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# An evaluation of the effects of process variables in the flux-cored arc welding of hardfacing deposits

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A dissertation submitted to the Faculty of Engineering, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Science in Engineering.

Johannesburg, 1985

DECLARATION

I declare that this dissertation is my own, unaided work, except where due acknowledgement is given. It is being submitted for the degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

(Signature of candidate)

day of 198

ABSTRACT

A lack of knowledge and objective data on the effects of welding process variables in the application and performance of weld-deposited hardfacings has led to a number of failures in the past and subsequent mistrust of the technology. In the work reported in this dissertation, a full factorial experiment was performed in an effort to evaluate the effects of arc current, voltage and polarity, as well as travel speed, stand-off distance and preheat, on the characteristics and properties of a commercial hardfacing deposit. A total of 64 welds were deposited under a wide range of welding conditions, using a 2,8mm "Cobalarc 100M" flux-cored wire.

The effects of the welding parameters were evaluated with the aid of a number of computer analyses, with arc current, voltage and polarity being shown to have the greatest effect on the wear resistance of weld deposits. It was found that a high arc current (360 Amps) gives the most satisfactory deposit in terms of weld metal dilution, deposition rate, and deposition efficiency, provided that electrode negative arc polarity is used. A low arc voltage (24 Volts) is also preferable.

For more cost effective use of hardfacings in abrasive wear resistant applications, the potential of this approach, and the results obtained, are clearly demonstrated. However, other than through the influence on deposit hardness and dilution, there is a lack of any significant direct correlation between laboratory wear rate and welding input variables in this testing programme. This can to some extent be attributed to the rather limited change in microstructure over the range examined, but possibly arising also from the variability introduced by the wear test itself. This serves to emphasise the importance of field trials in determining unequivocally the relative wear resistance in service applications.

In memory of my father

Robert Burrell Wilde

1926-1970

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# 1. INTRODUCTION AND APPROACH

## 1.1 Background and Motivation

To many, the use of welded hardfacing deposits for wear resistant applications is still considered a "black art". This can probably be attributed to a lack of technical awareness and understanding of this field as well as some 'bad' experiences.

A review of the available technical literature (Chapter 2), has shown that the successful application of hardfacings in wear resistant applications requires a systematic analysis and design procedure. This procedure must include the following steps.

1. A full study of the type of wear process involved. This should include a consideration of factors such as the environment, degree of impact, relative speeds, loads involved, hardness of abrading materials, shape and size of the abrasive particles.

2. An evaluation (usually based on past experiences and wear tests) of the material properties required to best withstand the working conditions defined by the

wear studies.

3. A specification of the most suitable (economically realistic) welding process and consumables, to provide the material properties required.

4. A complete welding procedure specification to ensure that the selected consumable is correctly deposited. Due regard should be given to the dilution, deposition rate and geometry of the weld bead.

A lack of attention to detail in any one of the abovementioned steps will often lead to the complete failure of the hardfacing deposit or at best provide a surface with disappointing wear resistance. For example, a weld bead deposited under the optimum welding conditions will have a low wear resistance if the incorrect alloy type is selected, whilst even the most appropriate (and often expensive) alloy type will not perform as expected if the deposition of this alloy is not correctly controlled.

The systematic analysis as defined above is, however, very seldom practiced by those involved with the specification of hardfacing projects and this is the main reason for the large number of failures experienced, and the subsequent 'mistrust' of hardfacings. Whilst this is an unfortunate set of

circumstances it is hardly surprising that this should in fact be the case. A review of the available literature, detailed in Chapter 2 to follow , has revealed the complexity of a detailed wear study, and the inherent dangers involved when applying the results obtained in small scale wear tests. There is also very little objective data available that would aid engineers in the selection of both the correct welding process and the optimum process parameters to use. Where data of this nature is available, it is generally more qualitative than quantitative and there is often a 'difference of opinion' from one author to the next.

This has in turn lead to the 'black art' situation, since engineers are often forced, by the constraints of time and money, to specify the use of a particular hardfacing alloy and process in a wear situation they know little about. They must often base decisions on misleading (although mostly well meaning) information offered by electrode salesmen and in-house shop floor welding personnel. Should the specified solution be a 'satisfactory' one, it is generally thought of as being due more to good fortune than sound judgement! This is, however, usually not the case, and arriving at an economic and technically satisfactory result will often require a number of trial and error iterations, sometimes with economically consequential failures in between.

