pulsed and dip transfer welding. These were performed because the changes in the voltage and the current signals are more distinct with these welding modes. A full range of experiments were carried out for both of these modes and the data from these experiments were exported to and analyzed using the DADISP package. For the purpose of the present work, several statistical and spectrum (eg, mean, standard deviation, auto-correlation, cross correlation, moving average, FFT etc.) functions were tested with the sound data (Figs 5.11a-f).

It was observed that by numerically integrating the sound data and then plotting a spectrum of the result, the frequency spectrum of the resultant integrated sound data was a closer match to that of the arc voltage and current signals. It was also seen that by taking a moving average of the sound data, the higher frequency content of waveform was removed and the pulse or dip structure of the process was clearly visible. It was clearly observed that there is a slight time lag between the sound signal and the arc voltage and current signals. This time lag was measured at approximately 1 msec.

After the investigation using the DADISP software, it was concluded that the integrated sound signal was approximately proportional to the arc current signal. Consequently, the STE monitoring software was modified to calculate and plot the integrated sound signal (by using a moving 5 point Simpsons algorithm). At this stage it was decided that the best way forward with the sound would be to attempt the same modelling exercise that was performed with the electrical characteristics (section 5.2). To do this, the STE monitoring software was again modified to calculate the statistics for the sound data for each experiment used previously.

Stepwise regression techniques were (using STATGRAPHICS) used to determine new models which were based on the assumption that since the integrated sound was proportional to the arc current, the model formats that were evaluated via the electrical characteristics may be repeated by replacing the arc current data with the integrated arc sound data. The data used for evaluating these models is shown in Tables 5.1a, 5.1b and 5.1e. It was observed that the models fitted the data very favourably. The models produced in this manner were as follows:

$$D = K_s(Spk-Sbk) \tag{5.8b}$$

$$Wm = \alpha_s S + \beta_s L S^2 \tag{5.9b}$$

$$D = K_6 + K_7 W_m \tag{5.10b}$$

where Wm is the wire electrode melting rate,
S is the integrated sound data,
L is the stick out distance.

5.4 Utilisation and Validation of the Models

As described in chapter 2, in order to obtain an acceptable model, a validation process must take place to confirm its usefulness. The models were initially incorporated into the monitoring software and calculated for each window of each data file (per run) of the experimental design. Further validation was accomplished by utilisation of the data files that were not used during the modelling exercise to test for experimental errors. Some of these data files were also included in the regression steps to test for improvements in the models.

The objective of the work was to produce an objective assessment of wire quality. In order to distinguish between wires of different quality, the measurement of quality must be based on a reference. Hence the usefulness of the models were based more on whether differences in the evaluation of the models would provide a comparison technique between the wires, rather than the literal meanings of the models themselves. However, in order to compare the wires in a structured manner, it is more useful to use parameters that are already understood by the industry. The next step in validating the model was to devise a comparison strategy.

The strategy developed utilised the evaluation of the model resultants as reference levels evaluated with the 'good' wire. Deviations from these values were calculated for each data window in the test run and statistically compared over the entire run. The actual strategy used to compare each model are described next.

Arc Length Model

A comparison of differences in quality based on the arc length model must take into account variations in torch to work piece distance caused by factors such as buckling of the plate as the plate gets hotter. Since the test is carried out by a semi automatic welding rig, the torch to workpiece distance should be constant. Hence, if any heating effects are apparent, a plot of the individual arc lengths for each window should show as a slope. In order to compensate for such problems, the slope of the arc length line was calculated first by a simple regression using the individual window arc lengths calculated across the test run.

The comparison technique was to calculate the individual window deviations from the calculated mean (sloping) arc length at that point (evaluated by using the regression line). It was empirically determined that a 'good' wire will have a much smaller mean deviation in arc length than a 'bad' wire. The process for comparison may be summarised in the following steps:

i) Calculate individual arc lengths based on equation (5.6) $A_1, A_2 \ldots A_n$: $(Al = K_v(V) + K_i(I) + K_c)$

ii) Calculate the slope and intercept, using all of the calculated individual window arc lengths $(Y=Mx+C)$ by simple regression.

iii) Calculate the individual reference arc length for each window, $A_r = C + Mt_n$ (where t_n is the window number)

iii) Calculate the mean deviation for the entire test run using the individual window arc lengths,

$$A_{dev} = \frac{\Sigma(A_n - A_r)}{n}$$

iv) Compare the calculated deviation to the allowable deviation as a percentage,

$$A_{adp} = \frac{(A_{dev})100}{A_m}$$

where A_m is the mean arc length $(\Sigma A_n \div n)$ for the run.

The Melting Rate Model

To compare this model, it was decided that the melting rate for the individual windows would be calculated and the mean melting rate for the test run calculated. The mean melting rate would then be compared to the mean wire feed rate measured during the test run as a percentage. The steps for comparison with this model were as follows:

i) Calculate the individual melting rate for each window using equation (5.9) $Wm_1, Wm_2 \ldots Wm_n$ $(Wm = \alpha I + \beta LI^2)$

ii) Calculate the mean melting rate for the test run,

$$Wm = \frac{(\Sigma Wm_n)}{n}$$

iii) Calculate the mean melting rate deviation as a percentage,

$$W_{dev} = \frac{(Wfr-Wm)100}{Wfr}$$

The Transfer model

In order to compare variations in transfer several techniques were available. A simple comparison of the droplet length to the mean droplet would have sufficed however, it was decided that a more useful comparison would be ability of the wire to get into spray welding mode. This was done by subtracting the calculated droplet length (model 5.2) from the predicted droplet length at spray level (model 5.3),and then using an interpolation technique to predict the current at which the spray transition would occur. The technique can be summarised as follows:

i) Calculate the droplet length for each window (model 5.7)

ii) Calculate the deviation from the droplet length at spray. (D - (0.8W_d)

iii) Interpolate to the wire feed rate at spray by using linear movement from the actual wire feed rate (using model 5.10).

Since from (model 5.10) droplet length at any point n is,

$$D_n = K_4 + K_5 W_n \qquad (5.10a)$$

and the droplet length at spray is,

$$D_s = K_4 + K_5 W_s \qquad (5.10b)$$

where W_s is the wire feed rate at the spray level.

Subtracting eqn. 5.10a from eqn.5.10b,

$$D_n - D_s = K_5(W_n - W_s)$$

hence,

$$W_s = W_n - \frac{(D_n - D_s)}{K_5} \qquad (5.11)$$

To predict the spray transition current eqn. 5.9 can be used, hence by using the known theorem $x = (-b \pm \surd(b^2 - 4ac)) \div 2a$, to solve quadratic equations the relative spray transition current may be calculated,

$$I_s = (-\alpha \pm \sqrt{(\alpha^2 - 4\beta L W_s)}) \div (2\beta L) \qquad (5.12)$$

This will yield two results only one of which will be valid (the other value being negative).

5.5 Consumable Weldability Quality Grading

The above models and comparison techniques were added to the STE monitoring software. In order to perform a true on-line test, acceptance limits were set up to provide A, B or C grades for each of the model comparisons described. the limits set up were as follows:

Arc Length Model:

Grade A: $A_{adp} < 2\%$
Grade B: $A_{adp} < 5\%$
Grade C: $A_{adp} > 5\%$

Melting Rate Model:

Grade A: $W_{dev} < 5\%$
Grade B: $W_{dev} < 10\%$
Grade C: $W_{dev} > 10\%$

Transfer Model:

Grade A: $I_s <= 1.05.I_{sp}$
Grade B: $I_s <= 1.10.I_{sp}$
Grade C: $I_s > 1.10.I_{sp}$

where I_{sp} is the known spray transition current for the reference wire.

The actual values of the limits were initially derived from an subjective assessment of the tolerable welding quality as observed from the results of the 'good' and 'bad' data. These acceptance limits for grading were later improved by carefully comparing the welder's results to the numerical data for all of the on-line tests.

5.6 On-Line Validation of the Quality Assessment Technique

In order to validate the quality assessment technique, the first step was to run the test with the data from the bad wires analyzed in the early work. In addition, further wires of known quality performance were provided by ESAB and tested in the presence of the experienced welder.

The welder was not told the results from the system obtained during welding, and his comments and 'grades' were compared to the results from the system. It was established that out of 14 wires tested only one result was doubtful. The welder suggested that the wire was acceptable, whereas the software suggested it should fail. After re-testing of the wire, the welder and the system were more in agreement. The results from these on-line trials are shown in Tables 5.3 and 5.4.

5.7 Using the Sound Data for Quality Assessment

In order to prove that the models derived from the sound data were also useful, the same strategy for quality assessment as the electrical characteristics were used. The arc length model, the melting rate model and the transfer model were re-calculated using the new variables obtained via the sound data modelling.

The quality grades obtained via this route were also compared to the on-line assessment of the experienced welder. It was found that in the case of the melting rate model, the results obtained were identical to those obtained from the electrical characteristics. However, the values for the arc length model and the transfer model contained a slight error. This error was overcome by changing the acceptance limits for these parameters. The grades from the sound signal then matched those obtained via the electrical characteristics. However, the evaluation of the actual arc length and predicted spray transition current produced different values with the sound data technique. The results from these on-line trials are shown in Tables 5.5 and 5.6.

5.8 Expanding the technique for use with other wires

Since the technique had proved itself successful with the 1.6 mm flux cored wire, it was thought appropriate that a more formal and simplified procedure for obtaining the quality assessment should be produced. This involved the writing of two new software programs.

The first program (called 'esab1') was a more user friendly version of the first package, together with a more graphical display of the results. The program was designed so that the quality grading strategy described in the previous sections was incorporated and both a graphical and numerical interpretation of the evaluation of the models were displayed on the screen (Figs 5.15 and 5.16). With the new software, the graphical display could show the position within a length of weld at which failure had occurred. The flowchart for the quality performance assessment modules are shown in Figs 5.12, Fig 5.13 5.14. Also, the improved program incorporated additional analysis tools, such as standard statistical functions, FFT analysis and Event analysis for general purpose data analysis. Typical menu and output display screens are shown in Appendix C (Figs 5.17a - 5.17l). This software program is described in more detail in Appendix D.

In order to make the software available for use with other types of welding wire, the coefficients for each model were included by reading a data file each time the program was run. The model coefficients that the program read in were:

Arc Length Model:	K_v, K_i , K_c	(for equation 5.6)
Melting Rate Model:	α, β	(for equation 5.9)
Transfer Model:	K_4, K_5	(for equation 5.10)
Wire diameter:	W_d	(for equation 5.11)
The Spray Transition Current:	I_{sp}	(for setting the grading level as described in section 5.5)

Hence, in order to utilise the system for other wire types, the above values are required for each case. However, the attainment of the above values requires the re-design of the experimental set up and the acquisition of the appropriate data. For this purpose, a second software program was written which could input the above values and create a correctly formatted data file for the first program.

In order to input the model coefficients listed (called 'qagen'), the user is required to utilise the 'esab1' software to output the mean statistics for each run of a new experimental phase. The experiments for a new wire must be designed in a factorial manner using the strategy described in section 4.4, with the known spray transition current and the nominal arc length, used as the centre points for the design. The following statistics are recorded from the program after each experiment:

Mean Voltage
Mean Current
Mean Wire Feed Rate
Mean Peak Voltage
Mean Background Voltage
Mean Peak Current
Mean Background Current

These parameters are available from the general monitoring tools available within the software. Once these parameters have been obtained, they must be used to calculate the model coefficients by using a standard statistical package (eg STATGRAPHICS) by performing a stepwise multiple regression algorithm to optimise the models into the known types mentioned.

To simplify the evaluation of the model coefficients further, another software program was written (called 'finger') which would request the user to enter the spray transition current and the nominal arc length. The program will then design the optimal experimental set up and request the user to set up the welding conditions for each point of the experimental design. The software will acquire the data for each point and at the end of the experimental phase will automatically evaluate the model coefficients and provide facilities to create a new data file for the 'esab1' program to use. This software program is described in more detail in Appendix E.

6. *GENERAL DISCUSSION*

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6.1 The Preliminary Experimental Investigation

The purpose of the present work was to produce an objective method to determine the performance of flux cored wires. The manufacture of new flux cored wires and development of new production techniques to enhance productivity and weldability requires a comparative method to provide numerical data from which the performance could be assessed.

The existing method used to determine the consumable performance, involves an experienced welder performing a short length of weld with a fixed welding procedure. After performing the weld, the welder would grade the wire into groups, for example 'A', 'B' or 'C', where 'A' means the wire's performance is judged to be excellent, 'B' means acceptable and 'C' means that it failed. This method relies purely on the experience and subjective assessment of the welder. In addition, there was no indication about the possible causes of failure or whether changes in mixtures etc. have enhanced the performance in any way.

The present investigation was initially directed towards the input parameters that were believed to be the basis of the welder's decision. These parameters were monitored by using a standard computer based data acquisition unit. The data acquisition used for the preliminary investigation (called the 'Databox') was configured to monitor the arc voltage, the arc current, the arc light signal (via a photodiode) and the arc sound signal (via a directional microphone). These signals were monitored because it was believed that the welder makes his decision by 'listening' and 'observing' the welding arc as well as by making judgments regarding the settings of the electrical parameters.

The welder is also known to use the weld pool appearance and slag behaviour to assess the consumable performance but collection of data on these aspects would entail on line video monitoring and image analysis, it was therefore discounted for the present work.

A preliminary experimental investigation of the signals led to the conclusion that a standard data acquisition device was limited in its ability to capture the necessary information. The 'Databox' data acquisition device was only capable of capturing data for a short length of weld (about 6 seconds worth). This is because standard data acquisition units are only equipped with a small amount of data memory (The 'Databox' has a data buffer of 32 kb). In addition, most commercial devices can only capture data in one continuous burst. Also, in the case of the 'Databox' the resolution was limited to 8 bit (ie

256 values).

Other difficulties encountered when using this standard data acquisition device were problems with transferring and analyzing the data produced. Special software programs were therefore written to convert the data into a format acceptable to standard data analysis packages. These comprised:

a. A program to convert the data files obtained from the 'Databox' (called box2ascii).

b. A program to obtain the relevant set up information and seperate the data for specific channels (called b2a2).

Despite these difficulties, several analysis techniques were developed at the preliminary stage which provided a useful basis for the remainder of the work. However, the amount of data analyzed represented only a fraction of a second in the welding period. In addition, the analyzing techniques used were all directed towards analyzing individual channels and factors. It was therefore difficult to detect differences between the 'good' and 'bad' wires except in the 'violent' cases of arc instability. For each of the wires tested, there were definite differences that could be detected subjectively in the current and voltage waveforms. However, the use of the standard statistical techniques and the inadequate amount of data available meant that no clear objective technique was found.

The investigation of the light signal was abandoned after the preliminary experimental stage. This was because it was considered that the data produced from the light sensor did not provide any additional information to that available in the arc voltage and current signals. This assumption was validated by comparing traces from the photodiode output with coresponding voltage and current traces. The general shape of the light intensity waveform is identical to the current trace. However, the mathematical modelling technique which resulted in producing an acceptable method of quality assessment was also later independently used to develop relationships between the quality performance and the sound signal. It is therefore possible that this technique may also have been successful with the light signal. It is suggested that it would be possible to achieve an acceptable technique for quality performance assessment by using a combination of the arc light and sound signals. These may be useful for situations where the electrical characteristics are not easily accessible or other welding processes such as TIG and MMA where the melting rate cannot be easily assessed.

Three modes of the transfer were employed during the GMA welding in the preliminary experiments, dip, pulsed and spray transfer. The analysis of the dip transfer mode proved mostly unsuccessful due mainly to the fact that the type and size of the wire were not designed to be welded in this mode.

To analyze the data, the standard deviation of the time between short circuits and the V/I characteristics for the arcing and short circuit periods were the most viable methods available. Although, these techniques were not successful in this case, it is believed that investigations of smaller diameter wires designed to be welded in this mode would almost certainly produce performance differences between 'good' and 'bad' wires by using these techniques.

In the case of the pulsed transfer mode, the power source generally compensates for instabilities and therefore arc instability was easy to detect. However, in cases where arc instability was serious, a technique that correlates the variation in the pulse parameters to the arc stability (via similar modelling techniques to those eventually employed for the spray transfer mode) may be useful. The precise technique employed will depend on the strategy of control used by the power source circuitry to keep the welding mode (Current or Voltage) constant. In some equipment, the peak current amplitude is varied to keep the arc voltage constant, whilst in other cases this is done by varying the background amplitude and frequency.

Following the preliminary investigation, only the spray transfer mode was considered. In view of the limitations of the commercial logging system a high speed data acquisition system which was capable of providing sufficient transient and statistical data to analyze a reasonable length of weld was designed. In addition, a proprietary software package, incorporating several mathematical, spectral and statistical functions was written in order to optimise the analysis procedure. The software was written in 'C' and designed in a modular format so that new analysis techniques could easily be incorporated as they were developed.

6.2 Welding Performance Assessment by Mathematical Modelling

The method that was devised focused on a computerised monitoring technique which analyzed the electrical characteristics of the welding arc and correlated them to a measure of the quality performance. The quality performance is assessed by using 'ideal' models developed from data derived from a wire whose quality was known to be acceptable.

The preliminary investigation led to the conclusion that a multi-variable technique was required using an improved data acquisition technique together with process specific software. At this time, it was decided to continue the study of the arc sound signal as it was one of the signals used by the experienced welder to make his subjective assessment. However, it was soon apparent that a satisfactory solution could be achieved by modelling only the electrical characteristics of the arc. Hence, monitoring of the sound signal was found to be unnecessary for the purposes of the work. For academic interests, however, the modelling technique was applied to the sound signal and the results from this work will be discussed later.

Arc Monitoring

The strategy of analyzing 'windows' of transient data captured over a reasonable length of weld, is one of the fundamental innovations of the system developed. Existing data acquisition systems are normally only capable of operating with a single sample rate. Hence, if transient monitoring was required, it was only possible to either obtain transient data for a short amount of time, or capture extremely large amounts of data.

The technique devised captures a total of 49152 samples in windows of 512 samples per channel at sample rates from 1 Hz to 200 kHz. (1536 samples/window for 3 channels, Voltage (V), Current (I) & Wire Feed Rate (WFR) = 32 transient windows). The interval between windows is variable from 0 to 64 seconds. By selecting the appropriate window interval, it is therefore possible to obtain sufficient transient information for any length of weld. It should be mentioned at this time that the design of the signal conditioning unit incorporates active Butterworth filter circuitry which limits the maximum signal frequency to 10 kHz. This was done to prevent interference from the thyristor chopper frequency of the welding power source.

In the case of the modelling work, the sample frequency was set to 20 kHz and the window interval set to 0.25 seconds and the system was configured to monitor the voltage, the current, the wire feed rate and the arc sound signal. This provided a total of 24 transient windows, and a sample rate of 5 kHz per channel. According to previous published work the droplet transfer frequency in the spray transfer mode is normally around 200-300 Hz. Hence, since the logging duration of a window is 0.1024 secs (2048 samples at 20 kHz), in any single window, it should be possible to detect about 20-30 droplet transfers. It is usual practice to have a sampling frequency which is at least 10 times the frequency of interest to obtain a reasonable reconstruction of the analogue signal. The higher the sample frequency, the better is the signal reconstruction of a single transfer. However, for stability measurement, it is also important to obtain enough droplet transfers per window to detect the frequency variations. Hence, a balance is required between the resolution of the waveform and the number of transfers detected.

As well as investigating the statistical aspects of the waveforms, FFT spectrum analysis on the current and voltage waveforms was also carried out. However, it was observed that the FFT spectrum for both 'good' and 'bad' wires contained a large content of high frequencies (1-5 kHz) which meant that the droplet transfer frequencies could not be detected by this method. This was most likely due to a lack of resolution of the variations in the waveforms. It is believed that by incorporating hardware offset and gain circuitry which removes the mean dc amplitude and amplifies the ac content, for the spray mode, the transfers would be observed more clearly in both the waveform and the FFT spectrum. Previous work (Adam and Stewart, 1989) found that the FFT spectrum can be used to distinguish between the dip, globular and spray transfer modes. However, they also found that the voltage variations were very small and it is likely that a similar hardware improvement as mentioned may have also enhanced their capabilities. It is believed that if the FFT could be utilised to detect the droplet transfers, then similar hardware filters to those used by Philpott (1986) (who analyzed the RF spectrum to detect loss of the gas shielding) could be employed as an enhanced stability monitor for all modes of transfer in GMA welding.

The Modelling Procedure

The models were developed by performing sets of factorial experiments centered at the spray transition current and using the current, the arc length and stand off distance as input variables, and the voltage and the wire feed rate as the output variables. After, using stepwise multi-variable regression analysis techniques to optimise the models, it was ascertained that the stand off distance has very little effect on the final models produced. Also, since the stand off distance was not actually monitored but was only set at the start of each experiment, it was believed to be inappropriate to devise a technique that relied on this factor as a process variable.

During the modelling stage, several relationships between the process variables were produced which could also highlight the differences in arc stability. However, some of these relationships were non-meaningful empirical relationships developed using the various process variables. Although some of these models were capable of providing a working solution, it was decided that the final quality performance analysis technique must be related to process factors that the welding industry is normally acquainted with.

The following models were produced:

i) The Arc Length Model

$$Al = K_v.(V) + K_i.(I) + K_c$$

where

Al is the arc length
V is the mean arc voltage
I is the mean arc current
K_v, K_i and K_c are model constants

The arc length is normally stable for optimal welding conditions. Hence, it may be inferred that any variation in the welding performance should be displayed as disturbances in the arc length. These disturbances can be due to a number of factors which are related to the ability of the arc to melt the wire. This melting depends on a combination of the electrical characteristics, the type of shielding gas used, the wire feed rate, the wire flux and the powder mixtures within the wire. Thus, the detection of amount of variations in the arc length is a reliable indication to the amount of arc instability that exists.

Since the mean arc length is also dependant on the torch to work piece distance, it was thought that any trend in the calculated value of arc length during a test should be compensated for. Hence, in the performance assessment software, a linear regression is calculated using the individual window arc lengths. The individual deviations from the predicted arc length (adjusted using the slope of the regression line) are calculated and a welding quality performance index computed which is based on the amount of deviation allowed during the welding test.

The ideal situation would be to physically measure the arc length during each logging window. At present this is not practically feasible although it is technologically possible by using the latest video and computer technology. Real-time video analysis of the arc would provide a measure of the arc length, but the significant processing speeds required and the high cost of such video equipment required suggest that it is not a realistic option.

ii) The Melting Rate Model

$$Wm = \alpha I + \beta L I^2$$

where

Wm is the wire electrode melting rate,
I is the arc current,
L is the stick out distance.

The melting rate may be defined as the rate at which molten droplets are transferred to the work piece. The melting rate model is an established empirical relationship (Halmoy 1987) which suggests that the melting is mainly due a combination of resistive and arc heating. The resistive component of the melting rate is affected by the stick out distance. Hence, if the stick out distance L varies because of either changes in the arc length or stand off, then the melting rate will change. For a stable arc, the melting rate should be equal to the wire feed rate. For performance assessment the total amount of deviation between the melting rate and the wire feed rate for each transient window was used to compute a performance index which grades the mean deviation for the duration of the test to an acceptable amount of deviation (see section 5.5). The melting rate model will give a useful indication of any internal changes made to the wire itself. The quality performance is assessed using the Halmoy relationship whose α and β terms are basically material related constants. Hence, any unexpected changes to the melting rate due to these factors should be highlighted by this model.

iii) The Transfer Models

$$D = K_v.(Vpk-Vbk) + K_i(Ipk-Ibk)$$

$$D = K_4 + K_5.W$$

where

K_v and K_i are constant from the Arc Length Model
K_4 and K_5 are model constants
D is the droplet detachment length
W is the wire feed rate

The transfer models provide the most direct indication of the performance of a particular wire. The arc length and the melting rate models will indicate the amount of arc stability. However, the transfer model technique predicts the wire feed rate and therefore current needed to achieve stable spray transfer. The variation in this value will therefore directly indicate if the quality of the wire is as good as the reference. The technique requires a pre-knowledge of the expected spray transition current and a performance index is calculated. This index is based on a comparison of the predicted spray transition current from the test to the known value of the reference wire.

The technique relies on the assumption that the mean arc voltage deviation per window is proportional to the change in arc length which in turn is proportional to the droplet size. This assumption is based on the experimental data from welding in both globular and spray transfer modes. The relationship was established by measuring the actual droplet sizes in each experiment using the video and image processing equipment and plotting them against the voltage deviation.

The plot of voltage deviation (droplet size) against current is a curve where the droplet length reduces fairly linearly with the wire feed rate and current when operating from the globular transfer mode to the start of the spray transfer mode. The curve then flattens at higher wire feed rates as the droplet size becomes almost constant. In later experimentation (ESAB 1993) it was found that if the factorial experiments are carried out whilst purely in the spray transfer mode (ie assuming that a higher spray transition current than it should be), then the relationship between voltage deviation and wire feed rate becomes unreliable.

One way to overcome the problem mentioned, may be to calculate the droplet length by multiplying the wire feed rate by the droplet transfer period. However, this requires an accurate measurement of the droplet transfer frequency which is believed possible if a greater amplification of the ac content of the voltage waveform is performed (see Arc Monitoring - FFT above).

The calculated mean droplet length and the mean wire feed rate are then interpolated to an expected droplet length (0.8 x wire diameter) at spray transition to give a predicted wire feed rate at spray transition. The predicted wire feed rate at spray is then fed into the melting rate model to give a predicted spray transition current.

The above models were developed by using stepwise multiple regression techniques utilising a single mean value from each experiment of a set of factorial designed experiments. The 'working point' of the factorial experiments was centred at the spray transition current and nominal arc length at this current. The models were developed using the standard techniques as described in section 2.8 and mentioned in section 5.5. The results from the regression analysis were shown in tables 5.1, 5.2, 5.3 and 5.4. It may be seen that in all cases, the standard errors were very low and the coefficients of determination (R^2) were very close to unity. Correlation analysis techniques were employed to prevent collinearity.

Validation of the models was achieved by three methods. Prior to developing the final models, some of the data was omitted and these were used to validate the models. Secondly, several new experiments were performed producing fresh data not used to test the models. Finally, independent experiments were performed with other unknown wires in the presence of an experienced welder.

On-line tests of wires (which are presumed to have been manufactured to the same performance) were performed in two stages. Firstly, the 'Group I' and 'Group II' wires used for the preliminary tests were re-examined with the modelling technique.

The implications, limitations, advantages and disadvantages of the structure of the models and the overall quality performance assessment technique will be discussed in the following sections.

6.3 Limitations and Sources of Error of the Modelling Technique

The technique of using the statistical models described for quality assessment has the following limitations and difficulties:

a) The quality assessment procedure is a comparative technique, which compares the data evaluated for a particular welding trial to a set of stored values for a wire of a similar type. This means that the stored data for each new reference wire must be derived from a set of factorial experiments and will be loaded into the testing software whenever a new wire is to be tested.

Although the modelling technique cannot be eliminated, a version of the software has been designed which will simplify the modelling exercise. The software will automatically design the settings required for the factorial experiments and automatically capture the data for each experiment and evaluate the model coefficients when all of the experiments have been performed. However, the software assumes that the correct settings of the current and arc length for each experiment were made. The various statistical error factors are also calculated in order to check the adequacy of the model. However, since the number of experiments are small, their usefulness is limited.

b) The technique relies on the calculation of statistical results based on data from a small number of experiments. Hence, the measurement of the arc length during the factorial experiments must be accurate or the evaluation of the model coefficients can cause serious inaccuracies.

c) The technique will only produce reliable results if the welding tests are performed at the working point used to derive the model coefficients.

d) The linear relationship between droplet length and voltage deviation is derived from the belief that since the arc length is proportional to the arc voltage or current, then the change in arc length must be proportional to the change in arc voltage or current. It is then assumed that the change in arc length must be due to the droplet transfer and is proportional to the droplet length. This is only a statistical relationship which proved very successful for the 1.6 mm reference wire used. However, the relationship may not be valid for all types of wire. In addition, the relationship is only valid from the globular transfer mode to just into spray transfer mode. This means that the experiments must be carefully designed to centre close to the spray transition current.

e) The arc length model includes both a term for the arc voltage and the arc current. The current term is included so that the model can be used both for constant current and constant voltage power sources. From previous work, a linear relationship between arc length and arc voltage in the working range is acceptable for constant current equipment. However, for constant voltage equipment the model assumes that the current is varied linearly to keep the arc length constant. Although this relationship was acceptable in the working range of the present work, it may not be true at different working points and for other power sources which may employ more advanced techniques for arc length control.

f) The melting rate model is based on the Halmoy equation and the technique depends on the assumption that the α and ß terms will remain constant for a particular type of wire. Although, a 'bad' wire will give different and varying burn off rates during a length of weld, the technique is unable to detect whether these are due to variations in the α and ß terms caused by abnormalities in the wire mixture or flux at these points.