A number of industries therefore tend to remain with a policy of replacement rather than repair, with a "better the devil you know" attitude to the problem. However, the increasing cost of materials, and therefore the cost of replacement parts, will in future force these industries to seriously consider the benefits and savings to be gained by the correct use of hardfacings.

It must, however, be realised that the success of any hardfacing project will depend largely on the correct application of tribological principles, and a complete understanding of the effects of welding process parameters on hardfacing deposits. The aim of this research project, therefore, was to evaluate in some detail the quantitative relationships between process parameters in the flux-cored arc welding process, and the relevant wear resisting properties of a hardfacing deposit.

## 1.2 Welding Process Selection

There were a number of reasons for selecting the flux-cored arc welding (FCAW) process for the purposes of this study, the most important of which are outlined below.

1. The study was limited to arc welding processes since the majority of hardfacings (80-90% by mass) are deposited with these processes. The manual metal arc (MMA), flux-cored arc (FCAW), and submerged-arc (SAW) welding processes are the most used for hardfacing operations.

2. FCAW is the 'newest' of the three abovementioned processes. The literature review (Chapter 2) also revealed that this process has received the least attention in previous research programmes and the results obtained could therefore be the most useful.

3. The FCAW process has an inherently higher duty cycle and deposition rate than the MMA process and with time and education will become more widely used than it is today.

4. The FCAW process is extremely versatile and can be used economically in a wide range of applications from the hardfacing of small components requiring a few grammes of deposit, to applications where tons of weld metal are deposited in continuous operation. Information gained from this study would therefore be applicable in a vast number of industrial applications.

5. The nature of the FCAW process also afforded the opportunity to assess the effects of welding parameters over a wider range of stable operating conditions than

would have been possible with the MMA process. Automation of the FCAW process is also possible so that welder effects could be eliminated from the experimentation.

## 1.3 Experimental Design

The design and analysis of welding experiments has, in the past, presented researchers with a number of problems. Most arc welding processes are controlled by several input parameters, and the study of the effects of one of these parameters over its operating range, whilst maintaining constant levels of the other parameters, is an extremely inefficient and costly procedure. An analysis of this type also gives no indication of the effects of that parameter at different levels of the other parameters (ie. interactions).

In recent years however, a number of researchers in the welding field (Chapter 2) have utilized so-called "factorial design" experiments. These have proved to be far more efficient since each of the test welds produced are used in the estimation of the effects of all of the input parameters (factors). A factorial experiment will also show any interaction between

factors that may occur.

t was therefore decided to use a factorial design experiment to evaluate tne effects of welding process variables on the wear resistance of hardfacing deposits. The factors (process parameters) in FCAW that have the greatest effect on the output of the process were determined from a review of the literature, and are listed below.

1. Arc current

2. Arc voltage

3. Travel speed

4. Torch stand-off distance (Stickout)

5. Substrate preheat

6. Arc polarity

Each of these factors was set at two levels, and a test weld was produced for each of the 64 possible factor combinations obtained in this way. The effect of each factor was therefore studied at all of the combinations of the other factors.

A semi-automatic FCAW system was automated, to

facilitate the accurate control of the travel speed and torch stand-off distance. A system of integrating circuits was also designed and manufactured so that the actual values of arc current and voltage could be measured. An analysis of how these actual values differed from the machine settings was then performed, in an effort to determine the possible level of control that could be achieved in a welding procedure of this nature. The deposition efficiency for each test weld was also recorded.

## 1.4 Measurements

The wear resistance of a hardfacing deposit depends on several parameters that are generally relatively simple to measure. The most important of these parameters are the dilution of the weld metal with the base material, the level of porosity, the deposit hardness and the width, height and penetration depth of the weld bead.

Each of the test welds was sectioned in five places, and measurements of the abovementioned deposit parameters were recorded. The average of each of these measurements was used in the analysis of the effects of the welding process parameters.

A study of the weld deposit microstructures was also performed in an effort to establish the degree to which the input factors have an effect. The microstructure is known to play a significant role in the wear resistance of a hardfacing deposit.

A small-scale laboratory wear test was also performed on each of the test welds. This involved the measurement of the mass loss of the wear test specimen after a set period of abrading by a fine particle wet abrasive under controlled loads and speeds.