The Halmoy equation also incorporates a 'Stick Out' term which is equal to (Stand-off - Arc length). This assumes that the 'Stand-off' remains constant during the length of weld. However, work piece buckling, torch movement and other reasons can cause the stand-off to change and therefore can affect the evaluation of this model.

g) The transfer model includes several assumptions that can affect its performance. Firstly, the technique assumes that there is a linear relationship between droplet length and the voltage and current deviations. As mentioned, this relationship is only true in the globular to spray range. Secondly, the technique assumes a linear relationship between the wire feed rate and the droplet length. Hence, it is important to centre the experiments at the spray transition current or the relationships may be inaccurate.

h) The automatic evaluation of the model coefficients is based on the data obtained from the factorial experiments which involves only a few data points. At present the software is unable to include additional data to improve the models.

i) The technique provides three factors which indicate the quality performance. Another factor which can affect arc stability is the gas shielding. At present it is not possible to determine whether the loss or reduction of the gas shielding is to blame for the performance changes.

j) Fundamental to the technique is the use of computer based data acquisition. Since, computers are very sensitive to electrical noise, the system was designed with high quality analogue filtering. However, the system is not capable of operating in an environment where high frequency start mechanisms for TIG welding are employed.

6.4 Mathematical Modelling of the Sound Data

As a result of an independent investigation of the sound data (captured at the same time as the electrical characteristics), it was found that the arc sound waveform represented a differentiated version of the voltage waveform. Hence, by performing a numerical integration of the sound data, it was possible to reproduce the main frequencies observed in the voltage and current waveforms with a slight delay.

The relationship was tested by performing experiments with pulsed and dip transfer GMA welding. The numerical integration clearly reproduced the shape of the current waveform. At this time it was decided to use the modelling technique devised by using the integrated sound data. It was found that acceptable models for the arc length, melting rate and the transfer could be produced by using the sound data in the same format as the electrical characteristics. The techniques were then further validated and tested with the data saved during the on-line tests described earlier. Although, the results obtained were not as good as those obtained from the electrical characteristics, it was believed that the overall performance of the technique was very successful.

It should be noted that the microphone can pick up background noise from the machinery or by someone talking as they pass by the equipment, hence the microphone must be directional and pointed perpendiclar to the arc. It is sugested that a differential technique that uses two microphones may be a method to limit the effects of background noise. One microphone may be pointed at the arc, whilst the other microphone is directed towards the background. A combination of hardware filtering and FFT software filtering techniques may be considered.

The fact that the mean deviation in the integrated sound data was found to be proportional to the droplet length suggests that there is a direct correlation between the arc audio signal and the arc current. The requirement of the numerical integration is due to the type of microphone employed which probably employs internal differential techniques to convert the sound to electrical voltages.

It may be suggested that the sound signal is a single factor, whereas the models produced by the electrical characteristics involved the use of two factors, ie the voltage and the current. However, it should be mentioned that the voltage and current signals are not in fact totally independent variables in the true sense of their meanings and each of the models only really requires a single variable to perform.

The work has shown that the sound signal can be used for quality monitoring. Since the satisfactory results were obtained from the electrical characteristics, it is not clear how the use of the sound signal can be used for practical purposes.

6.5 Advantages of the Modelling Technique

Previous work in the area of arc stability measurement with GMA welding has involved simple statistical factors which have been used mainly for dip transfer mode. Philpott (1987) was one of the first researchers to produce a practical device (called ARCGUARD) that incorporates a computerised monitoring technique which detects arc stability for automatic robotic welding.

Previous researchers working with mathematical models (eg Alfaro 1989, Scotti 1992, Modenesi 1990) have managed to produce empirical relationships to predict process parameters such as weld bead geometry etc. Others such as Galopin et al (1992) have tried to optimise the modelling methods for procedure and process enhancement. However, there are few examples which have provided a method of direct performance comparison.

The technique of capturing 'windows' of transient with gaps means that the processing capabilities of the computer and the amount of useful transient data required for a length of weld can be optimised.

The modelling technique effectively involves the 'finger printing' of the welding quality performance of the consumable by performing a number of pre-test experiments. Therefore, the procedure can be used to improve the performance of the consumable once the reference has been tested.

The automation of the data acquisition and analysis leads to a reduction in errors caused by inexperienced welders and faulty or misinterpretation of measuring equipment (unless of course the computerised system is faulty !).

The significance of the models described are well understood within the welding industry and represent physical events within the welding process and are therefore more practically suitable to purpose of stability assessment than purely statistical values.

6.6 Other Techniques That Can be Used

An alternative approach to analyze the data would be to use Artificial Neural Networks (eg Stroud 1991). This technique does not require any understanding about the physical principles and activities that are involved with the process. This can have both advantages and disadvantages. The advantages are that the network can be trained to detect the ideal waveform and compensate for instabilities. The disadvantages include the fact that the design of the network has to be optimised and has to be re-trained with new problems unless they existed within the range of the initial training data.

7. CONCLUSIONS

7. CONCLUSIONS

The purpose of the present work was to produce an objective method to determine the quality performance of flux cored wires. The existing method involved the subjective assessment of experienced welder performing a short bead-on-plate weld test using a fixed GMA welding procedure.

1. It was established that existing monitoring equipment was not capable of providing the transient data at the required sampling rate for the full duration of the welding test. Hence, a proprietary computer based monitoring system was built which was designed as a fully flexible instrument for on-line data analysis.

2. The 'transient window' sampling technique was necessary, whereby the data is captured in small blocks of transient data with a variable interval between each window. This technique provides both statistical and transient information for any duration of welding.

3. It was found that the visible light and audible sound signals followed the electrical characteristics of the arc. However, no extra information regarding the stability of the process was detected by using these signals and they were therefore later abandoned as components necessary for the quality performance technique.

4. Mathematical modelling techniques can be developed to obtain quality performance models based on assessment of the arc length, the melting rate and the droplet transfer.

5. The models were validated and used to set performance acceptance limits based on comparing the deviation of the monitored values to the predicted values evaluated from the reference wire.

6. The system, comprising a purpose built monitoring package, models and software was able to meet the requirement for objective assessment of wire quality.

8. RECOMMENDATIONS FOR FURTHER WORK

8. RECOMMENDATIONS FOR FUTURE WORK

The modelling technique was used to produce a method of assessing welding quality performance of fluxed cored wires. The system was produced by studying a particular 1.6 mm diameter wire. The following areas of research are suggested to optimise the performance of this technique:

1. Various combinations of powder mixtures and fluxes should be tested using the 1.6 mm wire and a database established to relate particular powders to the performance criteria.
2. The technique should be extended to test other types of flux cored wire and ordinary carbon steel wires.
3. The measurement of droplet size should be performed more accurately. The use of either the (Wfr x droplet transfer period) relationship or accurate video monitoring and image analysis should be investigated further.
4. The relationship between droplet size and wire feed rate was assumed to be linear over the operating range. It is suggested that further experimentation should be performed to establish a more accurate non-linear empirical relationship between the droplet size and the wire feed rate or current. By this method, a more accurate prediction of the spray transition current can be obtained.
5. The technique should be further developed to investigate the effect of changes in the type of gas shielding used.
6. The modelling technique can be used to develop models for the stand off distance and weld bead geometry. Hence, incorporating these models into the performance assessment software may improve the accuracy of the technique.
7. The execution of the factorial experiments and the modelling exercise could be automated further by directly controlling the moving table and the power source. By this method, all of the experiments can be carried out in a single length of weld. The arc length must be varied by adjusting the stand-off distance and measuring the actual arc lengths by video analysis after the welding test.

8. The system should be installed in the QA testing department of the wire manufacturer. At first, it can be installed in parallel to the subjective assessment tests of the manual welder and later the welder can be just there to weld. Eventually the welder can be replaced by an automated table mechanism.

9. Experimental work with dip transfer mode and the pulsed GMA welding should be continued so that the technique can be extended for consumables that operate in that mode.

FIGURES AND TABLES

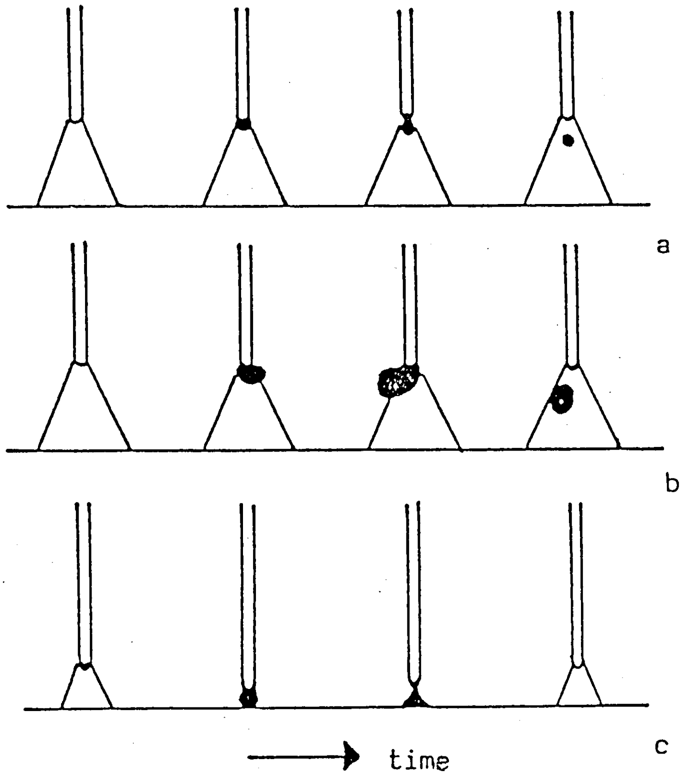


Fig. 2.1a The three metal transfer modes in GMA Welding
(a) Spray Transfer (b) Globular Transfer
(c) (Short Circuiting) Dip Transfer

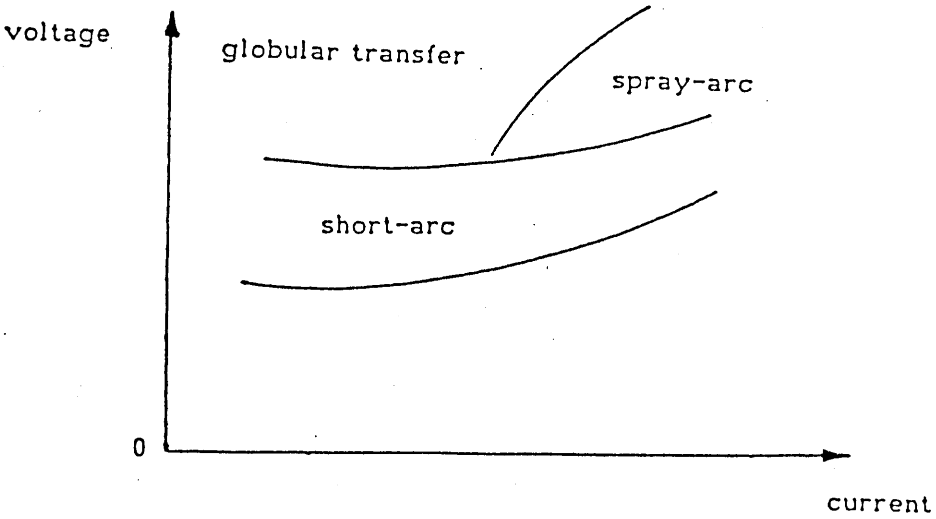


Fig 2.1b The relationship between the V/I characteristic to metal transfer mode (in principle)

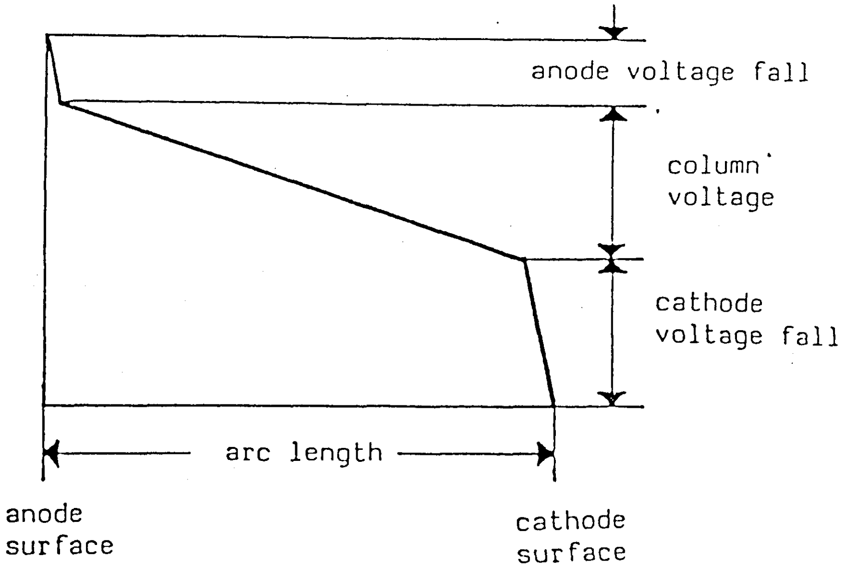


Fig 2.2 The three main zones of a welding arc and the potential fall in the respective zone.

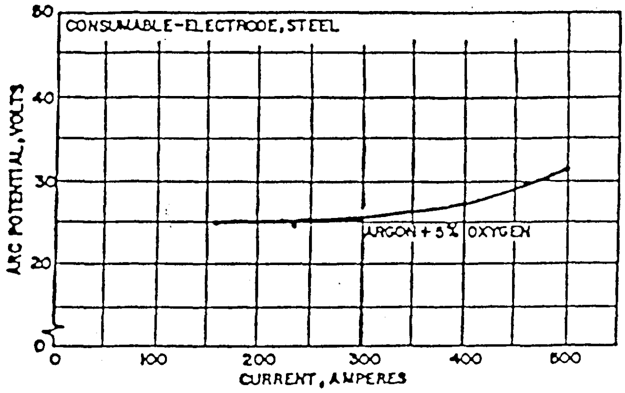


Fig 2.3 Typical V/I Characteristics of a welding arc at constant arc length.

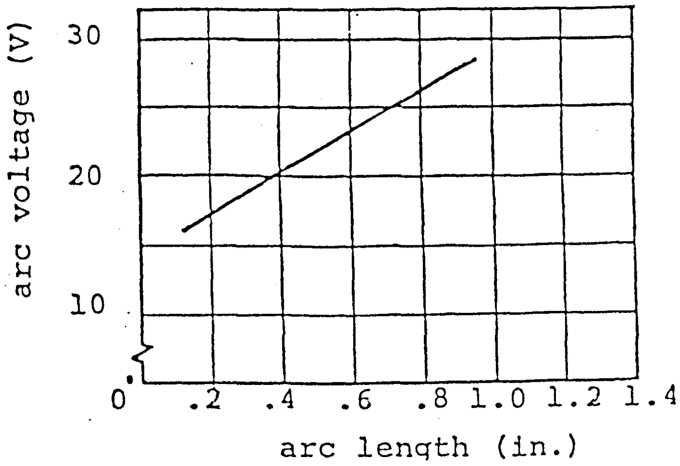


Fig 2.4 The influence of the arc length on the arc voltage at constant arc current.

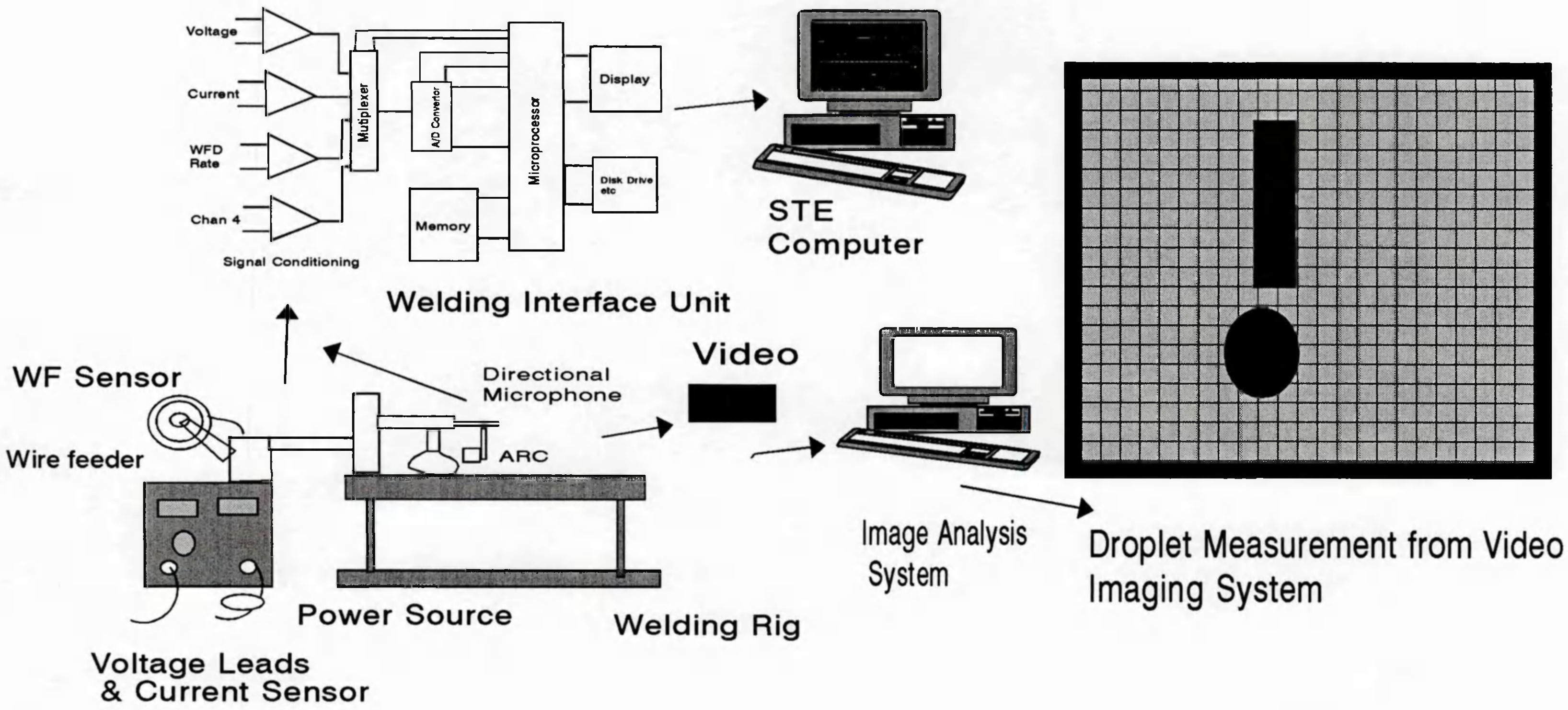


Fig 3.1 Block diagram of the Droplet Measurement System

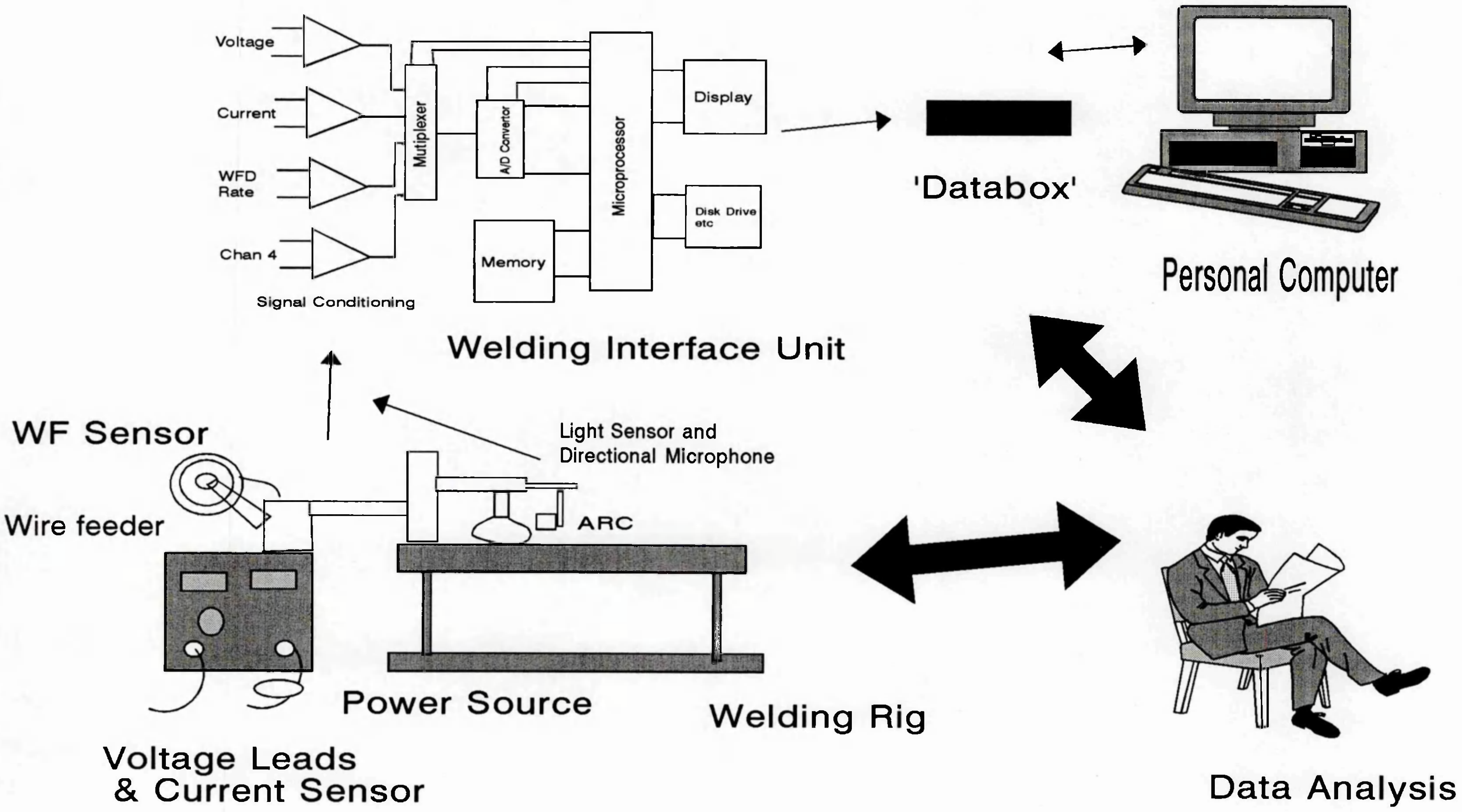


Fig 3.2 The 'Preliminary' Experimental Set up

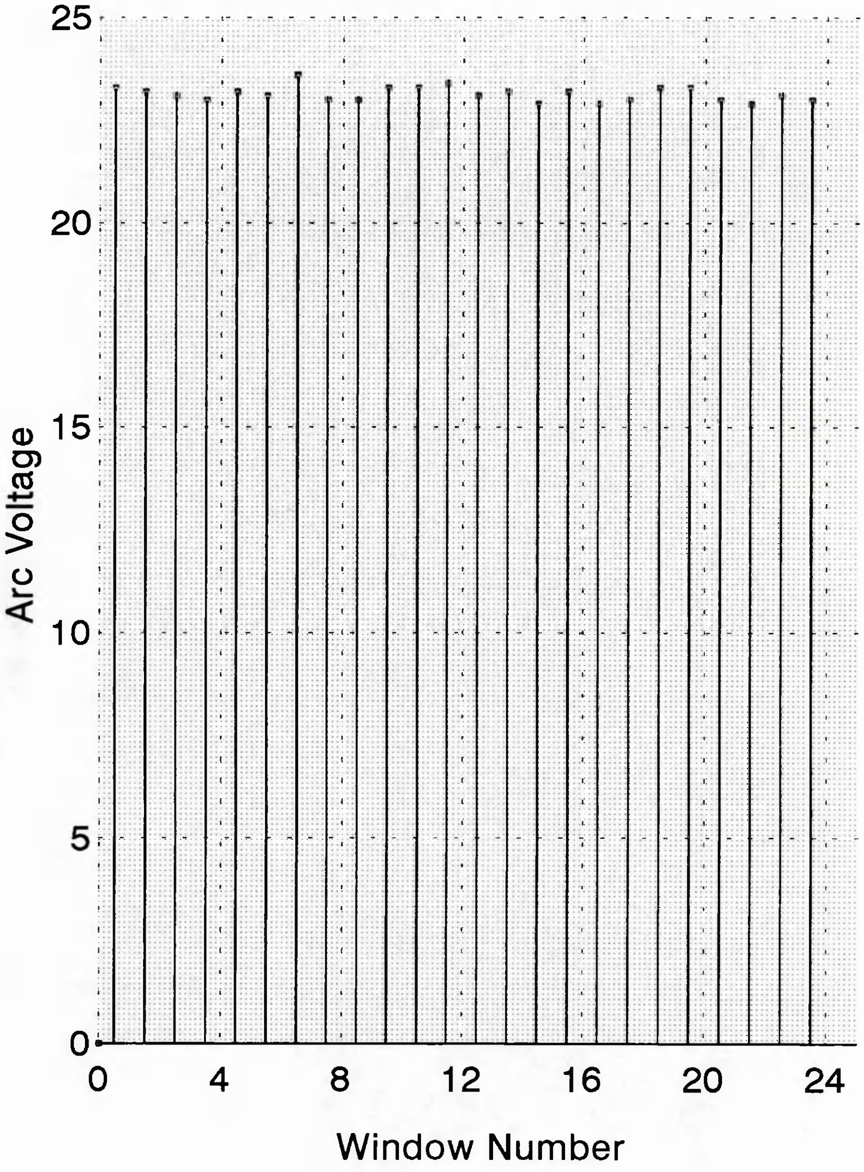


Fig 4.1 The Windowing Technique for Data Acquisition

* During each window a block of 512 samples are captured at a very high sampling rate. In between the windows the computer is free to perform other functions.

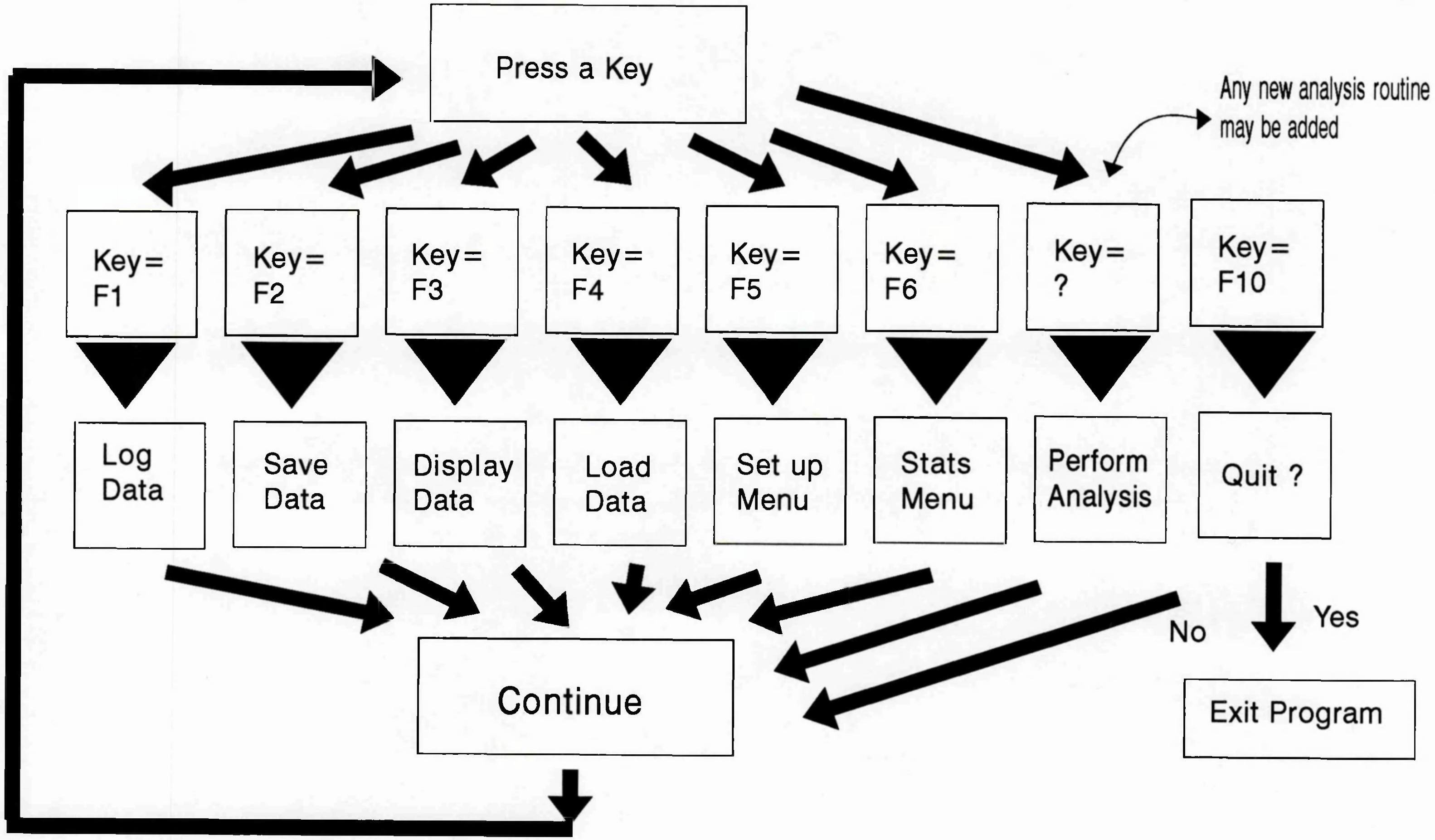
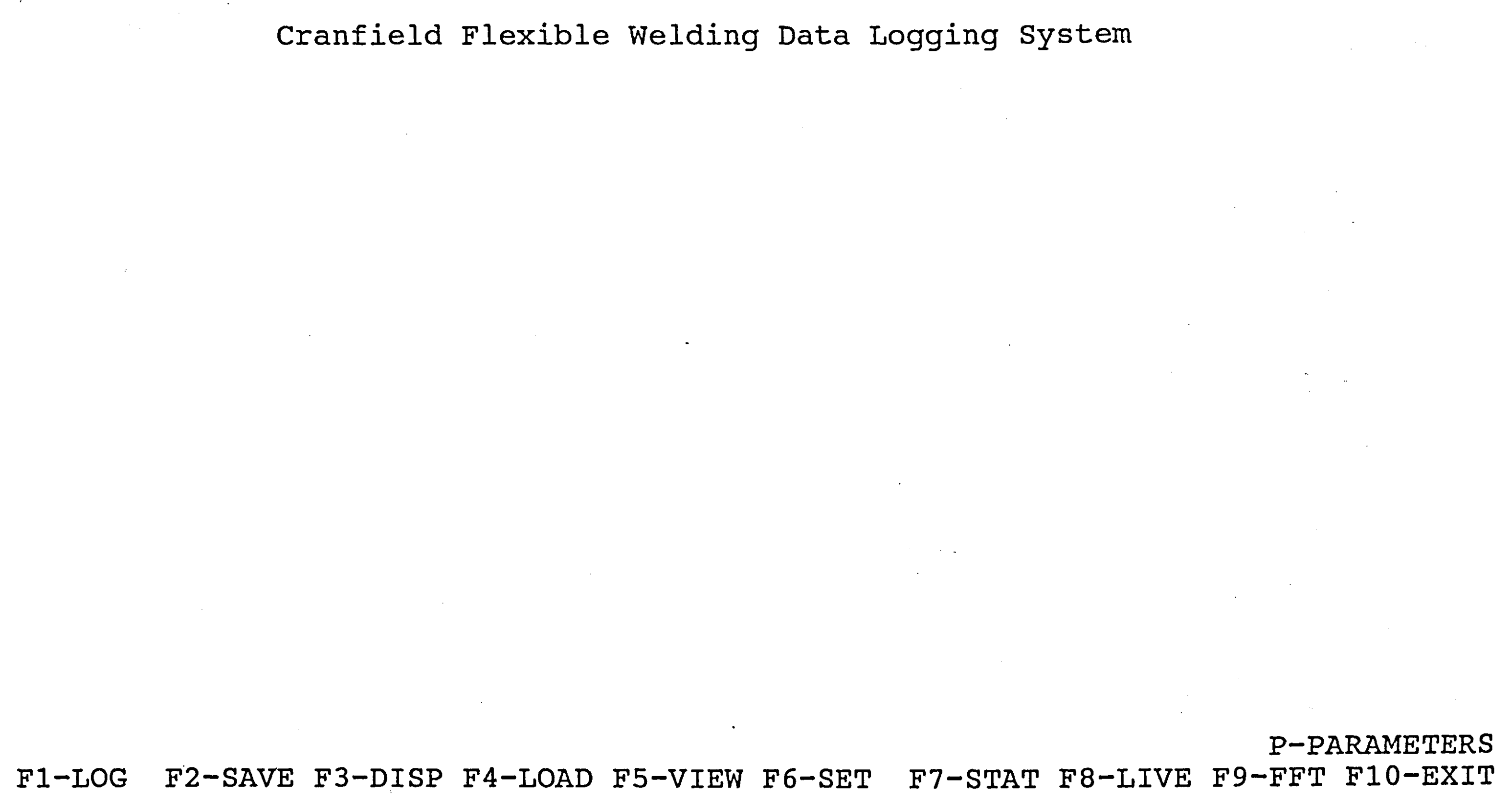
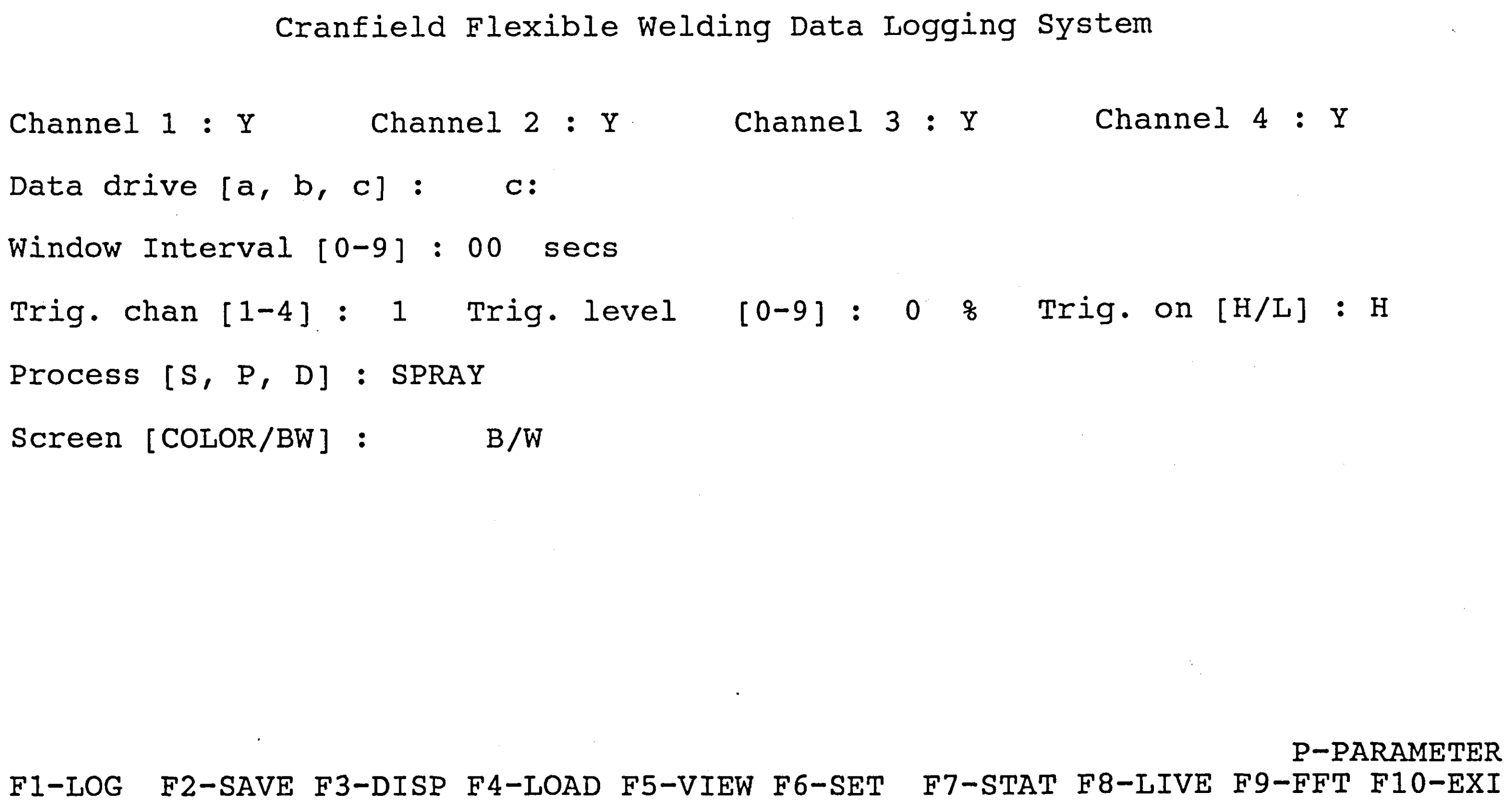


Fig 4.2 Specification of the Preliminary (QSAB7) Software



```
                    Cranfield Flexible Welding Data Logging System









                                                                      P-PARAMETERS
F1-LOG  F2-SAVE F3-DISP F4-LOAD F5-VIEW F6-SET  F7-STAT F8-LIVE F9-FFT F10-EXIT
```

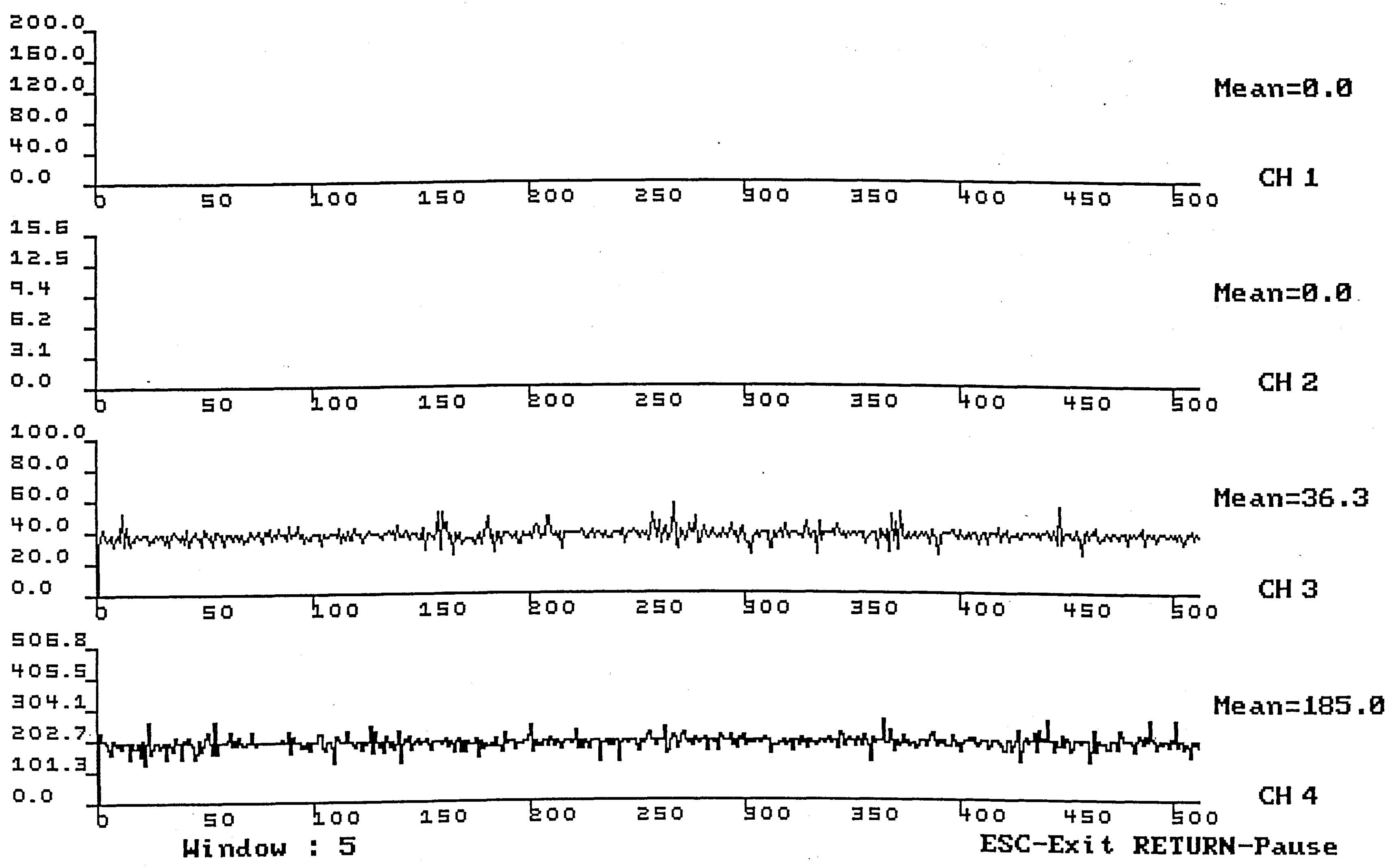
Fig 4.3a The Main Menu Screen of the 'QSAB7' Software

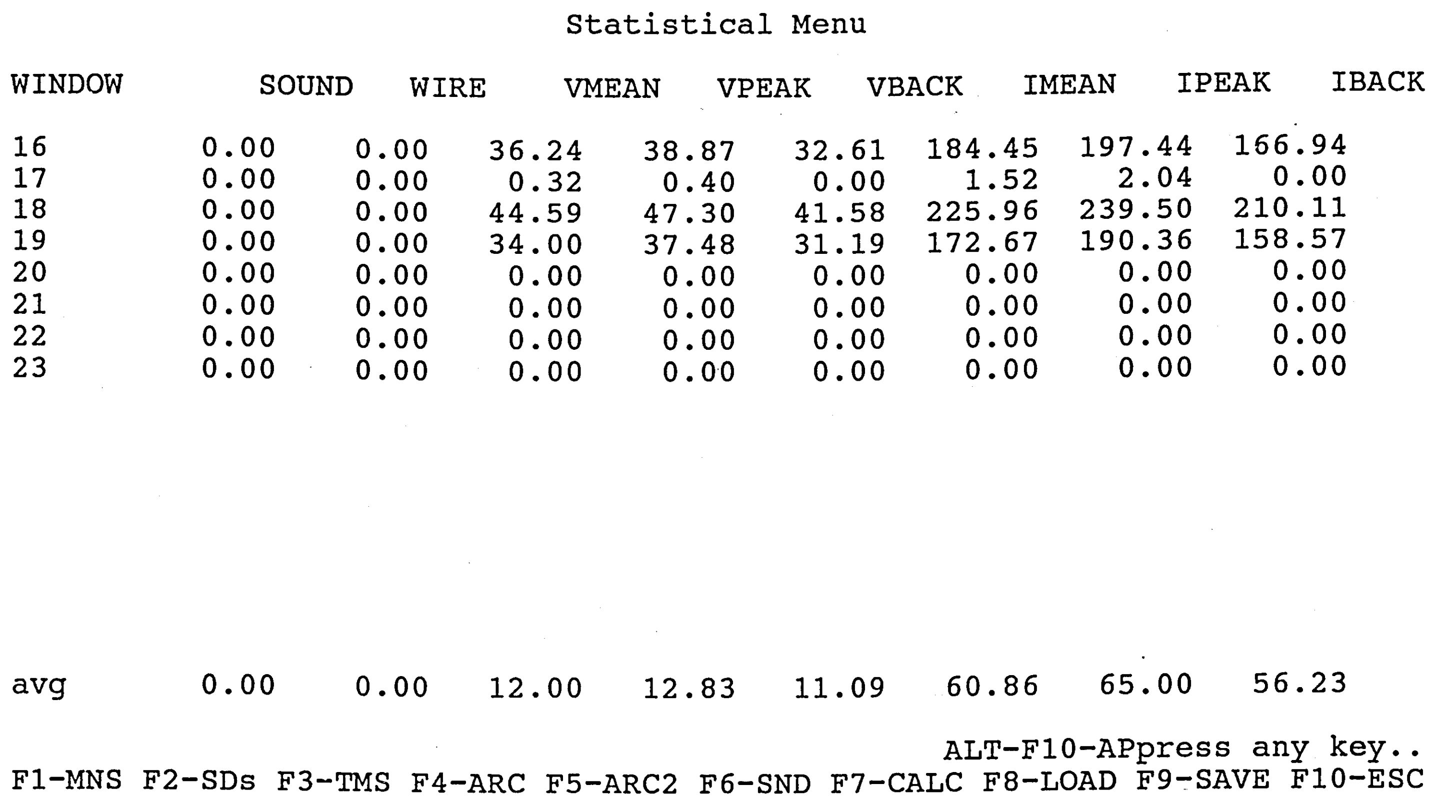


```
                 Cranfield Flexible Welding Data Logging System

Channel 1 : Y       Channel 2 : Y       Channel 3 : Y       Channel 4 : Y

Data drive [a, b, c] :    c:

Window Interval [0-9] : 00  secs

Trig. chan [1-4] :  1   Trig. level   [0-9] :  0  %   Trig. on [H/L] : H

Process [S, P, D] : SPRAY

Screen [COLOR/BW] :      B/W




                                                                   P-PARAMETER
F1-LOG  F2-SAVE F3-DISP F4-LOAD F5-VIEW F6-SET  F7-STAT F8-LIVE F9-FFT F10-EXI
```

Fig 4.3b Set Up Menu Screen of the 'QSAB7' Software

Fig 4.4a Typical Graphical Display of Transient Data from 'QSAB7 Software





```
                        Statistical Menu

WINDOW        SOUND    WIRE     VMEAN    VPEAK    VBACK    IMEAN    IPEAK    IBACK

16          0.00     0.00    36.24    38.87    32.61   184.45   197.44   166.94
17          0.00     0.00     0.32     0.40     0.00     1.52     2.04     0.00
18          0.00     0.00    44.59    47.30    41.58   225.96   239.50   210.11
19          0.00     0.00    34.00    37.48    31.19   172.67   190.36   158.57
20          0.00     0.00     0.00     0.00     0.00     0.00     0.00     0.00
21          0.00     0.00     0.00     0.00     0.00     0.00     0.00     0.00
22          0.00     0.00     0.00     0.00     0.00     0.00     0.00     0.00
23          0.00     0.00     0.00     0.00     0.00     0.00     0.00     0.00




avg         0.00     0.00    12.00    12.83    11.09    60.86    65.00    56.23

                                                ALT-F10-APpress any key..
F1-MNS F2-SDs F3-TMS F4-ARC F5-ARC2 F6-SND F7-CALC F8-LOAD F9-SAVE F10-ESC
```

Fig 4.4b Typical Statistical Output Screen of the 'QSAB7' Software

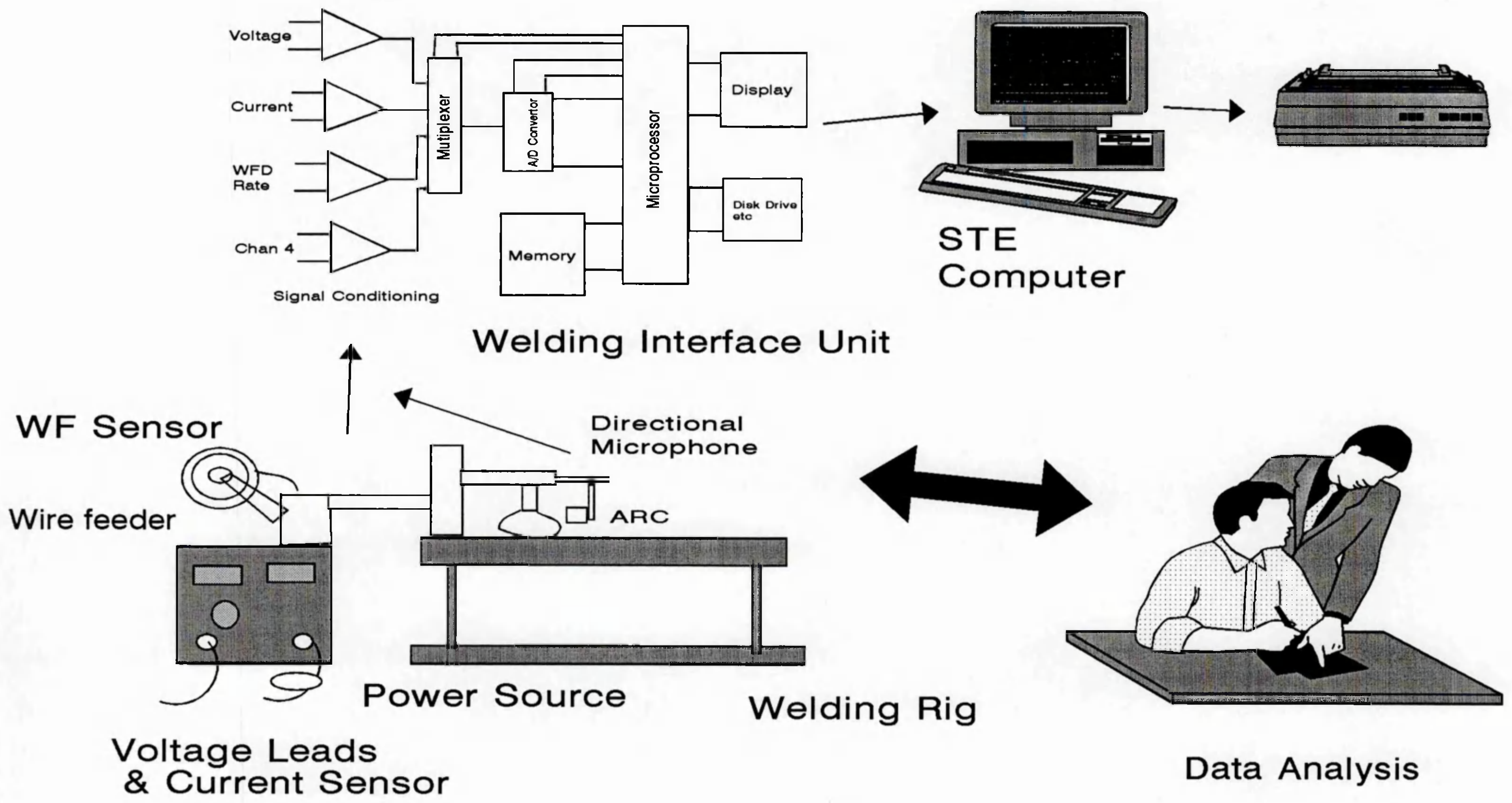


Fig 4.5 Block diagram of the Experimental Set Up

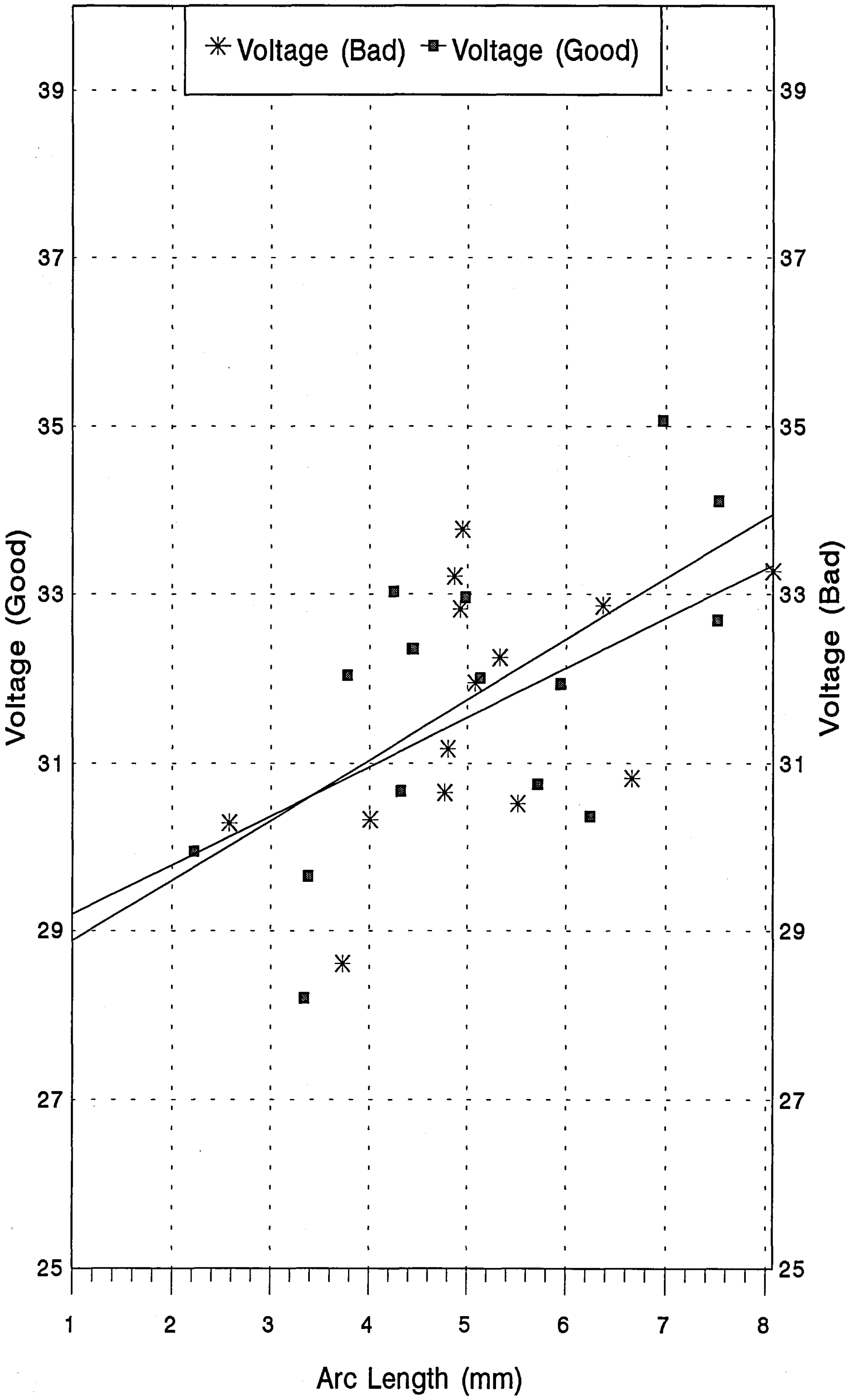


Fig 5.1 Arc Length Vs Arc Voltage for Good/Bad Wires

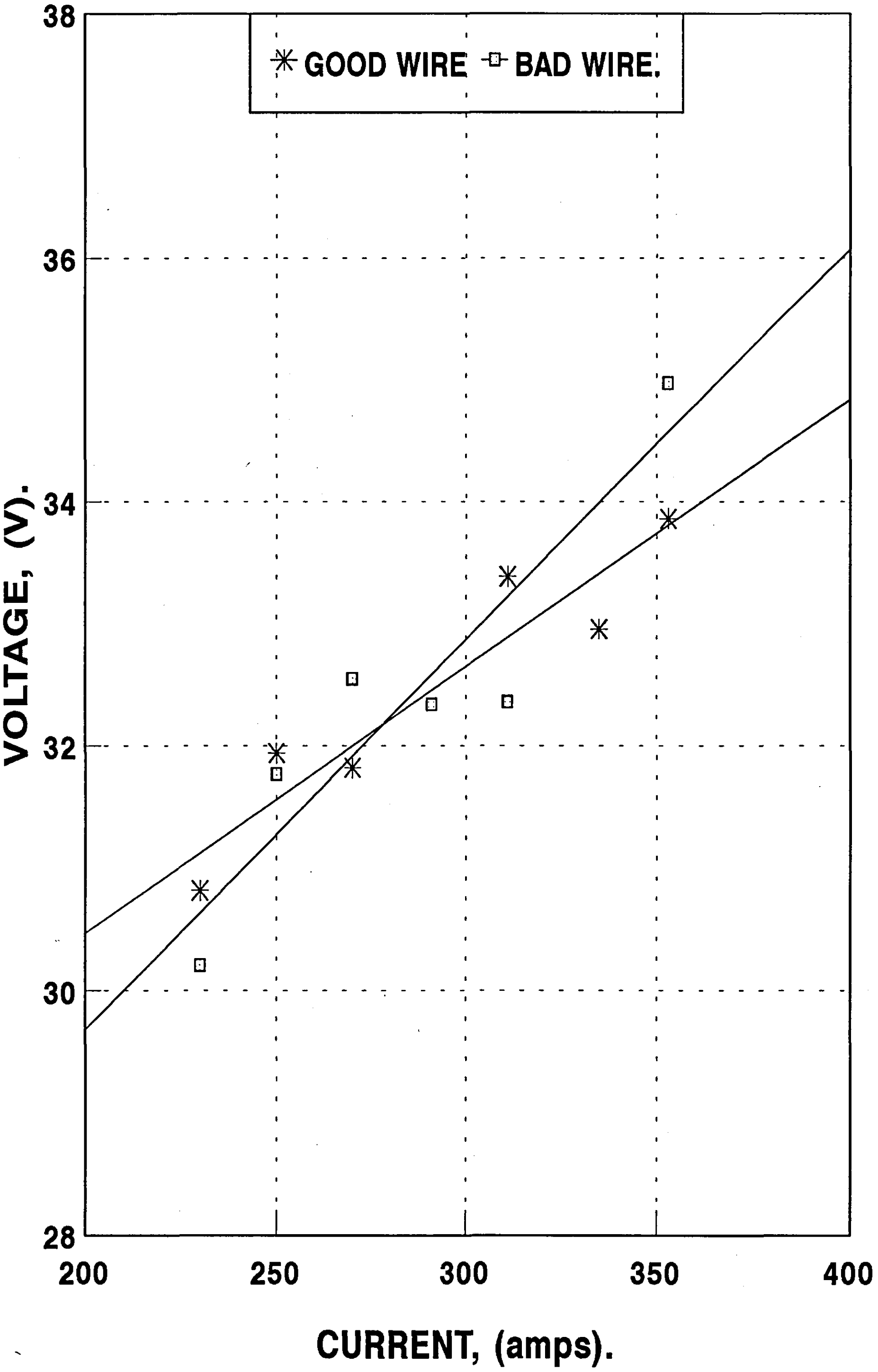


Fig 5.2 Mean Current Vs Mean Voltage (Spray GMAW)
[1.6 mm Flux Cored Wire (Stand Off 20mm, Stick Out 15mm)]

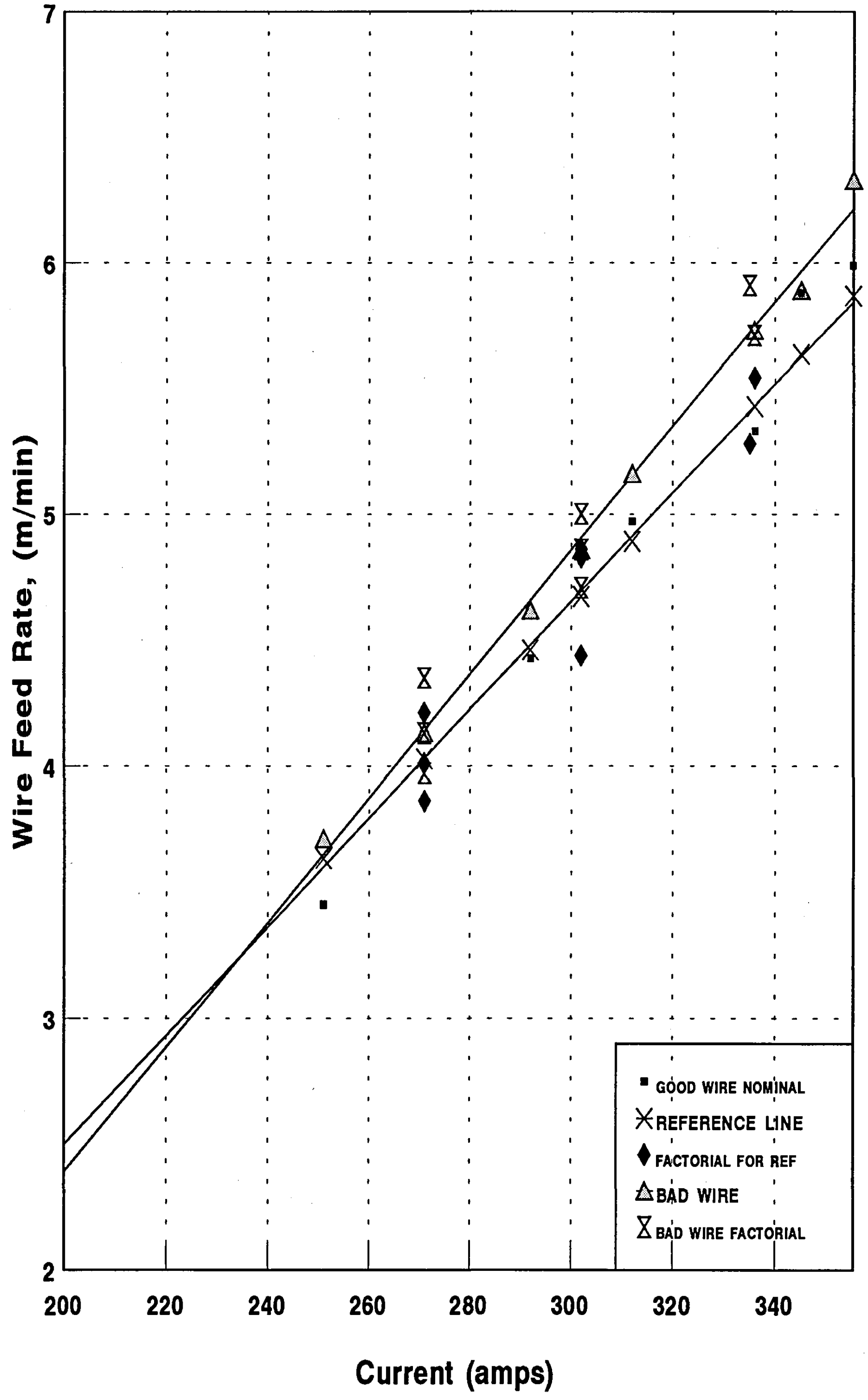


Fig 5.3 Wire Feed Rate Vs Current For Good/Bad Wires
[Fitted to W = 0.0095*I + .00000132*Isq*L]

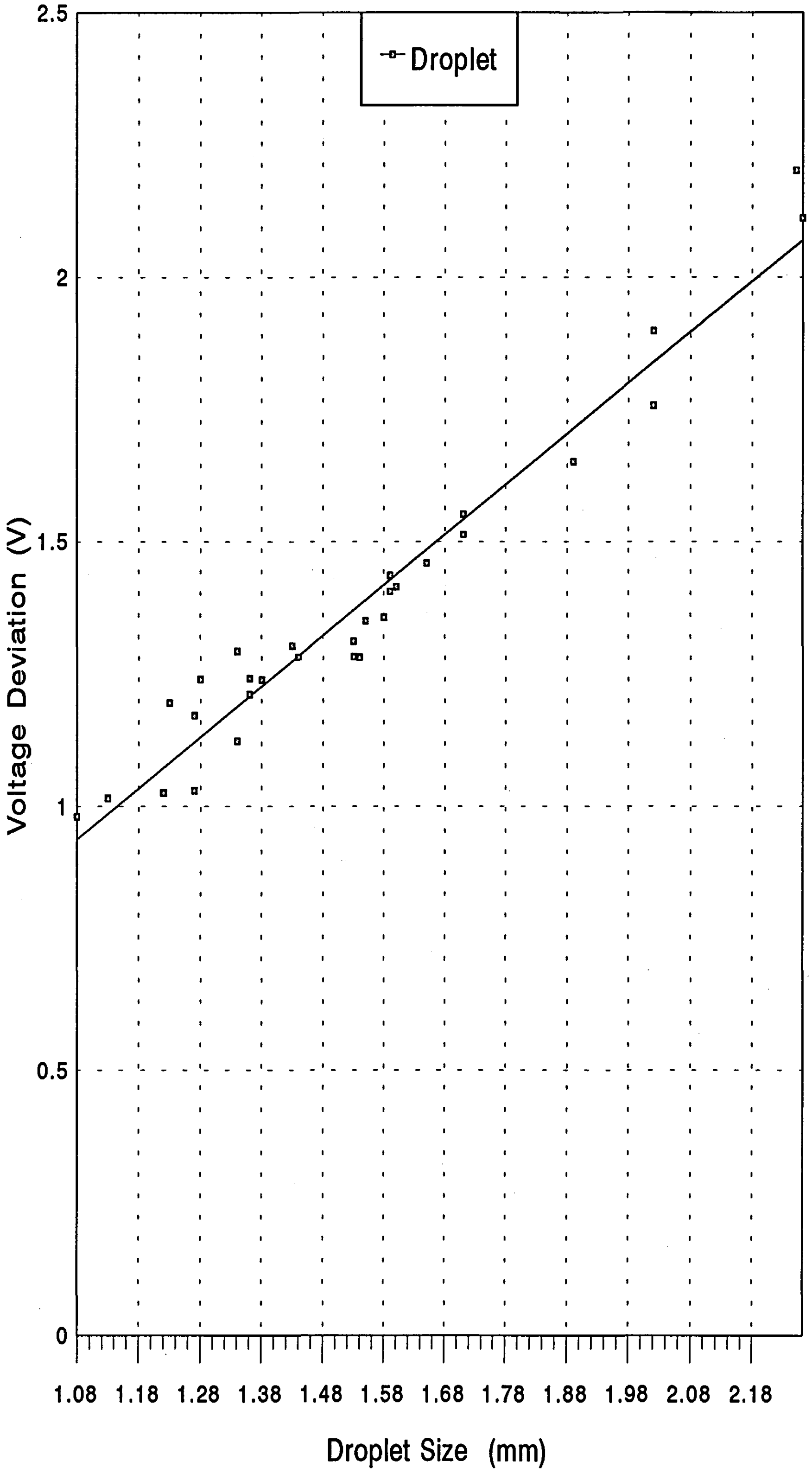


Fig 5.4 Comparison of Arc Voltage Deviation Vs Droplet Size

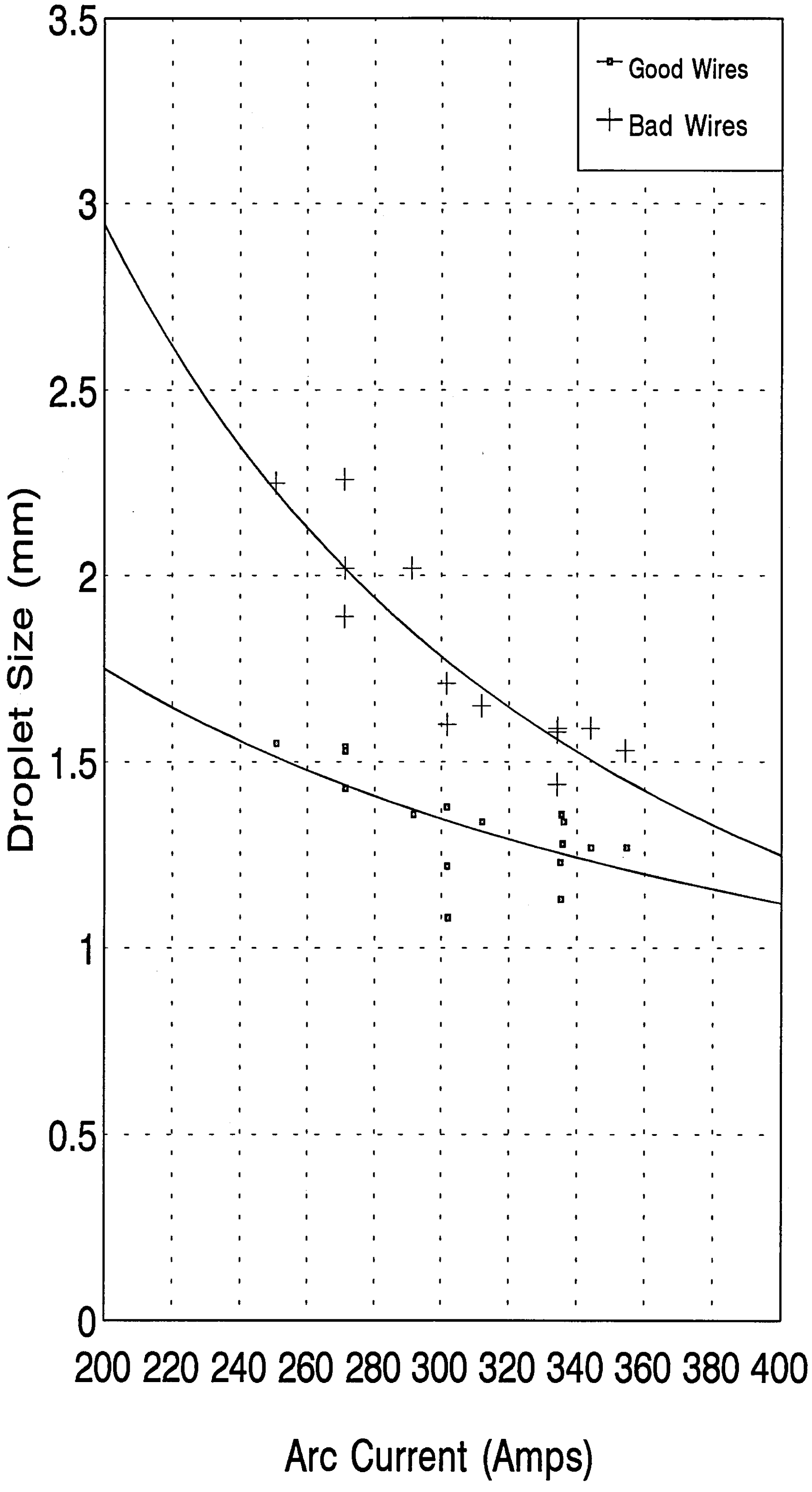


Fig 5.5 Comparison of Droplet Size Vs Current for Good/Bad Wires

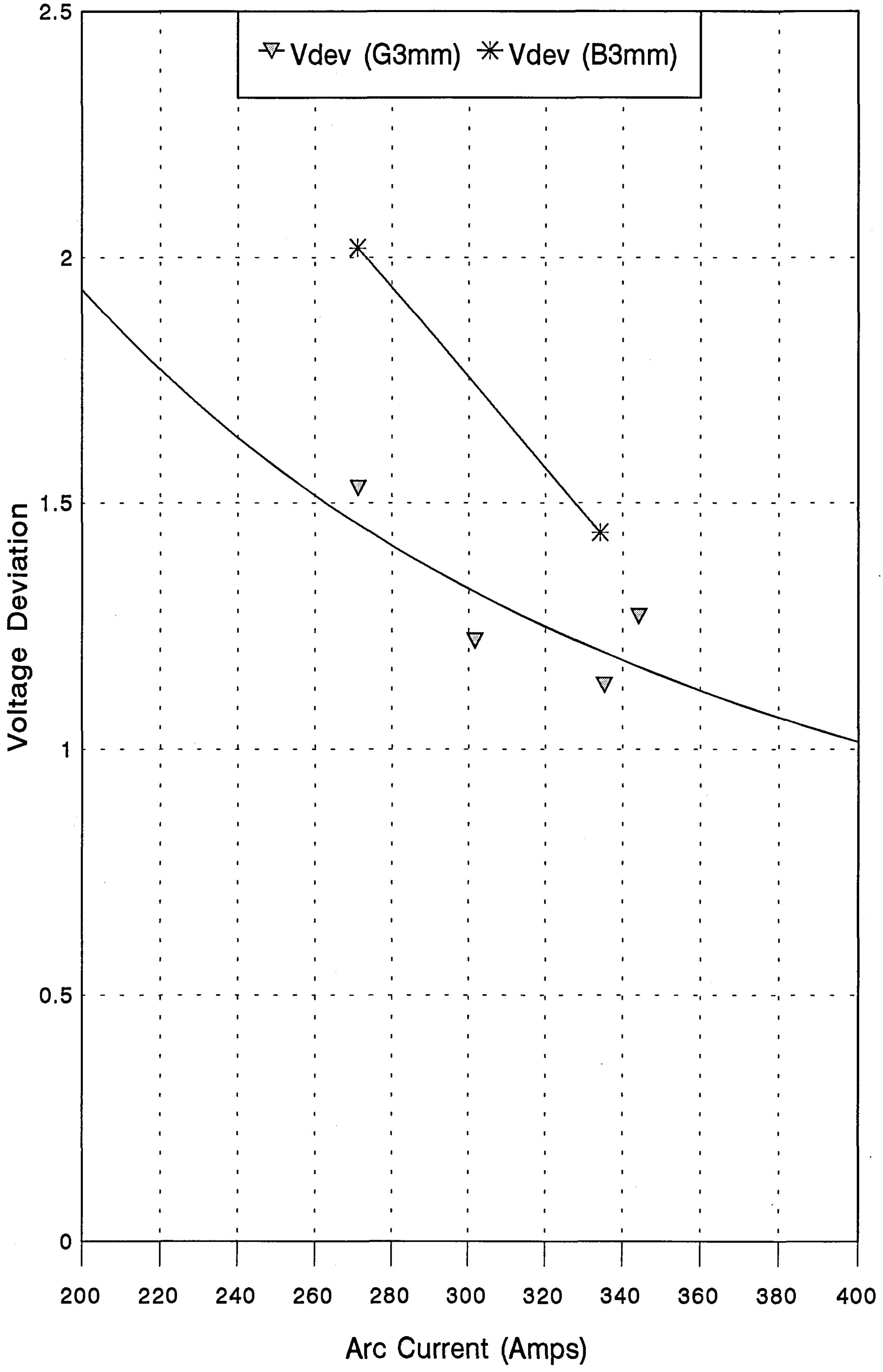


Fig 5.6 3mm Arc Length

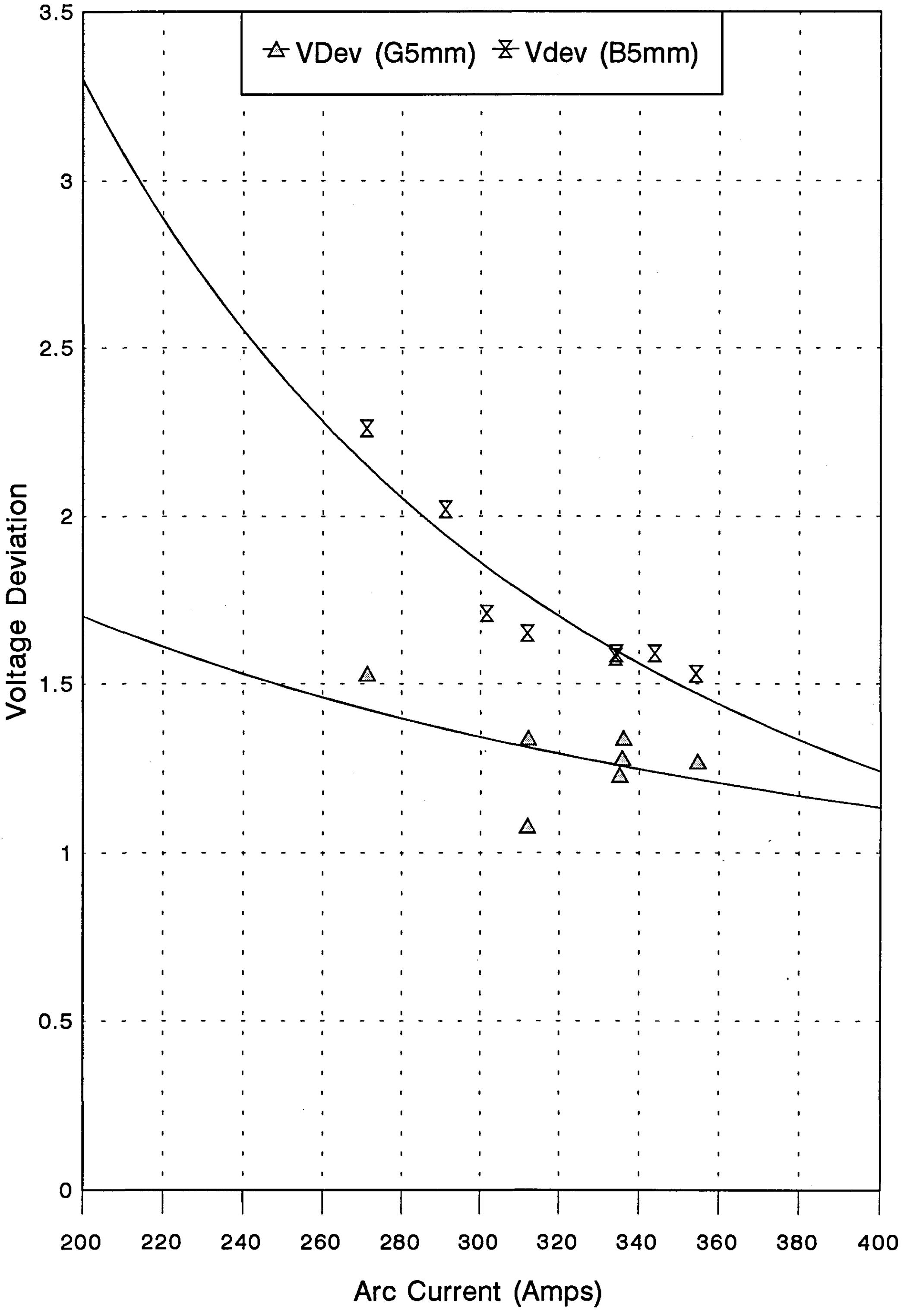


Fig 5.7 5mm Arc Length

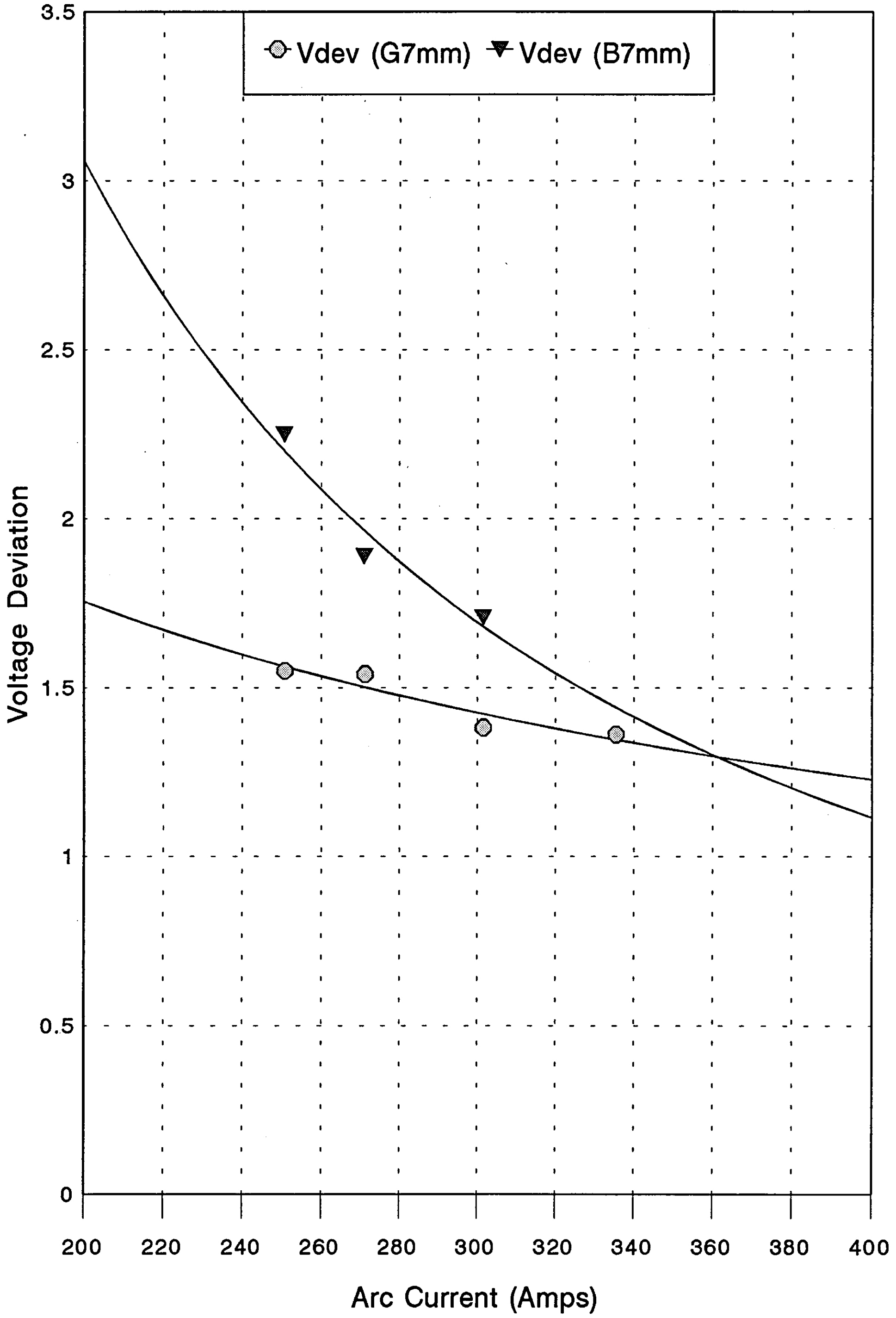


Fig 5.8 7mm Arc Length

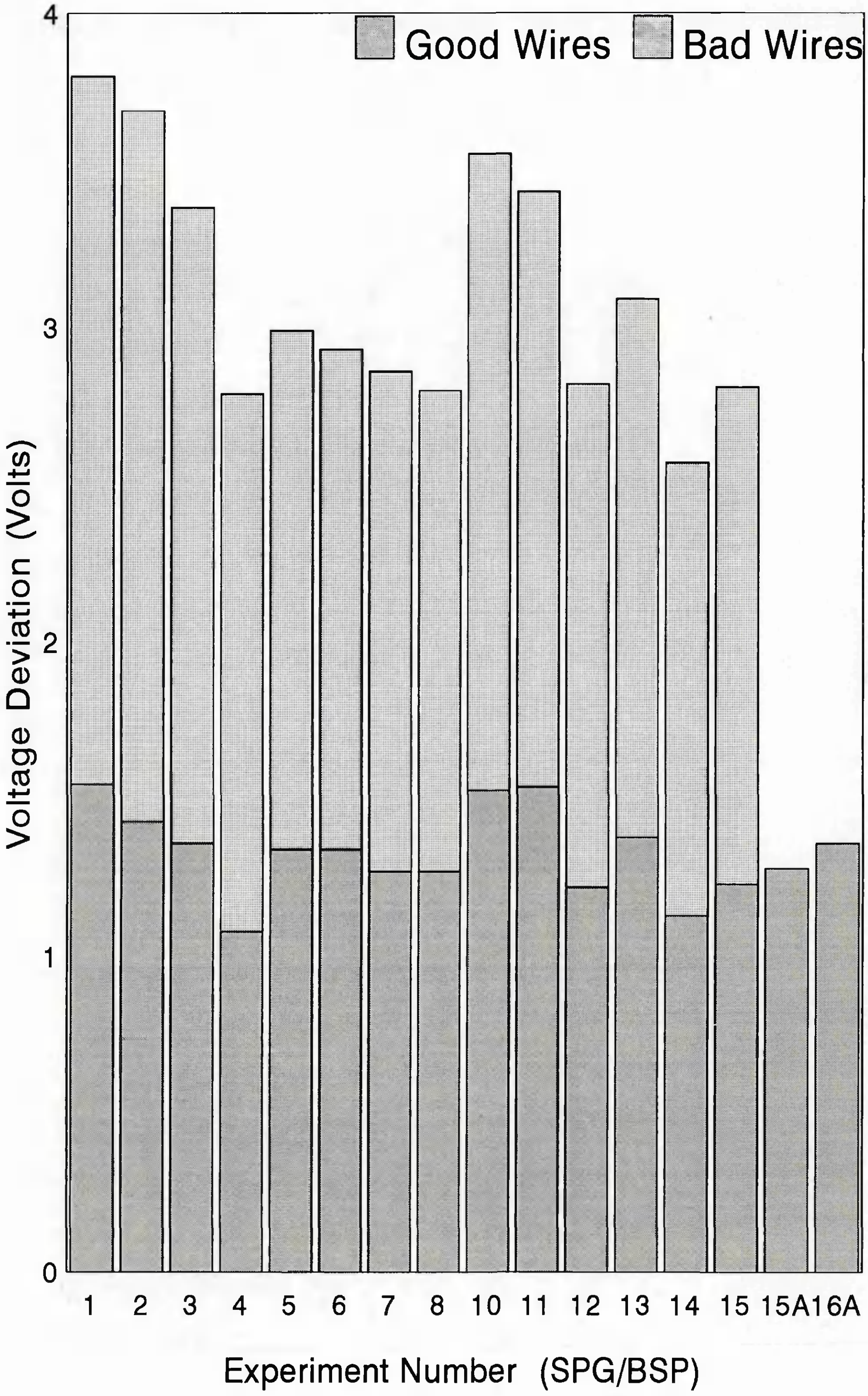


Fig 5.9 Comparisons of Voltage Deviations for Good/Bad Wires

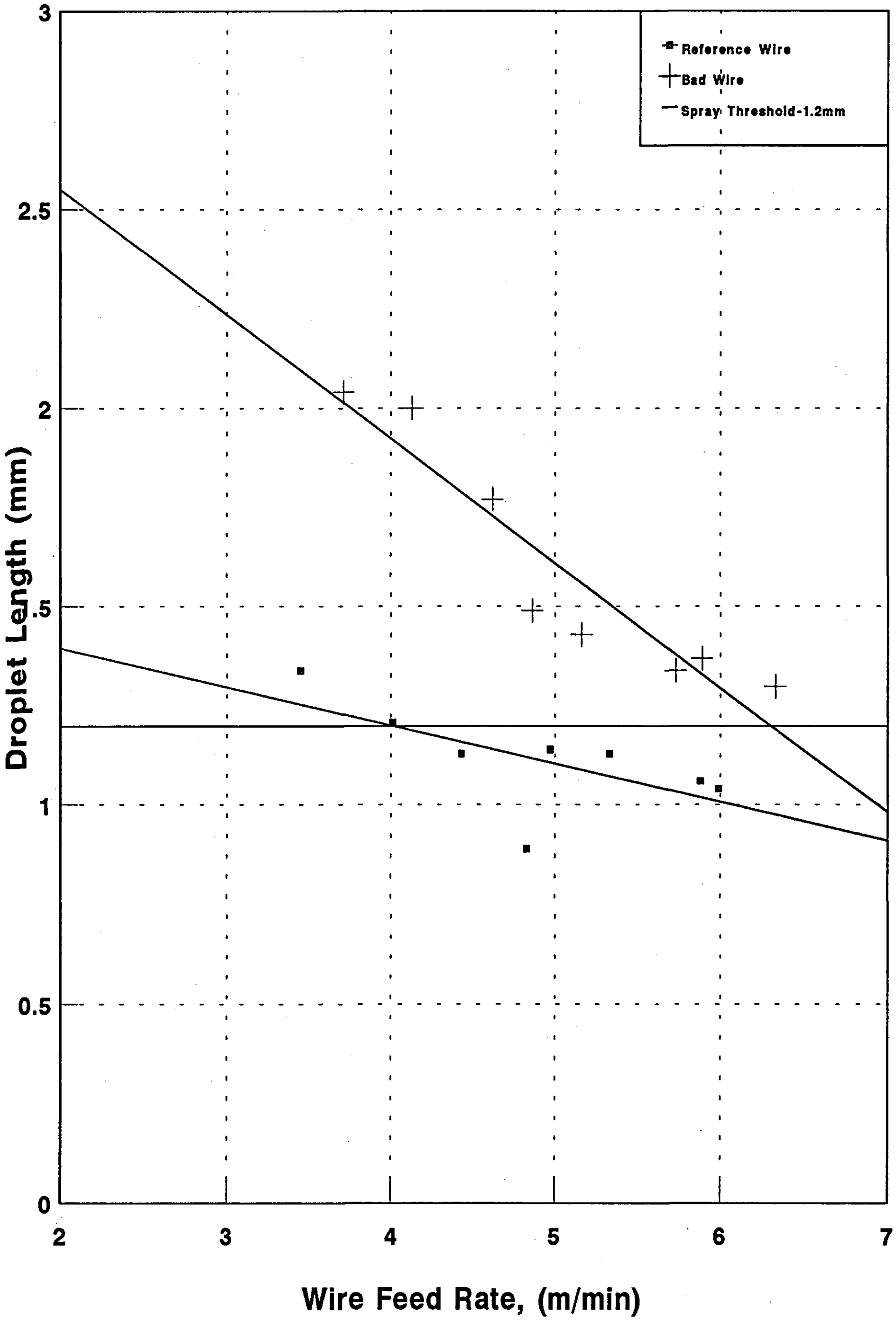
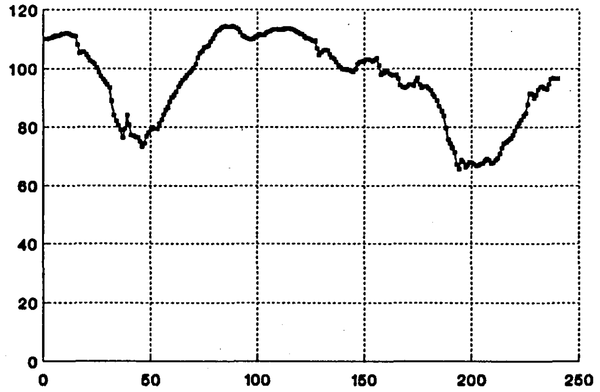
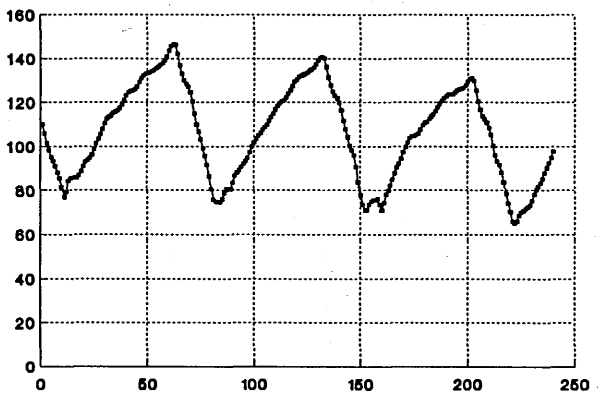


Fig 5.10 Droplet Length Vs Wire Feed Rate (Spray)



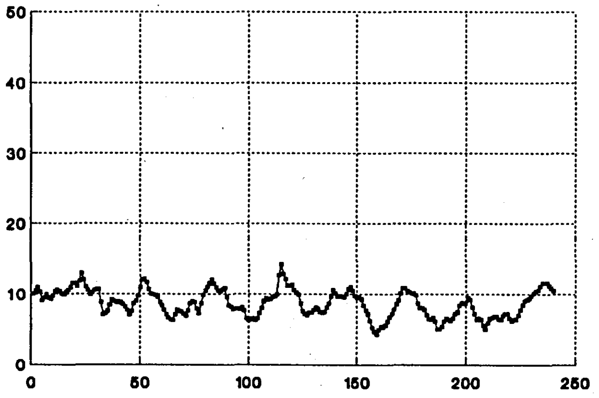
Typical Integrated Dip Sound Signal

(a)



Typical Intergrated Pulse Sound Signal

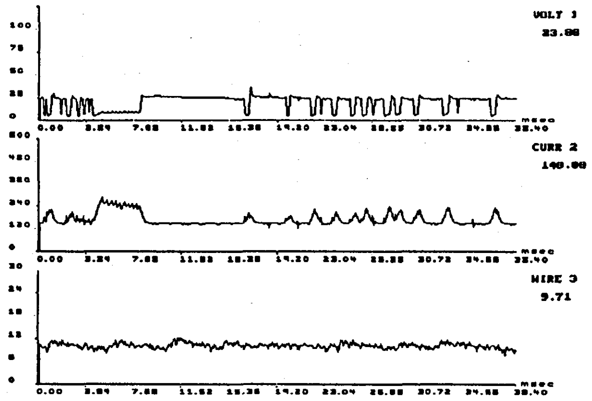
(b)



Typical Integrated Spray Sound Signal

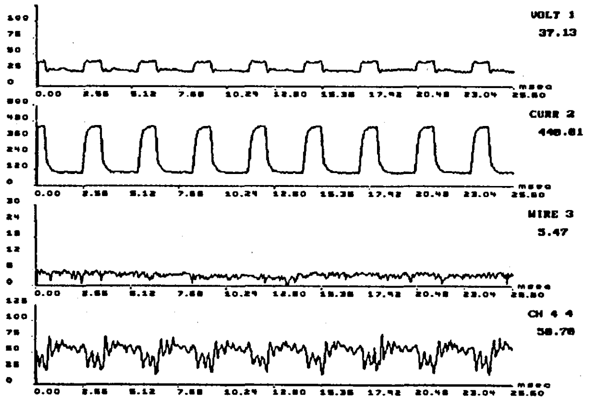
(c)

Fig 5.11 Investigation of the Sound Signal Using DADISP



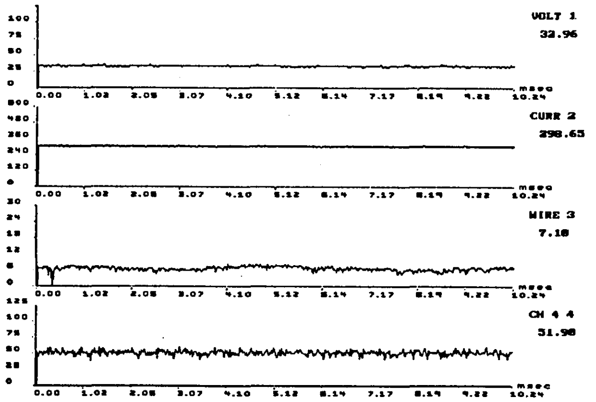
Typical Transient Data for Dip Transfer Welding

(d)



Typical Transient Data for Pulsed Welding

(e)



Typical Transient Data for Spray Welding (Reference Wire)

(f)

Typical Transient Data

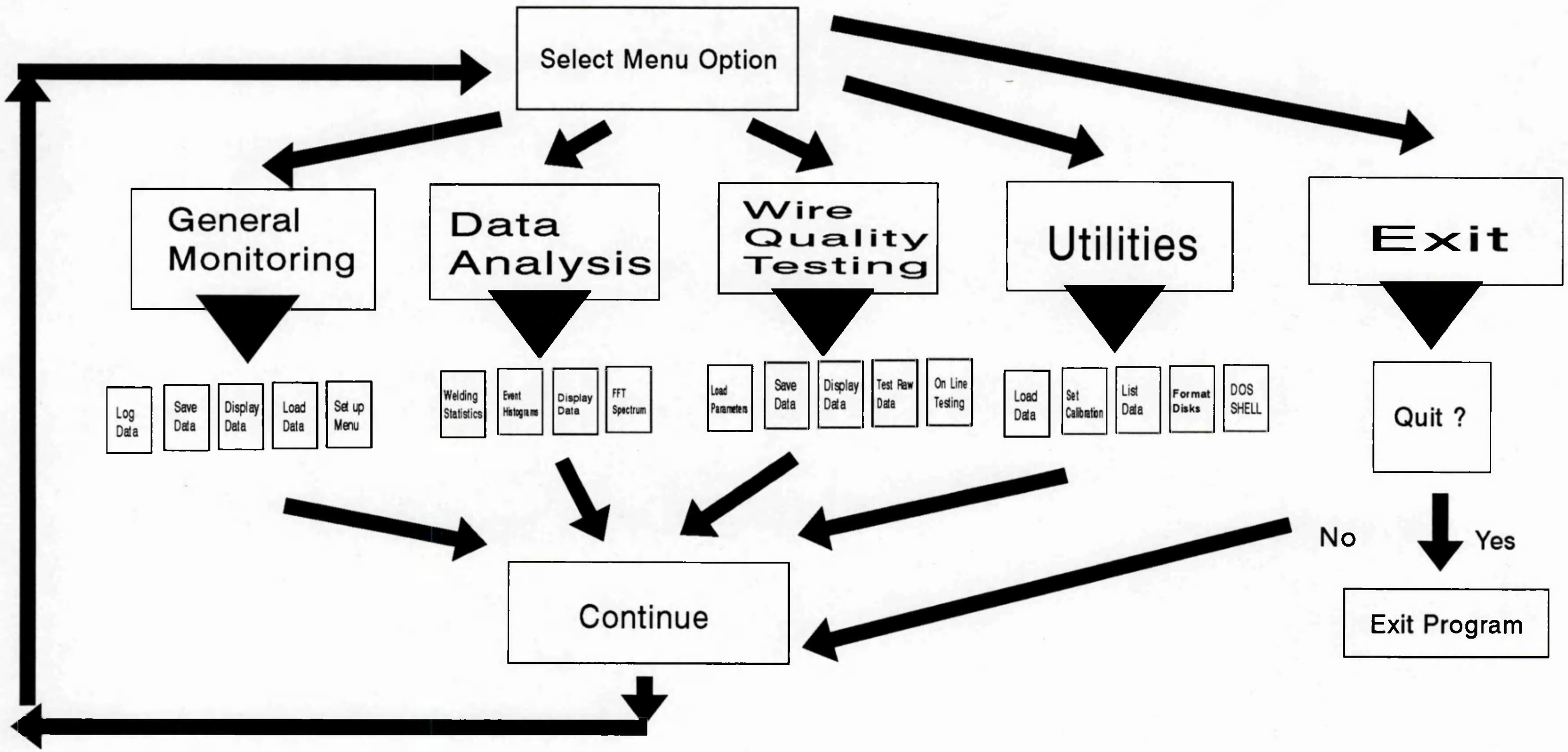


Fig 5.12 Specification of the Performance Monitoring (ESAB1) Software

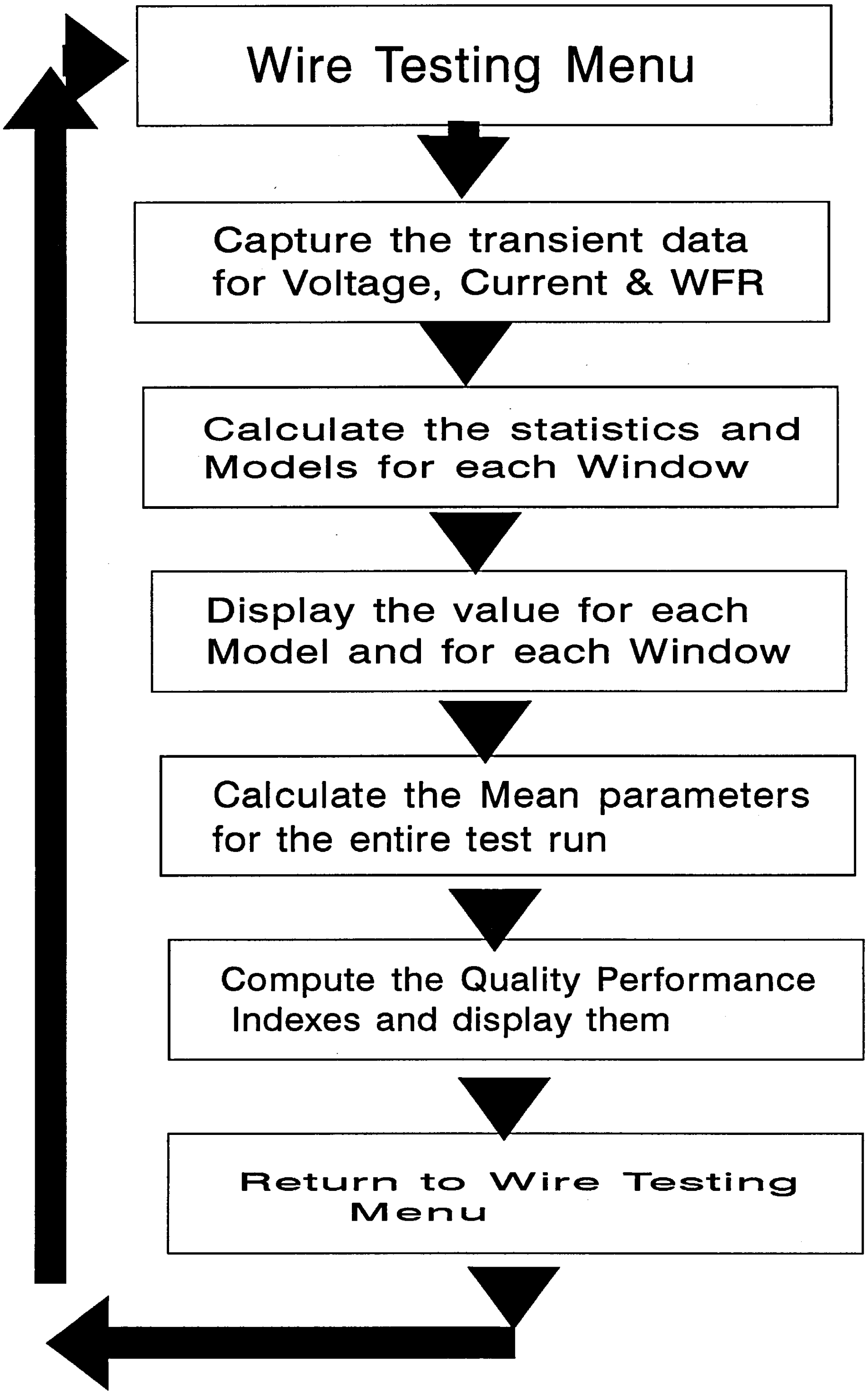
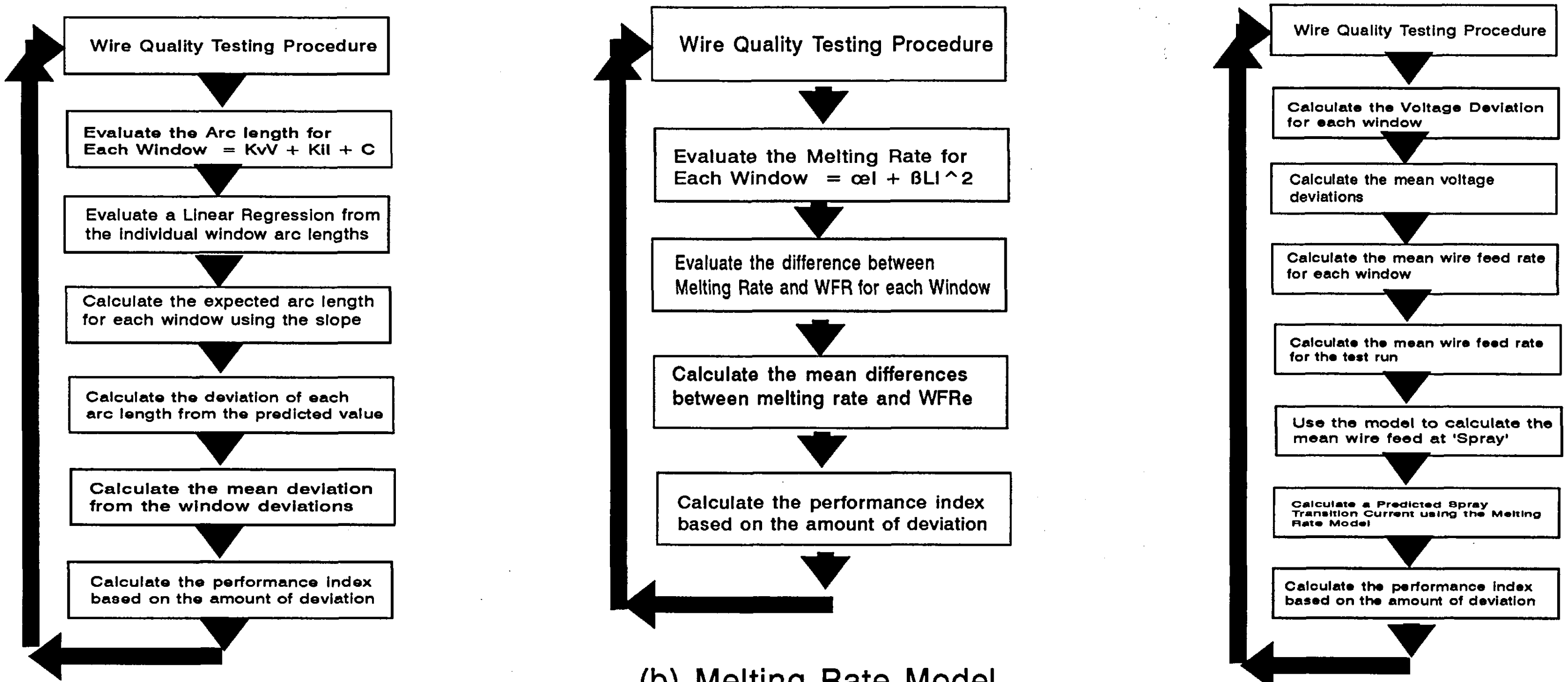


Fig 5.13 Flowchart of Wire Quality Testing Procedure



(a) Arc Length Model

(b) Melting Rate Model

(c) The Transfer Model

Fig 5.14 Flowchart for Evaluation of the Performance Indexes

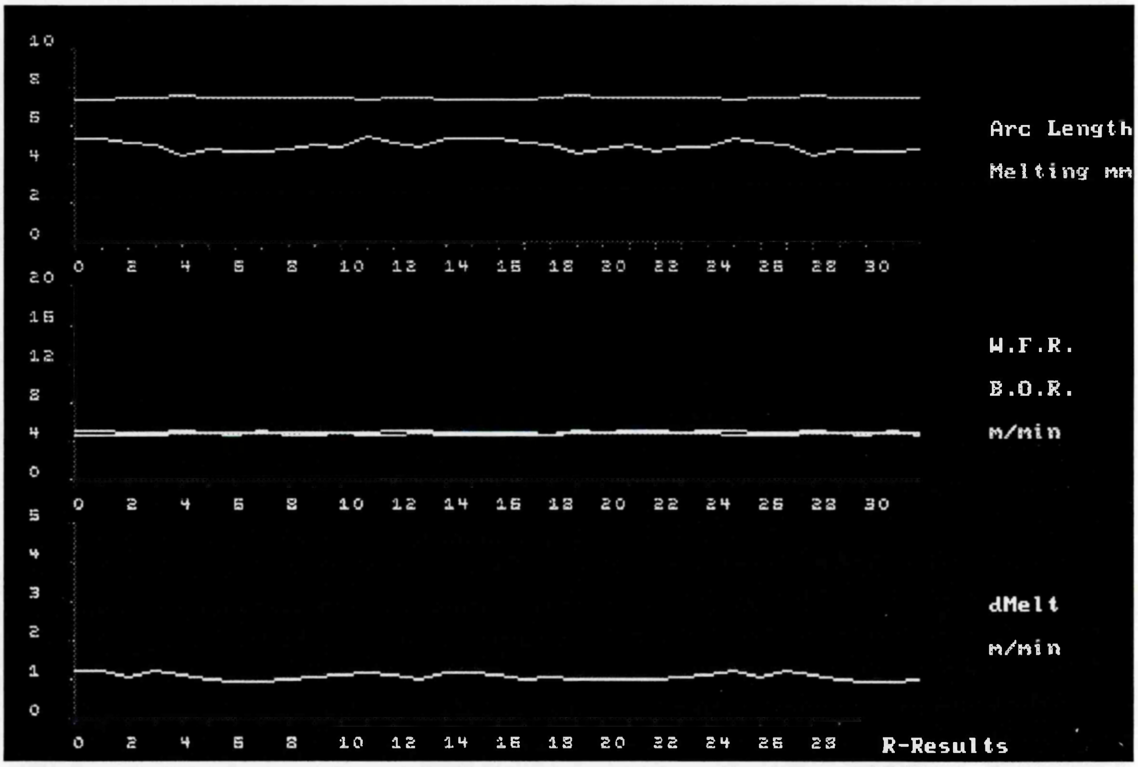
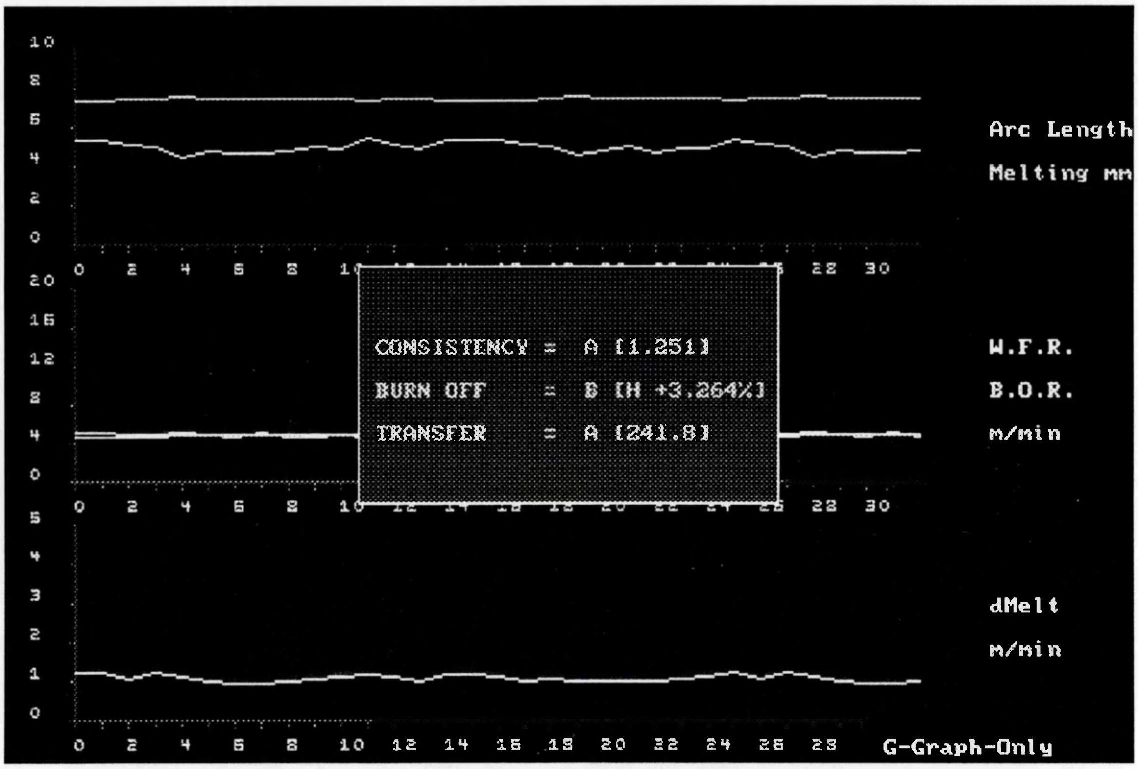


Figure 5.15 Typical Graphical Display of Results from (ESAB1) Software



```
CONSISTENCY  =  A [1.251]
BURN OFF     =  B [H +3.264%]
TRANSFER     =  A [241.8]
```

Figure 5.16 Typical Display of Quality Performance Indexes

File spg	Sm (b)	Wm	Vm	Im	Ip	Ib	Vp	Vb
1	99.10	3.67	30.37	250.79	252.14	247.23	31.11	29.67
2	99.03	4.01	30.75	271.27	273.52	268.49	31.48	30.17
3	99.10	4.43	31.94	291.65	295.31	290.06	32.55	31.33
4	99.24	4.83	30.67	301.9	303.22	298.86	31.16	30.20
5	99.13	4.97	32.01	312.07	314.90	310.26	32.63	31.40
6	99.01	5.33	32.96	336.14	338.72	333.66	33.53	32.32
7	99.09	5.88	32.04	344.17	346.88	341.90	32.52	31.38
8	98.92	5.99	33.03	354.67	358.65	353.38	33.55	32.43
10	99.03	4.21	28.20	271.27	273.88	268.54	28.92	27.52
11	99.10	3.86	32.69	271.25	273.39	268.17	33.39	31.97
12	99.04	4.86	29.65	301.67	303.44	298.57	30.19	29.10
13	99.10	4.44	34.11	301.59	303.48	298.55	34.8	33.54
14	99.09	6.2	29.95	335.30	337.88	333.48	30.48	29.47
15	99.05	5.86	32.35	335.14	337.85	333.24	32.92	31.82
15A	99.29	5.54	32.35	335.80	338.39	333.37	32.87	31.73
16A	99.27	5.28	35.07	335.47	338.45	333.25	35.72	34.49

Table 5.1a Overall mean parameters for reference wire

Where:

Sm - Mean Sound Amplitude
Wm - Mean Wirefeed Rate
Vm - Mean Arc Voltage
Im - Mean Arc Current
Vp - Mean Peak Voltage
Ip - Mean Background Voltage
Ip - Mean Peak Current
Ib - MEan Background Current

File spg	Ssd	Wsd	Vsd	Sdb	ALm	Darc	Melt	Burn
1	7.13	0.58	0.89	21.68	6.24	1.55	3.52	3.53
2	7.14	0.59	0.77	21.59	5.71	1.43	3.96	3.84
3	6.87	0.69	0.74	25.16	5.94	1.36	4.35	4.25
4	8.45	0.66	0.55	24.17	4.32	1.08	4.75	4.62
5	8.21	0.75	0.74	27.35	5.13	1.34	4.88	4.80
6	10.23	0.76	0.73	28.40	4.98	1.34	5.43	5.12
7	10.27	0.76	0.68	28.14	3.78	1.27	5.81	5.65
8	9.91	0.78	0.66	28.86	4.25	1.27	5.99	5.74
10	10.61	0.63	0.68	24.27	3.34	1.53	4.20	4.03
11	6.59	0.64	0.85	23.25	7.52	1.54	3.79	3.70
12	9.37	0.67	0.64	25.07	3.38	1.22	4.86	4.67
13	6.82	0.64	0.74	23.14	7.53	1.38	4.36	4.26
14	12.23	0.82	0.63	31.09	2.22	1.13	5.82	5.95
15	9.95	0.75	0.69	27.96	4.45	1.23	5.49	5.63
15A	9.92	0.77	0.69	28.11	4.43	1.28	5.51	5.32
16A	8.88	0.78	0.73	28.46	6.97	1.36	5.12	5.05

Table 5.1b Overall mean parameters for reference wire

Where:

Ssd - Std Deviation of Sound Amplitude
Wsd - Std Deviation of Wire Feed Rate
Vsd - Std Deviation of Voltage
Sdb - Sound in Decibels
ALm - Mean Arc Length
Darc - Mean Arc Length Fluctuation
Melt - Melting Rate
Burn - Burn off Rate

```
        Model fitting results for: ESAB1.arcl
--------------------------------------------------------------------------------
Independent variable          coefficient  std. error    t-value   sig.level
--------------------------------------------------------------------------------
CONSTANT                        -11.22536   0.012735  -881.4517     0.0000
ESAB1.volt                       0.929733   0.000454  2048.7875     0.0000
ESAB1.curr                      -0.042956   0.000025 -1711.8295     0.0000
--------------------------------------------------------------------------------
R-SQ. (ADJ.) = 1.0000  SE=      0.002703  MAE=       0.001966  DurbWat=  2.833
Previously:   0.0000          0.000000         0.000000          0.000
16 observations fitted, forecast(s) computed for 0 missing val. of dep. var.
```

```
        Analysis of Variance for the Full Regression
--------------------------------------------------------------------------------
Source              Sum of Squares     DF    Mean Square       F-Ratio   P-value
--------------------------------------------------------------------------------
Model                     35.8215       2       17.9108      2451333.     .0000
Error                0.0000949851      13  0.00000730654
--------------------------------------------------------------------------------
Total (Corr.)             35.8216      15

R-squared = 0.999997                        Stnd. error of est. = 2.70306E-3
R-squared (Adj. for d.f.) = 0.999997         Durbin-Watson statistic = 2.83272
```

```
        Further ANOVA for Variables in the Order Fitted
--------------------------------------------------------------------------------
Source                   Sum of Squares   DF    Mean Sq.     F-Ratio     P-value
--------------------------------------------------------------------------------
ESAB1.volt                   14.4107448    1   14.410745 1972306.70       .0000
ESAB1.curr                   21.4108040    1   21.410804 2930360.14       .0000
--------------------------------------------------------------------------------
Model                      35.8215488     2
```

Tables 5.1c Statgraphics Results for Arc Length Model (Reference Wire)

Model fitting results for: ESAB1.wire

```
--------------------------------------------------------------------------------
Independent variable            coefficient  std. error     t-value    sig.level
--------------------------------------------------------------------------------
ESAB1.curr*ESAB1.curr*ESAB1.stic 1.400474E-6  1.37495E-7     10.1856       0.0000
ESAB1.curr                        0.009424    0.000664      14.1821       0.0000
--------------------------------------------------------------------------------
R-SQ. (ADJ.) = 0.9994  SE=       0.126438  MAE=       0.085613  DurbWat=  1.428
Previously:    0.0000             0.000000           0.000000           0.000
16 observations fitted, forecast(s) computed for 0 missing val. of dep. var.
```

Analysis of Variance for the Full Regression

```
--------------------------------------------------------------------------------
Source                Sum of Squares    DF    Mean Square      F-Ratio   P-value
--------------------------------------------------------------------------------
Model                        403.150     2        201.575      12608.9     .0000
Error                       0.223813    14      0.0159867
--------------------------------------------------------------------------------
Total                        403.374    16

R-squared = 0.999445                         Stnd. error of est. = 0.126438
R-squared (Adj. for d.f.) = 0.999406         Durbin-Watson statistic = 1.42764
```

Further ANOVA for Variables in the Order Fitted

```
--------------------------------------------------------------------------------
Source                    Sum of Squares    DF    Mean Sq.     F-Ratio    P-value
--------------------------------------------------------------------------------
ESAB1.stick*ESAB1.curr*ESAB   399.934341     1   399.93434    25016.76      .0000
ESAB1.curr                      3.215446     1     3.21545      201.13      .0000
--------------------------------------------------------------------------------
Model                         403.149787     2
```

Tables 5.1d Statgraphics Results for Melting Rate Model (Reference Wire)

Model fitting results for: ESAB1.wire

```
----------------------------------------------------------------------------
Independent variable            coefficient  std. error    t-value   sig.level
----------------------------------------------------------------------------
ESAB1.snd                          0.142852   0.015781      9.0519     0.0000
ESAB1.stick*ESAB1.snd*ESAB1.snd    0.000119   0.000038      3.1136     0.0076
----------------------------------------------------------------------------
R-SQ. (ADJ.) = 0.9970  SE=      0.282685  MAE=      0.236204  DurbWat=  2.535
Previously:   0.0000          0.000000          0.000000          0.000
16 observations fitted, forecast(s) computed for 0 missing val. of dep. var.
```

Analysis of Variance for the Full Regression

```
----------------------------------------------------------------------------
Source              Sum of Squares    DF    Mean Square      F-Ratio   P-value
----------------------------------------------------------------------------
Model                      402.255     2        201.127      2516.90     .0000
Error                      1.11875    14      0.0799106
----------------------------------------------------------------------------
Total                      403.374    16

R-squared = 0.997227                         Stnd. error of est. = 0.282685
R-squared (Adj. for d.f.) = 0.997028         Durbin-Watson statistic = 2.53469
```

Further ANOVA for Variables in the Order Fitted

```
----------------------------------------------------------------------------
Source                     Sum of Squares   DF   Mean Sq.    F-Ratio   P-value
----------------------------------------------------------------------------
ESAB1.snd                      401.480178    1  401.48018    5024.11     .0000
ESAB1.stick*ESAB1.snd*ESAB1       .774673    1     .77467       9.69     .0076
----------------------------------------------------------------------------
Model                          402.254851    2
```

Tables 5.1e Statgraphics Results for Burn-Off Model Using Sound Data

File bsp	Sm (b)	Wm	Vm	Im	Ip	Ib	Vp	Vb
1	99.04	3.71	30.82	250.68	252.20	247.22	32.05	29.85
2	99.98	4.13	30.52	271.05	272.73	266.69	31.74	29.59
3	99.01	4.62	30.65	291.08	294.14	288.30	31.70	29.80
4	98.96	4.86	31.17	301.57	303.63	298.41	32.01	30.41
5	98.97	5.16	31.95	311.90	315.10	310.01	32.73	31.19
6	98.98	5.73	32.25	334.34	337.23	331.49	33.94	32.50
7	98.94	5.89	33.21	343.99	346.89	341.69	33.99	32.52
8	99.02	6.33	33.77	354.33	356.20	350.91	34.48	33.08
10	98.89	4.35	28.61	271.16	273.02	267.13	29.57	27.68
11	98.96	3.97	33.27	271.02	272.40	266.73	34.19	32.42
12	98.92	5.00	30.33	301.62	303.45	298.54	31.12	29.63
13	98.95	4.71	32.86	301.51	303.63	298.41	33.70	32.10
14	98.96	5.91	30.29	334.16	337.01	331.56	30.97	29.68
15	98.97	5.71	32.82	334.22	336.80	331.11	33.51	32.07

Table 5.2a Overall mean parameters for 'Bad' wire

Where:

Sm - Mean Sound Amplitude
Wm - Mean Wirefeed Rate
Vm - Mean Arc Voltage
Im - Mean Arc Current
Vp - Mean Peak Voltage
Ip - Mean Background Voltage
Ip - Mean Peak Current
Ib - MEan Background Current

File bsp	Ssd	Wsd	Vsd	Sdb	ALm	Darc	Melt	Burn
1	6.76	0.55	1.32	20.70	6.66	2.25	3.49	3.57
2	9.43	0.57	1.31	22.31	5.51	2.26	3.98	3.95
3	9.16	0.65	1.16	25.06	4.77	2.02	4.47	4.43
4	9.27	0.65	0.97	24.50	4.80	1.71	4.69	4.66
5	9.57	0.75	0.94	28.10	5.08	1.65	4.88	4.94
6	9.00	0.74	0.88	27.85	5.33	1.59	5.34	5.50
7	11.12	0.79	0.89	30.05	4.87	1.59	5.63	5.65
8	10.42	0.93	0.85	34.49	4.95	1.53	5.86	6.04
10	9.95	0.60	1.18	23.24	3.73	2.02	4.16	4.17
11	6.49	0.61	1.08	22.21	8.07	1.89	3.73	3.80
12	10.52	0.66	0.91	25.20	4.01	1.60	4.79	4.81
13	7.91	0.66	0.97	24.57	6.37	1.71	4.50	4.51
14	11.73	0.73	0.79	27.85	2.58	1.44	5.74	5.67
15	10.07	0.83	0.88	31.56	4.93	1.58	5.40	5.49

Table 5.2b Overall mean parameters for 'Bad' wire

Where:

Ssd - Std Deviation of Sound Amplitude
Wsd - Std Deviation of Wire Feed Rate
Vsd - Std Deviation of Voltage
Sdb - Sound in Decibels
ALm - Mean Arc Length
Darc - Mean Arc Length Fluctuation
Melt - Melting Rate
Burn - Burn off Rate

File spg	Consistency	Burn-off	Transfer
1	A1.42	B4.15%	C356A
2	A1.20	A1.12%	B326A
3	A1.09	A1.87%	B321A
4	A1.20	A1.64%	A223A
5	B2.49	A1.96%	B336A
6	A1.34	A1.82%	C353A
7	A0.95	A1.20%	B346A
8	A1.64	A0.00%	C352A
10	A1.06	A0.25%	C359A
11	A0.62	A1.81%	C372A
12	A1.22	A0.03%	A278A
13	A1.34	A1.76%	B340A
14	A1.69	C6.50%	A303A
15	A1.42	C6.79%	B333A
15A	A1.39	A0.60%	B337A
16A	A1.68	B3.13%	C371A

Table 5.3 Quality Assessment Gradings for Individual Experiments of Reference Wire

Where:

Consistency - Variation of Predicted Mean Arc Length from Stand-Off Setting
Burn-Off - Variation in Predicted Burn-Off Rate and Wire-feed Rate
Transfer - Predicted Spray Transistion Current

File bsp	Consistency	Burn-off	Transfer
1	A1.98	C6.46%	C598A
2	A1.11	B3.85%	C605A
3	A1.93	B3.34%	C542A
4	B2.23	B3.58%	C455A
5	B2.14	C5.76%	C450A
6	A1.67	C7.31%	C456A
7	B2.91	B4.51%	C460A
8	C3.63	C7.97%	C460A
10	A1.90	B4.66%	C522A
11	A1.06	C6.37%	C507A
12	A1.57	B4.42%	C420A
13	A1.11	B4.57%	C460A
14	A1.53	B2.99%	C397A
15	B2.18	C5.83%	B451A

Table 5.4 Quality Assessment Gradings for Individual Experiments of 'BAD' Wire

Where:

Consistency - Variation of Predicted Mean Arc Length from Stand-Off Setting
Burn-Off - Variation in Predicted Burn-Off Rate and Wire-feed Rate
Transfer - Predicted Spray Transistion Current

Table 5.5 Wire Assessment Comparisons
Welder Vs Computer Based System

Test No.	Wire	Welder Assessment		Computer Assessment		
				Consistency . . . mm	Burn-Off %	Transfer Amps
1	6717	9	A	1.1	+5.2	235
2	5.2.1	5	C	1.4	+8.6	442
3	6438	8	A	1.2	+2.3	319
4	5.2.2	8	A	(1.0)	(+9.8)	(379)
(2)						
4a	5.2.2	8	A	1.1	+19.6	472
5	4108	6	B	1.3	+11.2	365
6	BWP	6	B	(2.0)	(+18.2)	(308)
(2)						
6a	BWP	6	B	1.5	+19.9	377
7	AW2	5	C	2.2	+18.9	467
8	CES	4	C	2.2	+5.6	558

* Tests were made in random order

* (2) These were repeat tests

Table 5.6 Wire Assessment Comparisons Welder Vs Computer Based System Re-Assessed Using Sound Data

Test No.	Wire	Welder Assessment		Computer Assessment Consistency mm	 Burn-Off %	 Transfer Amps
1	6717	9	A	0.9	+5.0	251
2	5.2.1	5	C	1.3	+8.8	478
3	6438	8	A	1.1	+2.1	323
4	5.2.2	8	A	(1.0)	(+8.6)	(404)
(2)						
4a	5.2.2	8	A	1.0	+17.6	452
5	4108	6	B	1.2	+12.2	341
6	BWP	6	B	(1.9)	(+17.2)	(310)
(2)						
6a	BWP	6	B	1.4	+20.6	380
7	AW2	5	C	2.3	+18.1	496
8	CES	4	C	2.2	+5.3	533

* Tests were made in random order

* (2) These were repeat tests

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APPENDIX A

ESAB
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ESAB GROUP (UK) LIMITED
HERTFORD ROAD, WALTHAM CROSS
HERTS. EN8 7RP ENGLAND

Issue : 1

Date : APRIL 1988

FCW INSPECTION WELDING TEST

PRODUCT : BULK B420

COLOUR : GREY/BLACK

Nominal Size	Stickout (mm)	Amps	Arc Volts	Gas Shield	Gas Flow CuFt/H	Test Bar mm
1.2	20	280-300	31-33	ARGO 20	40	9
1.4	20	300-320	31-33	ARGO 20	40	9
1.6	25	330-350	31-33	ARGO 20	40	12
2.0	25	400-420	31-33	ARGO 20	40	12
2.4	25	430-450	31-33	ARGO 20	40	20

Welding Procedure

Material Type Mild steel

DC Positive &
DC Negative

Joint Configuration : T fillet

Position : HV

Deposition Method : Spray transfer, push technique all sizes

Lead Angle : 70-80 degrees

Run Lengths : 6-8 inches to give leg lengths equal to 1/4 inch minimum, 3/8 inch maximum

Observations

Arc Action : Smooth stable spray transfer

Slag : Hardly noticeable on welding

Spatter Very light

Slag Cover : Thin section, isolated islands on weld surface

Slag Colour : Medium brown, silicate type

Removal : Easy, not usually necessary

Deposit : Regular flat/convex, fine ripple

Also 2m shorting test and feedability test on DC +ve only

Initiated By R Fish

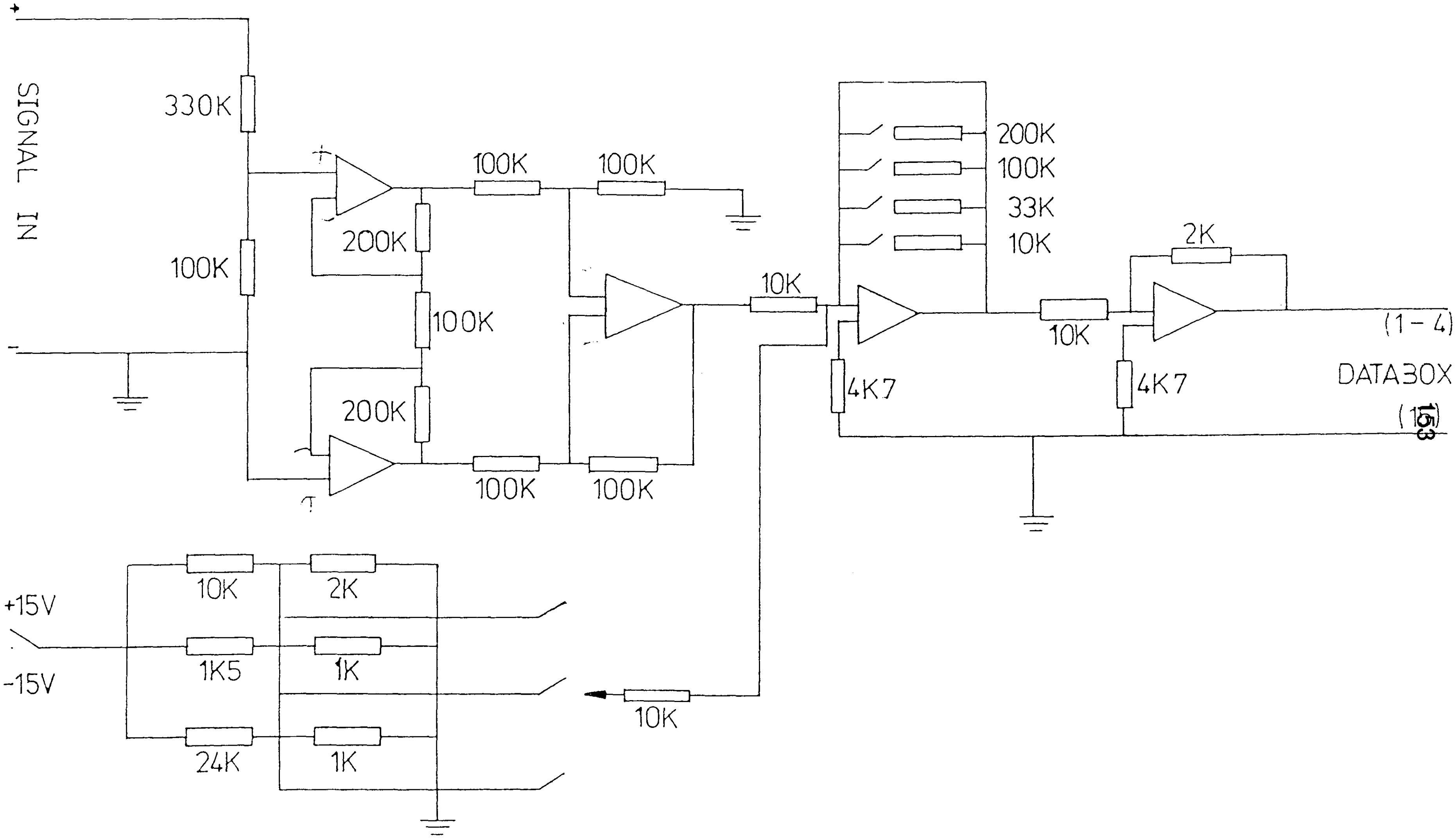
Date : 11/4/88

Approved By :

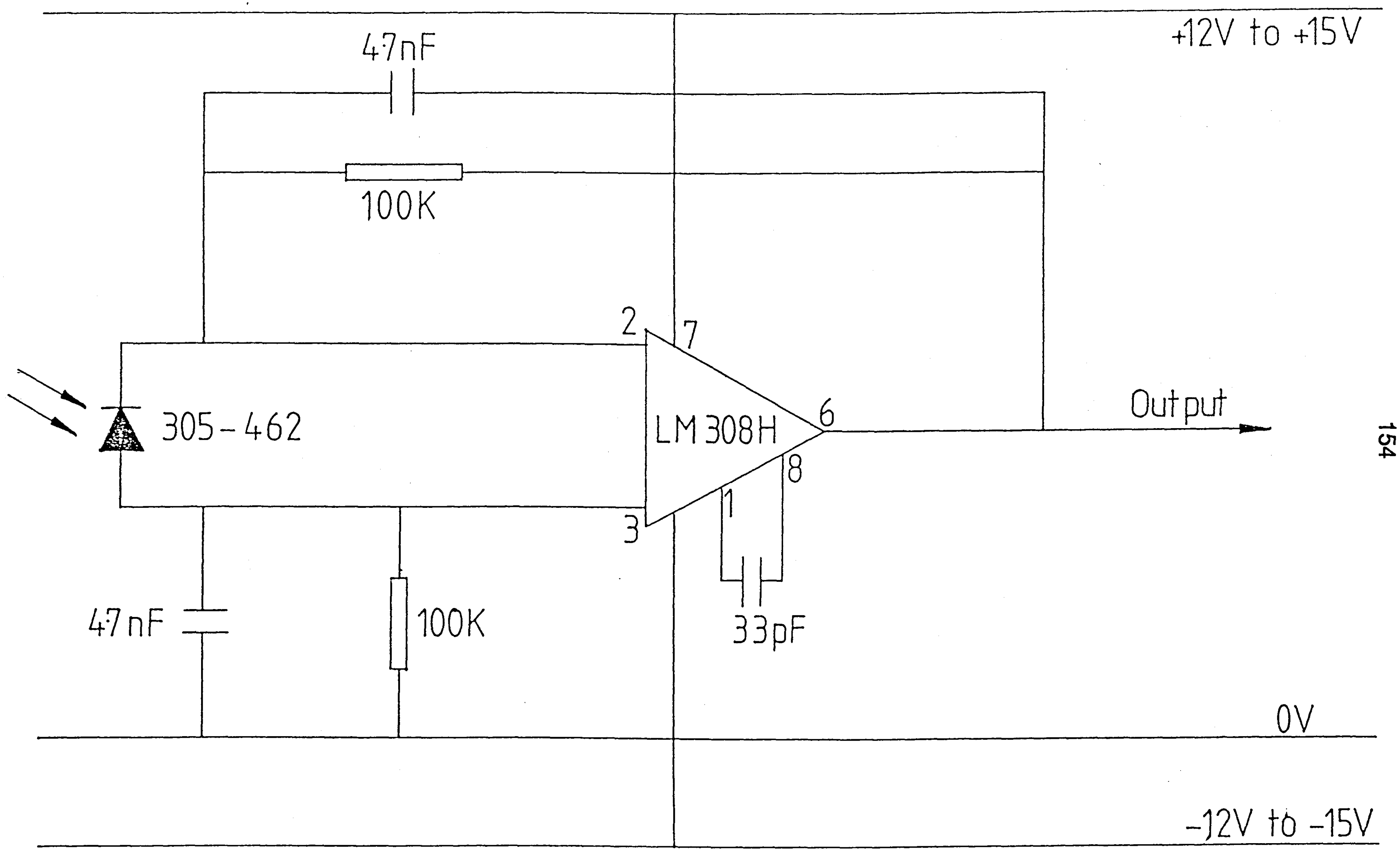
Date : 23-6-8

The Subjective Procedure for Assessment of Quality Performance

APPENDIX B



Circuit Diagram for Signal Conditioner Unit Built for 'Databox' Preliminary Investigation



Signal Conditioning Circuitry for the Photodiode

Description of Key Press Operations for the QSAB7 Software

F1 - Log

This key is used to initiate data acquisition. The data acquisition depends on the triggering conditions set up. If the triggering conditions match, the system will acquire 48k bytes of samples in windows at the set sample rate and window interval. However, the user can stop acquisition by pressing the ESC key.

F2 - Save

When this key is pressed the operator is requested for a file name and destination. If the file name given already exists, the operator is asked wether the existing file is to be overwritten. A negative response will cause the procedure to be abandoned. When the file name has been accepted, the entire captured 48 kb data in memory is saved in binary format together with the set up conditions for that data.

F3 - Disp

This key is used to graphically display the data in memory. When this key is pressed, the data is graphically displayed in windows and is scrolled until all of the windows have been viewed. When a particular window is displayed, the operator can press the <Enter> key to pause that window. At this point, a menu will be displayed which will allow the operator to either Zoom a particular channel or display a data cursor which will give a measure of any individual sample value in that window. The operator can press <Enter> to continue the scrolling or <ESC> to abandon the procedure.

F4 - Load

This key allows the operator to re-load data captured and saved previously. Once loaded, the operator can re-display or analyze the data if required. When this key is pressed, the operator is requested for the file name. If the file name entered does not exist, a list of the data files at the destination given is displayed. Otherwise, the data is loaded into memory.

F5 - View

When this key is pressed, the sampled data array is displayed numerically and scrolls until all of the data has been displayed. The operator can press <Enter> to pause the screen at any time.

F6 - Set

This key is used to set up all of the data logging conditions as well as any other programmable set up required for the software. The condition to set up is performed by using the arrow keys to highlight the required position and <Enter> to change the value. The parameters that could be set up are described below:

Channels to Log

There are four channels that can be monitored (1-4). These were used for Sound, Wire Feed, Voltage and Current. Since the total amount of data memory was 48 kb, the amount of data captured for each channel depends on the number of channels logged.

Window Interval

To obtain high speed transient data over a long length of welding, it was decided that the samples would be captured at the maximum sample rate (65 μs per sample) in blocks of 512 samples per channel and then have an user selected interval before another block is collected. By this method, each block or 'window' of data can be individually statistically analyzed and compared to other 'windows'. Hence, both transient and slow inconsistencies may be detected.

The window interval sets the time duration between capturing the blocks of data samples. This may be set from 0 (continuous logging) to 64 seconds. The length of welding monitored depends on this value.

Trigger Channel

Before each window of data is stored, the trigger channel is monitored to see if the trigger conditions have been achieved.

Trigger Level

The trigger channel is monitored for achievement of the level setting before storing.

Trigger Direction

Similar to an oscilloscope, the data is only stored if the trigger channel data is in the required direction High or Low.

Sample Rate

For the STE based PC, the sample rate was set by incorporating a delay between acquiring samples as the A/D board did not have a variable sample rate. The delay was created by running a dummy software loop and the number of times this loop was run determined the sample rate. It was calibrated by using a signal generator to determine the required count for a correct sample rate.

Channel Gains

Since the A/D board had 8 bit resolution for a 0 to 5V input signal, the actual signal range at the maximum value must be used to calibrate each channel. The required calibration can be saved to disk once set, and the program automatically reads this value in, each time it is run.

F7 - Stats

When this key is pressed, a new menu appears which allows the operator to calculate and display the statistical data. When the program was first written this only calculated the means, standard deviations, peak, background, peak time and background time for each channel. However, as will be described later, during the research other statistical parameters became important and these were added to the menu as and when required.

F8 - Live

This procedure simulates a digital storage scope. The program continuously acquires a single window of data and graphically displays it on screen. In this mode, the data cannot be saved, but the cursor and zoom facilities are available in a similar manner to the F3 key as described in section earlier.

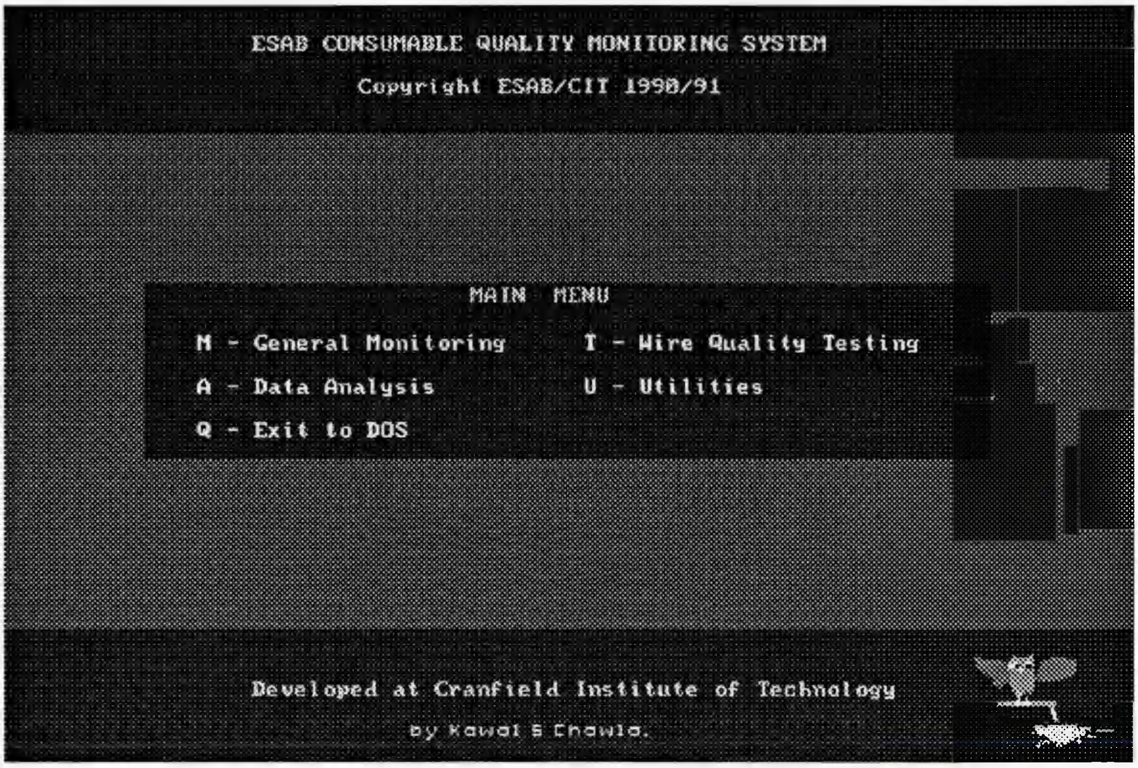
F9 - FFT

The FFT spectrum of any 'window' and channel can be calculated and displayed by pressing this key. When this key is pressed, the operator is prompted to enter the required window and channel numbers.

F10 - Exit

When this key is pressed, the program exits to DOS.

APPENDIX C



```
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MAIN  MENU
M - General Monitoring      T - Wire Quality Testing
A - Data Analysis           U - Utilities
Q - Exit to DOS

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by Kawal S Chawla.
```
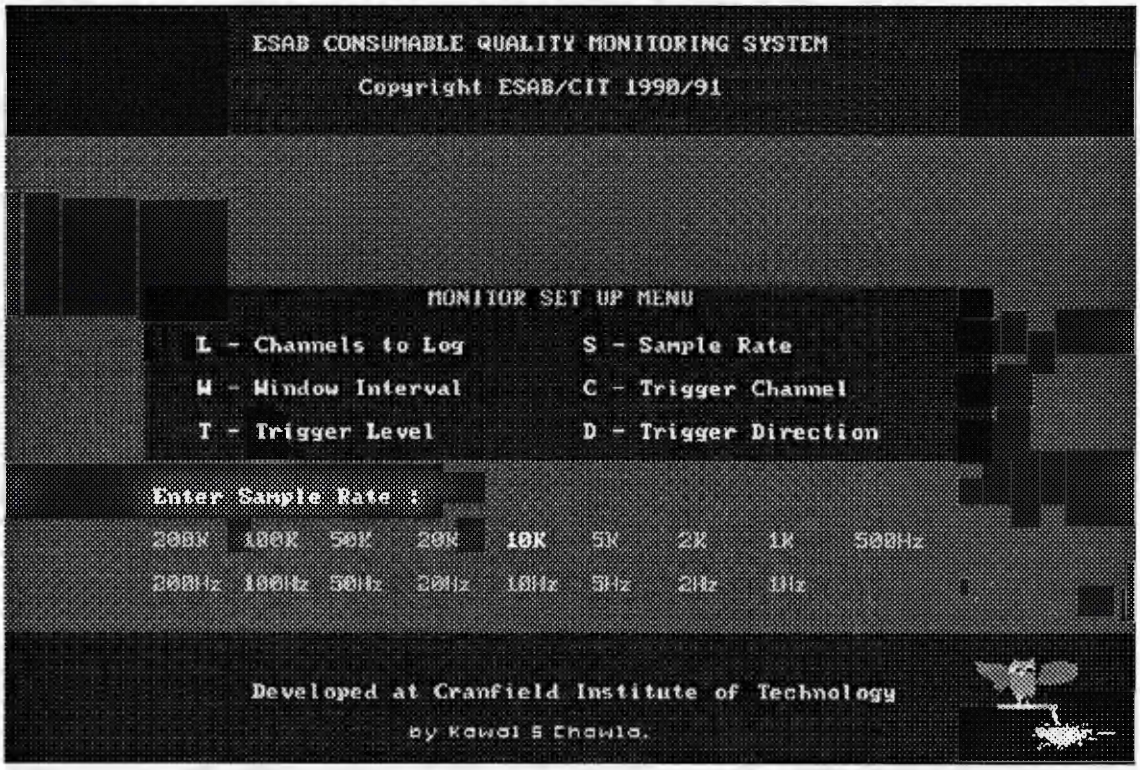

Figure 5.17a Main Menu Display of (ESAB1) Software



```
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MONITOR SET UP MENU
L - Channels to Log         S - Sample Rate
W - Window Interval         C - Trigger Channel
T - Trigger Level           D - Trigger Direction

Enter Sample Rate :
200K   100K   50K    20K    10K    5K     2K     1K     500Hz
200Hz  100Hz  50Hz   20Hz   10Hz   5Hz    2Hz    1Hz

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```
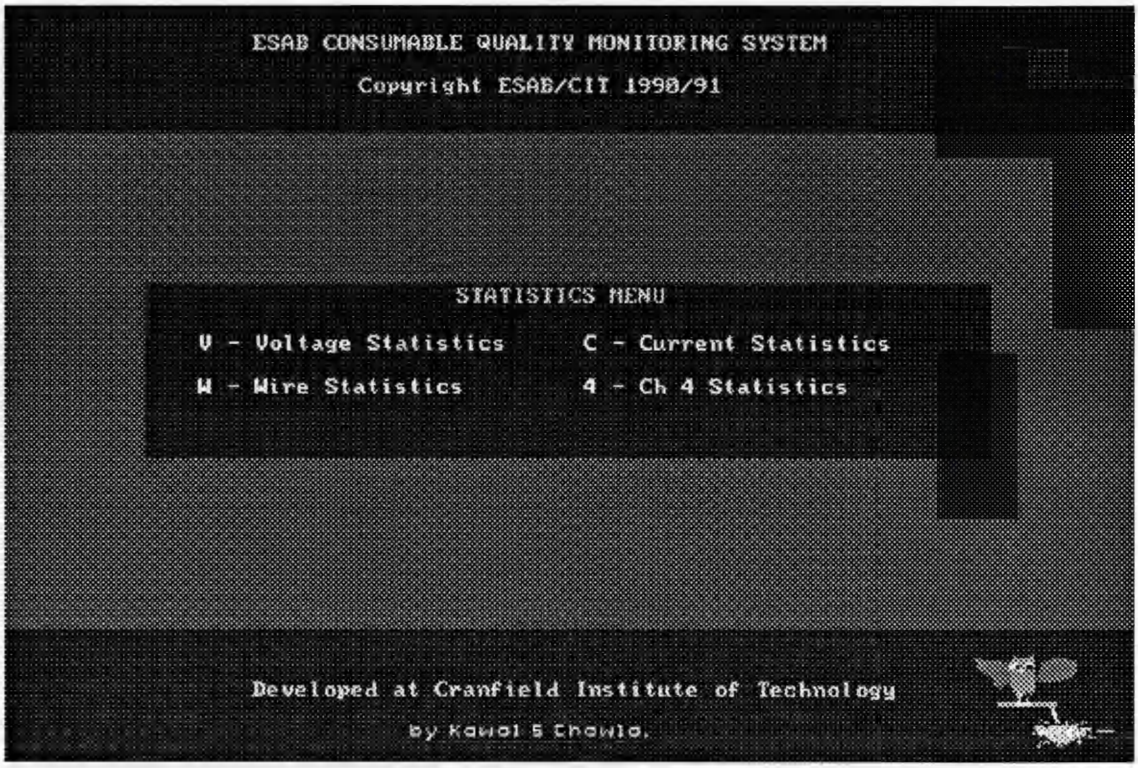

Figure 5.17b Monitor Set up Menu (Setting of Sample Rate Displayed)



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STATISTICS MENU

V - Voltage Statistics
C - Current Statistics
W - Wire Statistics
4 - Ch 4 Statistics

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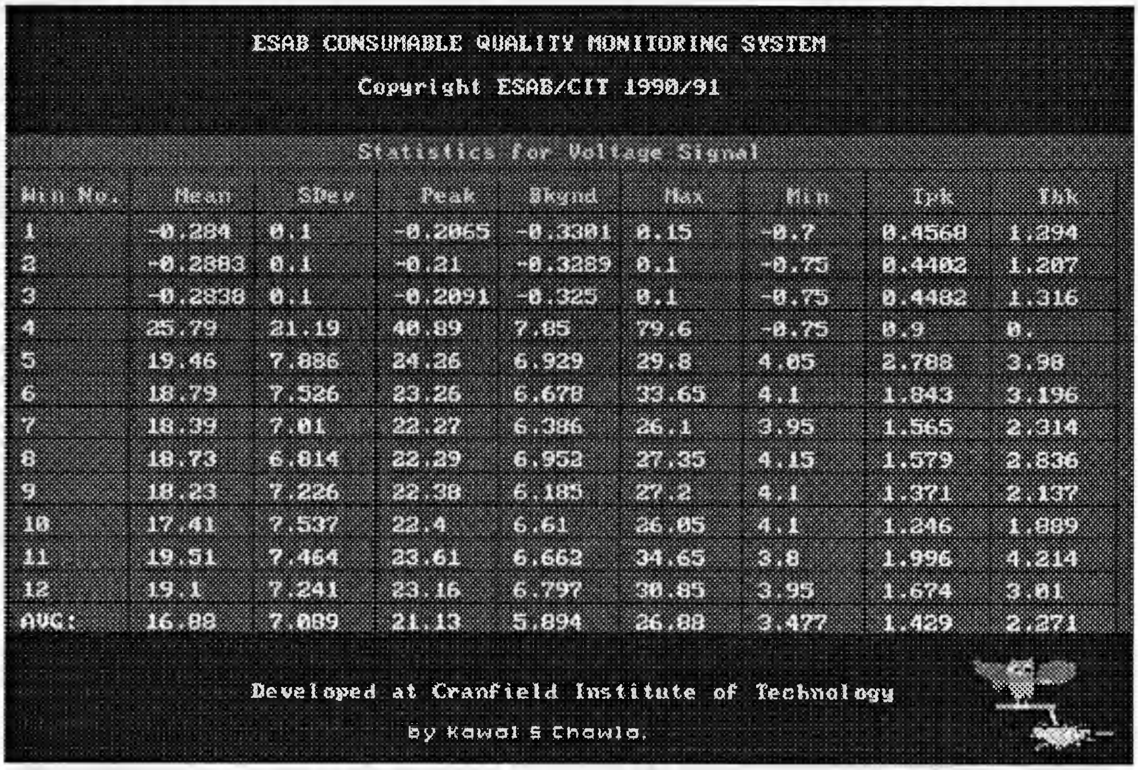
Figure 5.17c Statistics Menu Display of (ESAB1) Software



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Statistics for Voltage Signal

Win No.	Mean	SDev	Peak	Bkgnd	Max	Min	Ipk	Ibk
1	-0.284	0.1	-0.2065	-0.3301	0.15	-0.7	0.4568	1.294
2	-0.2883	0.1	-0.21	-0.3289	0.1	-0.75	0.4402	1.207
3	-0.2838	0.1	-0.2091	-0.325	0.1	-0.75	0.4482	1.316
4	25.79	21.19	40.89	7.85	79.6	-0.75	0.9	0.
5	19.46	7.886	24.26	6.929	29.8	4.05	2.788	3.98
6	18.79	7.526	23.26	6.678	33.65	4.1	1.843	3.196
7	18.39	7.01	22.27	6.386	26.1	3.95	1.565	2.314
8	18.73	6.814	22.29	6.952	27.35	4.15	1.579	2.836
9	18.23	7.226	22.38	6.185	27.2	4.1	1.371	2.137
10	17.41	7.537	22.4	6.61	26.05	4.1	1.246	1.889
11	19.51	7.464	23.61	6.662	34.65	3.8	1.996	4.214
12	19.1	7.241	23.16	6.797	30.85	3.95	1.674	3.01
AVG:	16.88	7.089	21.13	5.894	26.88	3.477	1.429	2.271

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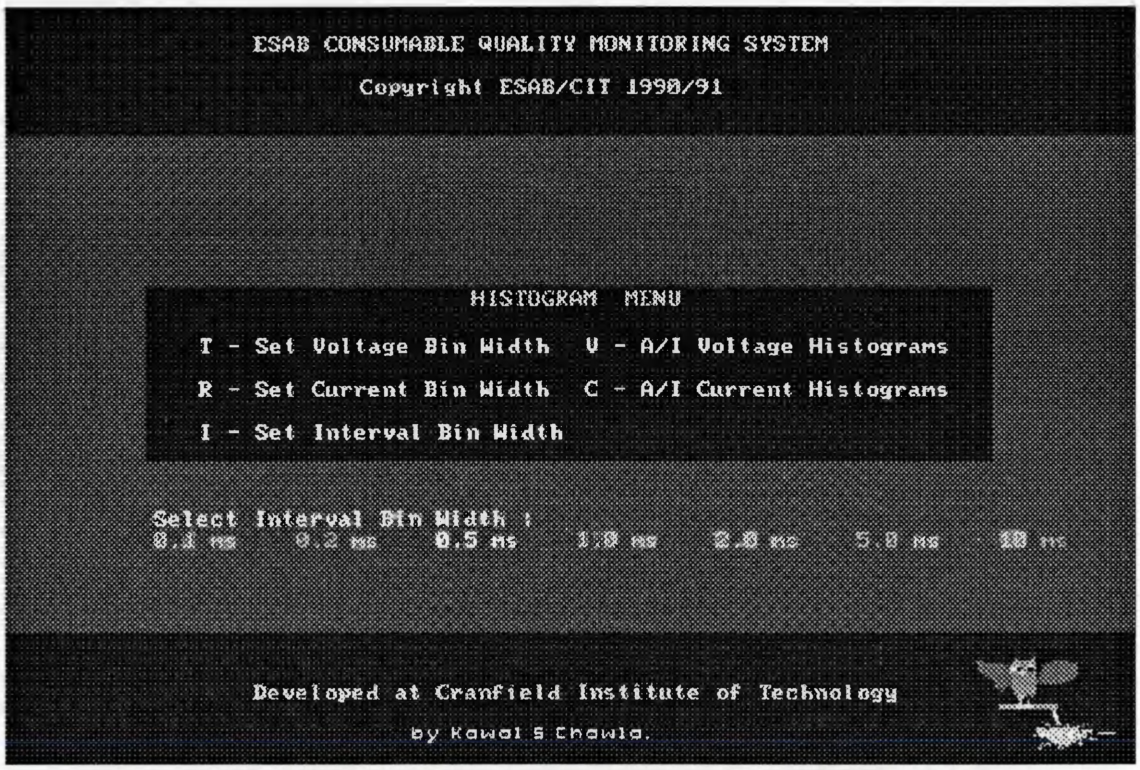
Figure 5.17d Typical Statistical Analysis Display from (ESAB1) Software



```
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HISTOGRAM  MENU
T - Set Voltage Bin Width   V - A/I Voltage Histograms
R - Set Current Bin Width   C - A/I Current Histograms
I - Set Interval Bin Width

Select Interval Bin Width :
0.1 ms    0.2 ms    0.5 ms    1.0 ms    2.0 ms    5.0 ms    10 ms

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```
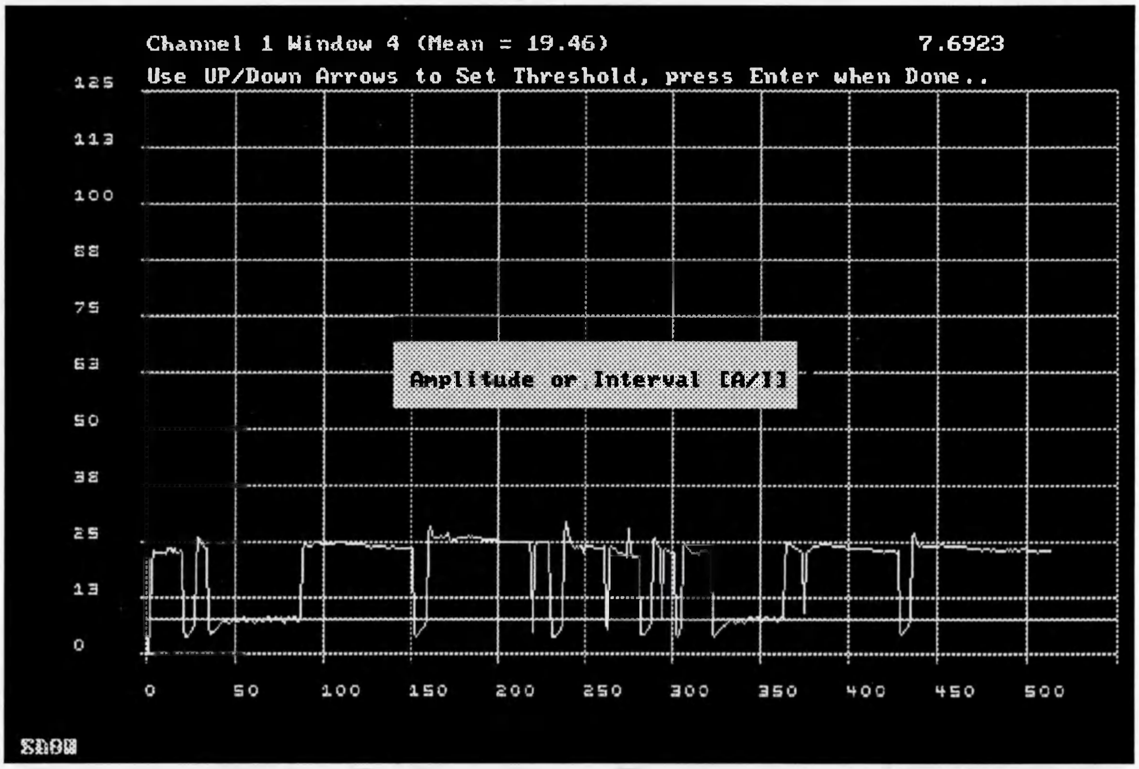
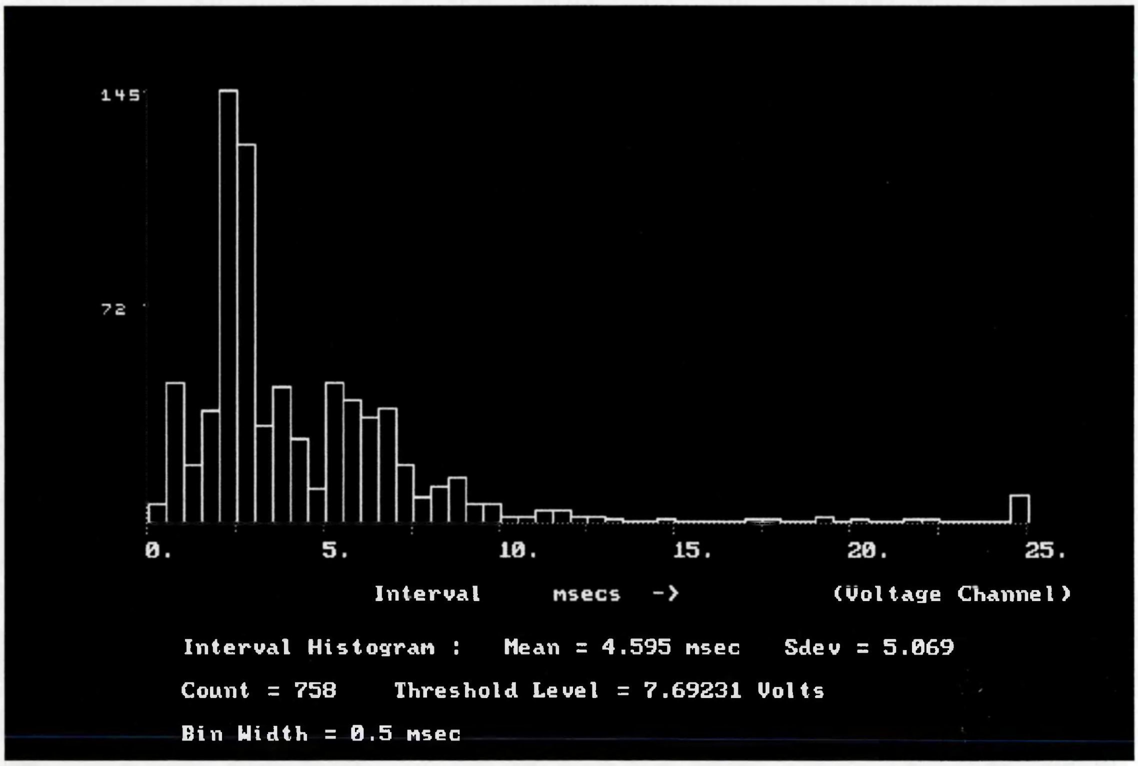

Figure 5.17e Event Analysis Menu Display of (ESAB1) Software



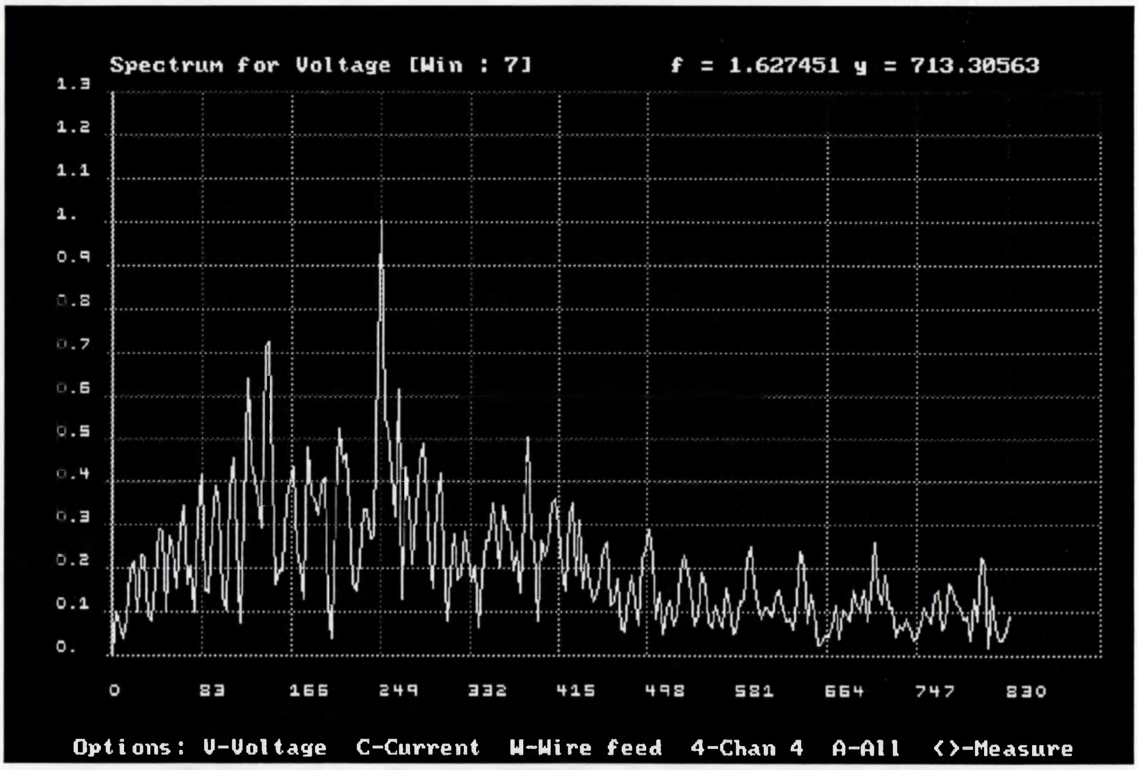
```
Channel 1 Window 4 (Mean = 19.46)                    7.6923
Use UP/Down Arrows to Set Threshold, press Enter when Done..

Amplitude or Interval [A/I]
```

Figure 5.17f Setting The Short Circuit Threshold for Interval Histogram



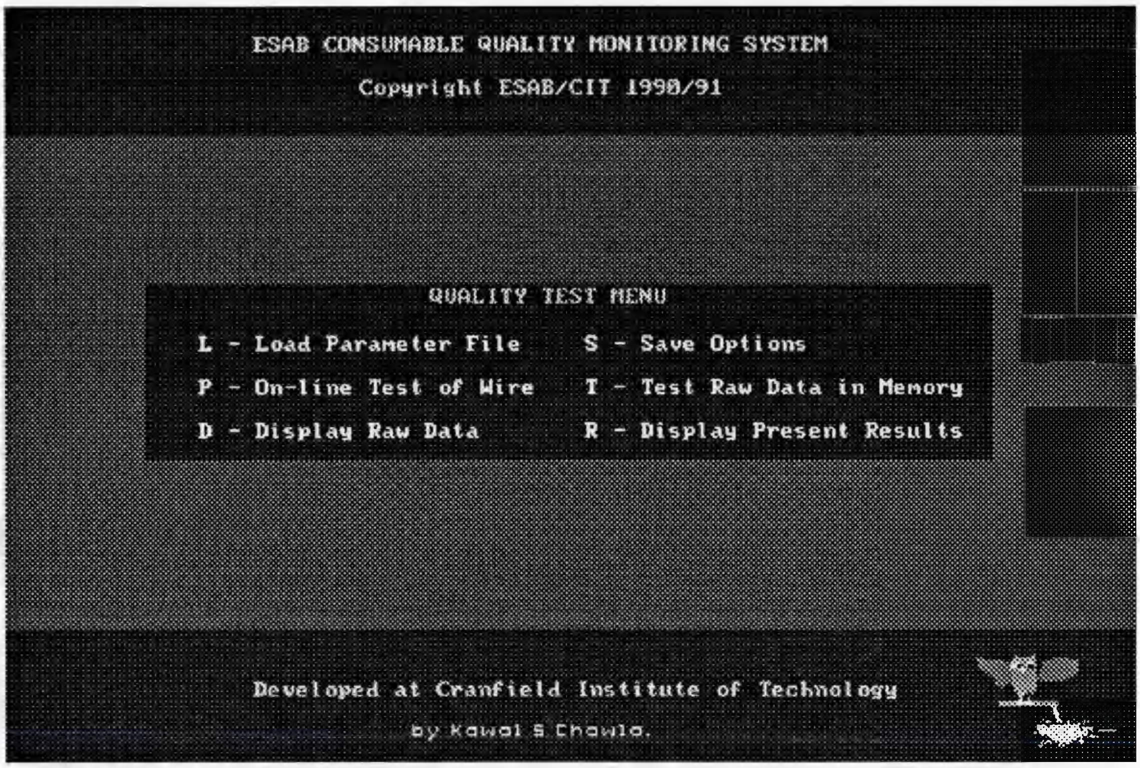
```
Interval Histogram :   Mean = 4.595 msec   Sdev = 5.069
Count = 758    Threshold Level = 7.69231 Volts
Bin Width = 0.5 msec
```

Figure 5.17g Typical Display of Interval Histogram for Dip Transfer Mode



```
Spectrum for Voltage [Win : 7]        f = 1.627451 y = 713.30563
```

Figure 5.17h Typical FFT Spectrum for Dip Transfer



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QUALITY TEST MENU

L - Load Parameter File
S - Save Options
P - On-line Test of Wire
T - Test Raw Data in Memory
D - Display Raw Data
R - Display Present Results

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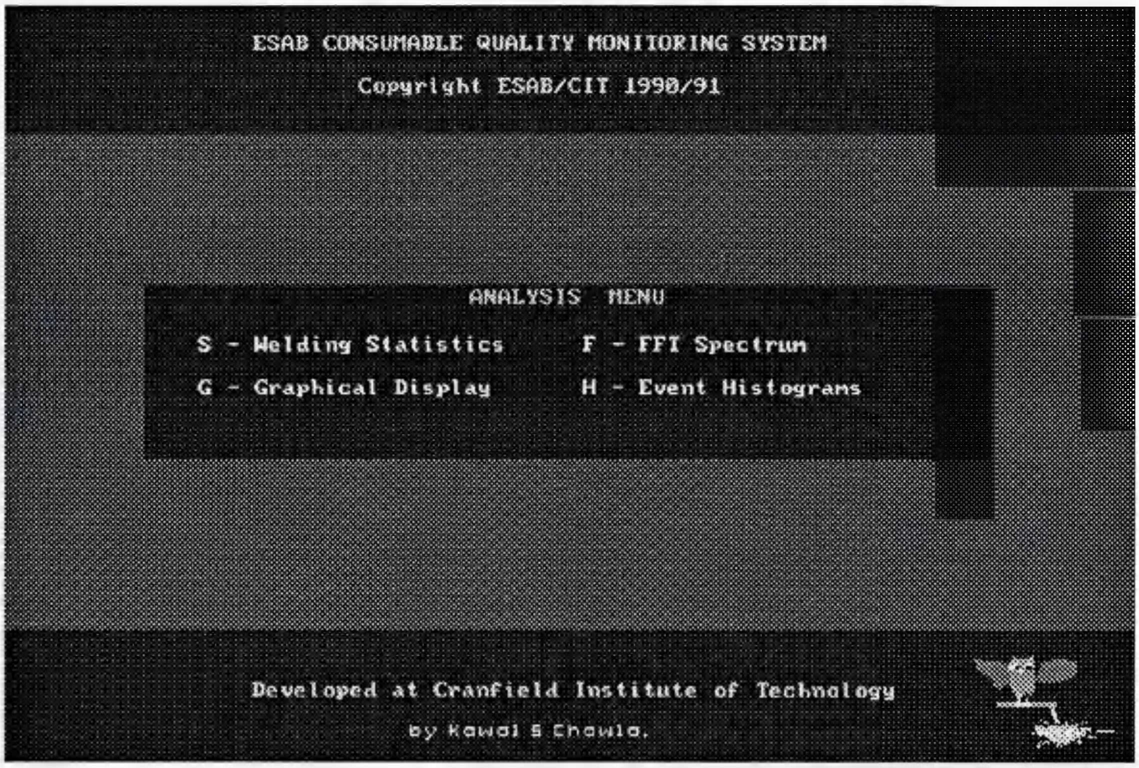
Figure 5.17i Wire Quality Testing Menu Display of (ESAB1) Software



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ANALYSIS MENU

S - Welding Statistics
F - FFT Spectrum
G - Graphical Display
H - Event Histograms

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Figure 5.17j The Analysis Tools Menu Display of the (ESAB1) Software

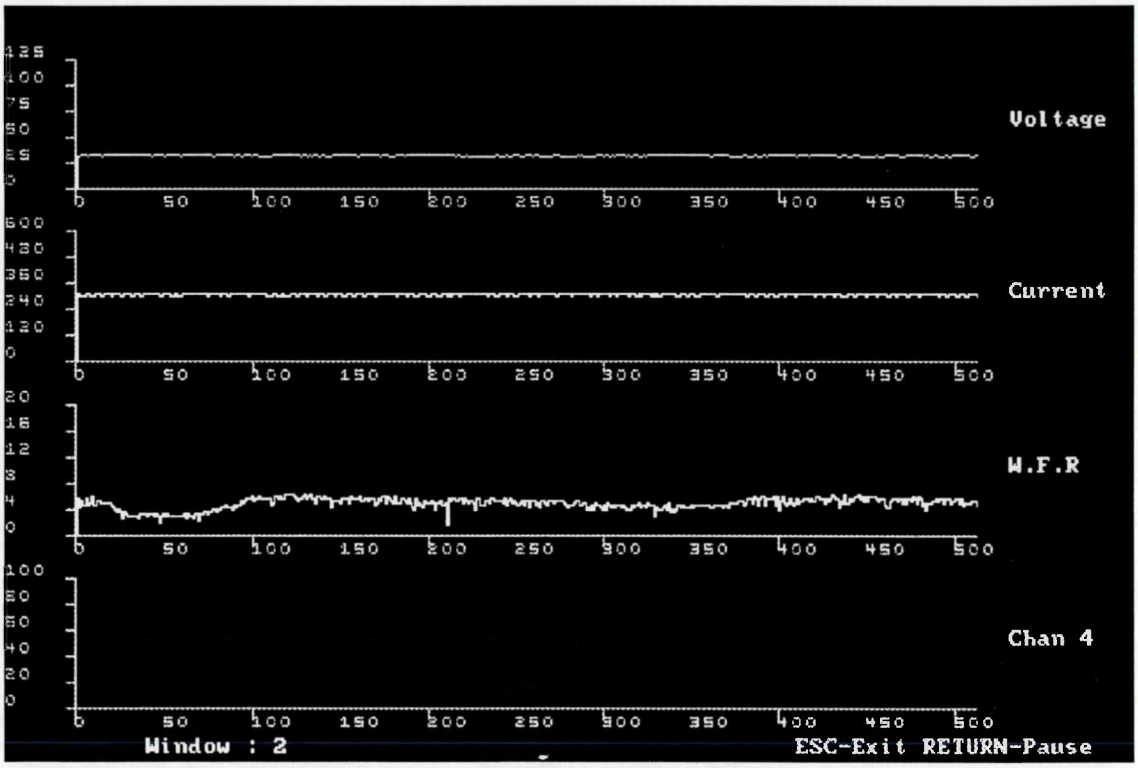


Figure 5.17k Typical Transient Window (Ref. Wire) of (ESAB1) Software

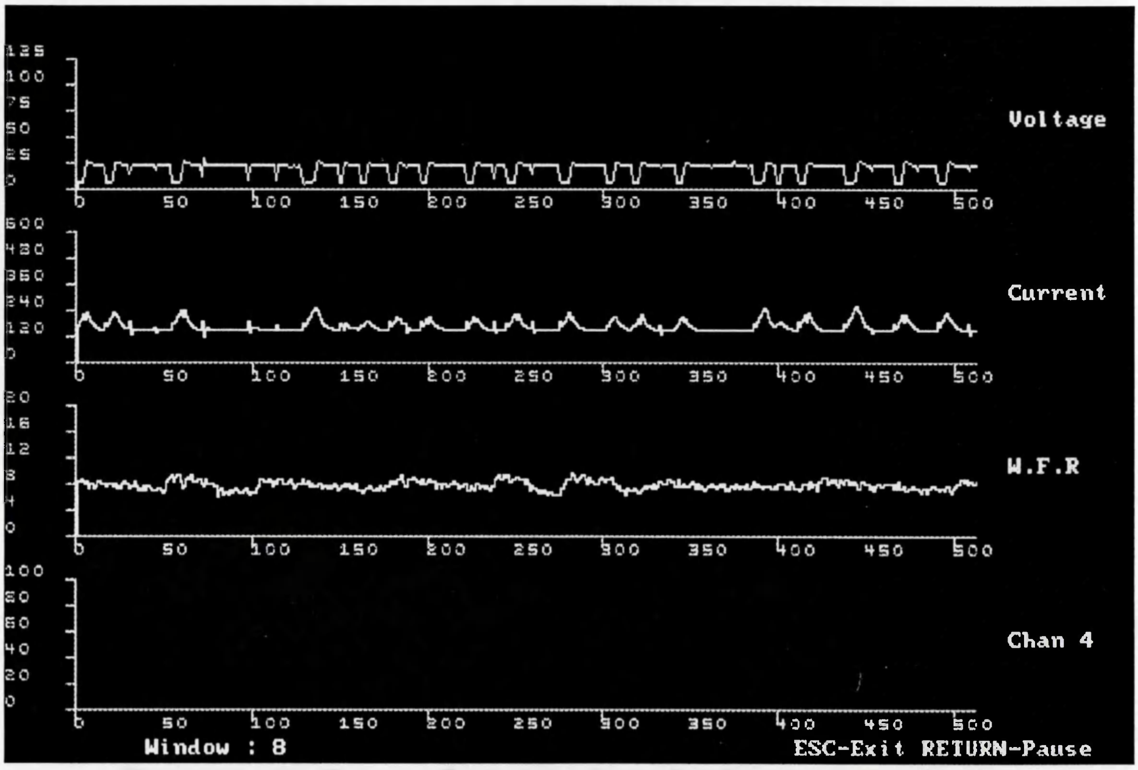


Figure 5.17l Typical Transient Data for Dip Transfer Mode

APPENDIX D

Description of the (ESAB1) On-line Wire Testing Software

This program was written to provide a more user friendly version of the original quality testing software ('qsab7'), together with a better graphical display of the results.

The results are displayed with both graphical and numerical interpretations of the evaluation of the models for each test carried out (typical results are shown in Figs 5.15 and 5.16).

The flowchart for the quality performance assessment modules are shown in Figs 5.12, 5.13 and 5.14. The strategy for on-line assessment can be described by the following steps:

1) The model coefficients for a new wire are evaluated. This procedure may be performed by two methods:

    a) By performing the factorial experiments by designing new experiments, using the general monitoring tools within the 'esab1' software, using a statistical package to calculate the coefficients and finally using the 'qagen' software (Appendix E) to create a parameter file for the 'esab1' software.

    b) By performing the factorial experiments using the 'finger software (Appendix F) to guide the operator through the experimental stages and automatically create a parameter for the 'esab1' software.

2) The parameter file containing the model coefficients for the wire to be tested is loaded into the program.

3) A roll of the wire to be tested is loaded into the wire feeder ready for welding.

4) The equipment is set up for the test procedure. The power source is configured to provide the working point current, voltage and wire feed rate. The stand off is set to the required length and the on-line testing is selected with the monitoring system.

5) The software sets up the monitoring system to capture the Voltage, Current and Wire feed rate with the required sample rate, window interval and triggering conditions for the wire.

6) A bead on plate weld is performed until the monitoring system has captured the required 'windows' of data.

7) The software evaluates the model data for each window and adjusts the arc length model to compensate for possible stand off changes by using simple regression.

8) The arc length performance assessment is determined by calculating the mean deviation in arc length during the test. A grade is assigned based on the amount of allowable deviation during the test.

9) The melting rate performance assessment is determined by calculating the mean deviations between the individual window wire feed rates and calculated melting rates. A grade is assigned based on the amount of allowable deviation during the test.

10) The transfer assessment is determined in 5 stages:

    a) The voltage and current deviations are calculated for each window.

    b) The droplet lengths are calculated for each window from a), using the model coefficients. The mean droplet length for the entire test is calculated.

    c) The wire feed rate at spray is calculated by interpolation by using the transfer model. This is obtained by the calculation of the mean wire feed rate, the droplet size and the wire diameter.

    d) The predicted spray transition current is determined by using the melting rate model. This requires calculation of the mean stick out (stand off - arc length). The solution is obtained by solving the quadratic equation and ignoring the negative value.

    e) A grade is assigned based on the amount of allowable deviation between the known spray transition current and the predicted value.

11) The individual window model evaluations are graphically displayed on the screen as they are calculated and the performance assessment indexes are displayed in the centre of the screen after they have been calculated.

The wire quality testing menu also has options for saving, retrieving and re-analyzing previously captured data. In addition there are facilities to load the parameter file for a particular type of wire and save the window statistics and QA results for reports etc.

In addition to the wire testing menu, the software also has facilities to provide general monitoring capabilities, welding statistics, FFT spectrums for any window and channel and perform event histograms for the monitored data. These monitoring tools were included because they were not available in standard data acquisition systems and some of them were essential to complete the work described in this thesis. It was decided that since these tools were useful within the scope of the present work. They may be useful for many other applications and the development of further enhancements in the future.

The following pages describe the operations of the general monitoring and analysis capabilities included in the software.

General Monitoring Menu

The General Monitoring Menu provides the following facilities:

Log Data
Graphical Display
Set up
Oscilloscope Mode
Write Data to Disk
Read Data from Disk

Log data

If this option is selected, the system starts to acquire data depending on the settings made on the 'Set Up' menu. If triggering conditions have been set then acquisition will commence when these conditions have been satisfied.

Graphical Display

Once data has been acquired, it can be displayed graphically by selecting this option. The user can scroll and display the transient data acquired for each window.

If the 'Cursor' option is selected, the user may read individual data values within a window of data. If the left and right arrow keys are moved, a cursor line is displayed and the data value at that position for each channel is displayed at the side of the graphs. Selecting Slow or Fast controls the amount of movement of the cursor. In 'Slow' mode the cursor will move a single sample for each arrow key movement. In 'Fast' mode, the cursor will move 20 samples for each arrow key movement. As the cursor key is positioned, the sample number at that position is displayed at the bottom of the screen.

By selecting the 'ZOOM' options, the data for a single channel will be displayed, together with the mean value for that channel. The user may print any of the graphic displays by pressing the 'ALTP' keys. The user may leave the graphical display by pressing the ESC key.

Set Up Menu

The set up menu allows the user to change the following monitoring variables:

Channels to Log
Sample Rate
Window Interval
Trigger Channel
Trigger Level
Trigger Direction
Welding Mode

Write data to disk

This option allows the user to save the data in memory to disk. The path for saving the data must be set in the Utilities menu. The data may be saved in either Binary or ASCII format.

Read data from disk

This options allows the user to load a previously saved binary data file. The procedure is exactly the same as for saving binary data. The user will be prompted if the file name requested does not exist or is invalid.

Oscilloscope Mode

This mode emulates a digital storage scope. The mode uses all of the set up parameters as for normal logging. The system grabs 512 points per channel set approximately every second and displays them graphically on screen. The display mode is the same as for the Graphic Display mode described above except that the window number will always be 1. All of the facilities for the Graphic Display mode are available. This data cannot be accessed by the Analysis or Save options.

Analysis Menu

The Analysis Menu provides the following facilities:

Welding Statistics
FFT Spectrum
Graphical Display
Event Histograms

Welding Statistics

By selecting the appropriate channel, the required statistics for that channel will be displayed if logged. The system will first calculate the statistics before displaying them. If a slow PC is used, this can take several seconds. The statistics calculated are as follows:

Mean,
Standard Deviation,
Mean Peak,
Mean Background,
Maximum,
Minimum,
Peak Time,
Background Time.

The peak and background times are calculated using the sample rate setting. These calculations are done for all of the windows logged and an overall average is calculated over the number of windows logged. These statistics are displayed separately for each channel.

The plot statistics option gives a graphical display of the calculated statistics described above. By using the arrow keys, the appropriate statistics will be displayed. Any of these plots may be printed by a dot matrix printer by pressing the ALTP keys when displayed.

FFT Spectrum

If the user wishes to measure the frequency spectrum of a particular window this option is selected. The user is prompted for a window number. Once a window number has been entered, the spectrum of all of the logged channels will be displayed.

The maximum frequency that can be detected with the FFT is:

Max Freq. = Sample Rate/(4 * No. of Channels).

Hence with a sample rate of 200k with all channels logged, the maximum frequency is 12500 Hz. The resolution of frequencies with the cursor is

Resolution = Max_Freq/256.

Graphical Display

This was described in the Analysis menu section.

Event Histograms

The **Welding Statistics** and the **FFT Spectrum** are very useful for assessing the behaviour of the process. Another useful technique for assessing the stability of the process is the **Event** or **Stability Histogram**. This technique involves the setting of a threshold level from which events above and below the threshold are counted. There are two forms of **Stability Histograms**, the **Amplitude Histogram** and the **Interval Histogram**.

The system can calculate the amplitude or interval histogram for either the voltage or current channel. The histogram is calculated by counting occurrences above a threshold on either the current or voltage channel and placing the counts into amplitude or interval bins whose width must be set. However, this procedure requires that the window interval is set to zero prior to capturing the data. If the window interval is not set to zero, the histogram can still be calculated, but it will be meaningless.

If either of the set options are selected, the possible bin widths for the selected type will be displayed. The present setting will be highlighted. Use the left or right arrow keys to highlight the required setting and press ENTER or ESC to select.

Once the user has selected the bin width, the histograms for voltage or current can be calculated by selecting either the voltage or current histograms. If one of these options is selected the user will be prompted to enter a window number from which the threshold line can be drawn. If the required window number is selected, the voltage or current data for that window will be displayed and a horizontal cursor line at the present threshold for that channel will be seen. Use the Up/Down arrow keys to move the cursor line to the required position and press the ENTER key. The cursor line may be set for one of two speeds, FAST and SLOW.

When the required threshold level has been entered, the user will be prompted to choose the type of histogram required:

Amplitude or Interval Histogram [A/I] ?

Press either the 'A' or 'I' key for the required choice. After a few seconds the calculated histogram will be displayed.

If the user wishes to change the threshold level and re-calculate the histogram or simply want to see the 'other' histogram, press the ENTER key again and the data and threshold cursor will be re-displayed. Use the Up/Down arrow keys to change the threshold level or press ENTER again and select the 'other' histogram for the same level.

The **Interval Histogram** is especially useful for assessing dip transfer GMAW welding, where the stability of the transfer is determined by the regularity of the short circuits. For optimal welding, the standard deviation of the time between short circuits should be minimised.

The **Interval Histogram** is also useful for power sources which alter the frequency of the pulse width to control the arc length. In this case, the variation in the standard deviation of the period time could indicate the amount of effort that the power source is having to make to keep the process stable or to keep the welding mode constant.

The **Amplitude Histogram** is especially useful for **Pulsed GMAW** welding, where the power source controls the amplitude of the pulse to keep the welding mode constant. In this case, the standard deviation will indicate the amount of variation in the process.

The **Event Histograms** are a general purpose tool for many applications. The technique has been utilised by many researchers and has proved very successful in assessing and improving the process.

Utilities Menu

As well as the general monitoring and data analysis facilities, the software also provides the following utilities to assist the user:

Set Data Path
Read Data from Disk
Set Calibration
List Data files
Format a Disk
DOS Shell

APPENDIX E

The 'QAGEN' Software for Editing Model Coefficients

This package was written in order to provide a means of creating the parameter file required by the 'esab1' software for performing the on-line testing of wire quality performance.

After performing the factorial experiments for a new type of wire and using a standard statistical package to analyze and produce the models (as described in chapter 5), the user may enter the various model coefficients, set the acceptance limits for producing the performance grades and create a data file that may be loaded by the 'esab1' software.

The program consists of two editor menus to input the various values and a save option to create the parameter file.

APPENDIX F

The 'FINGER' Software for on-line 'finger printing' of Flux Cored Wires

The 'finger' software was written to simplify the method of performing the factorial experiments and evaluate the model coefficients. The software incorporates the data acquisition functions, the experimental design and the regression analysis modules in a single package. This software is used to create the parameter file directly after data acquisition.

The program operates by performing the following steps:

1. The user enters the working point for the performance test, ie. the nominal spray transition current, arc length, stand off and wire diameter.
2. The user enters an 8 character reference number for the wire.
3. The software calculates the number of factorial experiments required to obtain a reasonable model and sets up the monitoring equipment for the correct data logging configuration.
4. The software calculates the arc length and welding current settings required for each experiment.
5. The software prompts the user to set up the equipment to provide the required arc length and welding current for the first experiment and to start welding.
6. The software will graphically display the transient data for each window and channel as it is acquired until the data buffer is full.
7. The software prompts the user to stop welding.
8. The software prompts the user to set up the equipment to provide the required arc length and welding current for the next experiment and to re-start welding.
9. Steps 6-8 are repeated until all of the factorial experiments have been completed.
10. After the last experiment has been completed, the software prompts the user for a choice to repeat any of the experiments or perform further experiments within the scope of the experimental design.

11. Once all of the experiments have been completed, the software calculates and displays the coefficients for each of the performance models ie arc length, melting and the two transfer models. The software also displays the value of the coefficient of determination and standard error to provide information about the validity of the relationship.

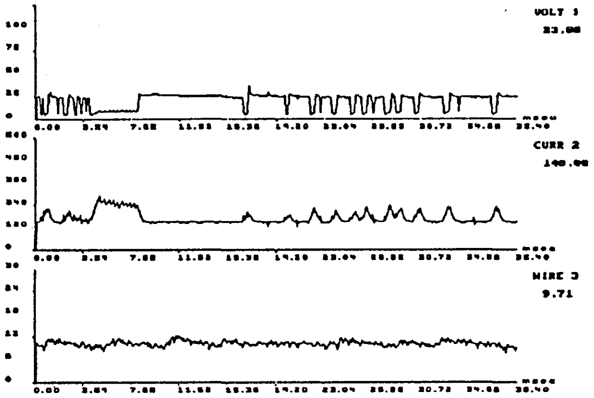
12. The software will save the data as a parameter file if required.

13. The software will return to step 1.

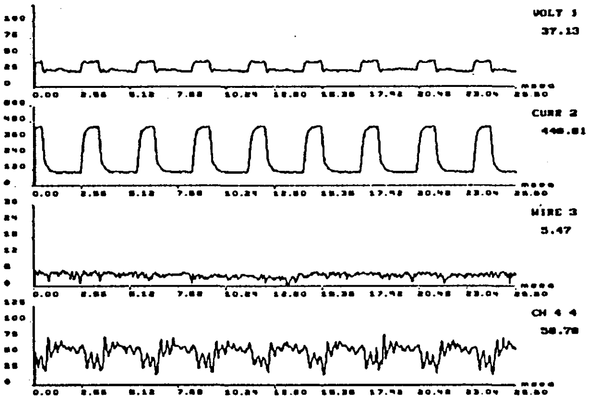
The design of the experiments is performed by using an enhancement of the 2^k factorial design technique by selecting high and low values for the factors at 5%, 10%, 15% and 20% above and below the working point.

The regression analysis is performed by two especially written modules which calculate the coefficients for the simple and multiple variable regression functions. The technique was derived from first principles and was tested and calibrated by inputting and analyzing the experimental data that was used for producing the original models with the STATGRAPHICS software package.

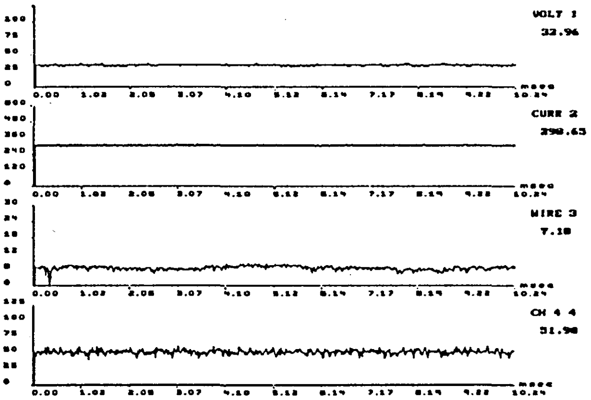
125A



Typical Transient Data for Dip Transfer Welding
(d)

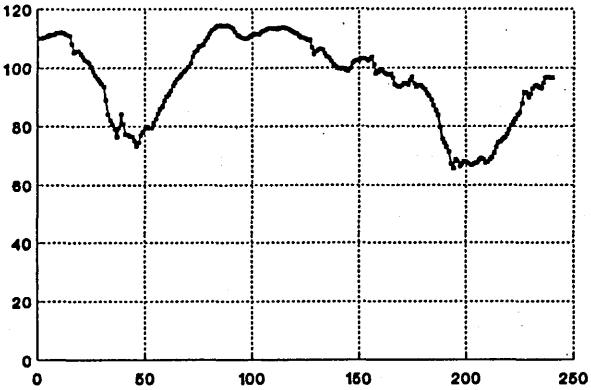


Typical Transient Data for Pulsed Welding
(e)



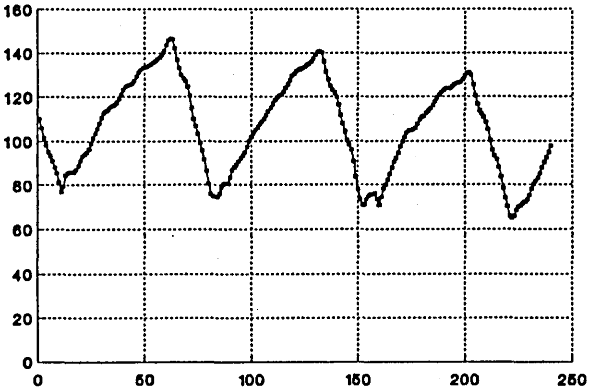
Typical Transient Data for Spray Welding (Reference Wire)
(f)

Typical Transient Data



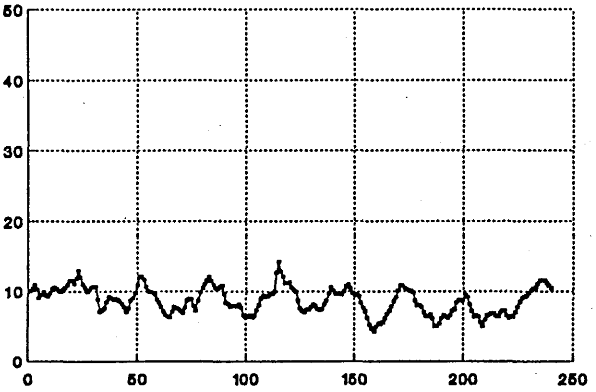
Typical Integrated Dip Sound Signal

(a)



Typical Intergrated Pulse Sound Signal

(b)



Typical Integrated Spray Sound Signal

(c)

Fig 5.11 Investigation of the Sound Signal Using DADISP