## 1.5 Analysis of Results

Two different sets of analysis were performed with the aid of statistical applications packages available on the main-frame computer at the University of the Witwatersrand.

The first of these was an analysis of variance to determine the effects that each of the welding process factors has on the parameters affecting the wear resistance of the hardfacing deposit. The significance cut-off was set at the 5% level, and all second and third order interactions of the factors were investigated.

A multiple linear regression analysis was then performed using the significant data from the analysis of variance. Several equations relating the geometry, dilution and hardness of the weld deposits to the input factors were developed.

## 1.6 Summary

The present 'mistrust' of hardfacings in industry today must, due to ever increasing economic pressures, give way to a more widespread use of hardfacings in the future. Hardfacings have been used successfully, and have realised significant savings in a number of applications in the past (Chapter 2). This situation can only be achieved if the use of a hardfacing deposit is based on the correct application of all of the principles involved. The present lack of data available on this subject is, however, giving rise to a 'gap' between the need for greater use of hardfacings and the means for economically satisfying that need.

It is hoped that the information gained in this study will help in some measure to bridge this gap and bring about a more widespread and responsible use of hardfacings in the future.

# 2. LITERATURE REVIEW

## 2.1 Introduction

This review, athough dealing primarily with the deposition of hardfacing alloys by welding, is prefaced by an introductory section on wear, since it is imperative that any study of hardfacing is based on an understanding of the principles of tribology. The section on wear is followed by an introduction to hardfacing where the "state of the art" is considered, in an attempt to describe how harufacings are used and misused in modern industry.

The Flux-Cored Arc Welding (FCAW) process is then discussed in detail in a following section together with a review of the experimental work undertaken in this field.

The review concludes with a section on factorial design experiments and their relevance in the study of the effects of welding process variables.

Wear has been described as "the unintentional removal of material from rubbing surfaces" (1) or as "the undesirable displacement of material from a surface" (2). Neither of these descriptions is necessarily complete or entirely correct they both contain the most important point ie. that wear involves an unwanted loss of material. Although these descriptions border on the elementary, the actual causes of wear and the mechanisms involved are far from simple (1).

2.2.1 Classification

There is, as yet, no universally accepted classification of the different types of wear. However, most authors (1-4) describe wear as being either abrasion. adhesion, fatigue or corrosive wear. It is seldom found in practice, that any one of these types of wear acts independently, and this serves only to complicate the selection of a suitable wear resistant material. Since this project deals mainly with abrasion resistant materials, it is only this category of wear that will be considered in any detail, although for completeness, the other areas are also briefly considered.

2.2.2 Abrasive Wear

Abrasive wear occurs when material from a surface is

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Abrasive wear occurs when material

ploughed or gouged out by a much harder surface or body (1,2,4). It is generally divided into two sub-sections viz: two body or three body abrasion. Two body abrasion occurs where the hard abrasive is one of the two rubbing surfaces, whereas in three body abrasion the abrasive is generally a small particle trapped between two sliding surfaces (1,2). It should be noted, however, that these two categories are not different in kind since the action of abrasion is the same in each case (1).

There is some considerable disagreement in the literature as to the most effective way of controlling abrasive wear. Most authors (1,2,4,5,6) emphasize the importance of material hardness with varying emphasis on the role played by toughness, while others (3,7) maintain that the microstructure of the material is also vitally important. This difference in emphasis is probably due to an over simplification of a given wear system by the individual authors.

Brown (7) suggests the relationship between wear parameters and microstructure depicted in Figure 2.1. This model is probably closer to the actual case and gives a good idea of the main variables to be considered in any situation involving abrasive wear. The complete list of variables that have an effect on abrasive wear will, however, continue to grow as more experimentation is performed in this field. Vasil'ev

(8) has, for example, shown that the orientation of columnar crystals with respect to the wear surface can alter the abrasive wear life by a factor of four.

Altnough by now it snould be clear that material hardness is definitely not the only factor to consider in a given abrasive wear situation, it is nevertheless a very important one (5). It is also a factor that is relatively easy to quantify and will therefore probably remain a useful parameter for consideration. The as worn surface hardness is becoming a more accepted criterion for grading the abrasion resistance of a material, since this also gives a measure of the work hardening ability of the material.

Some authors (4,5) show the idealized diagram (Figure 2.2) of wear rate of materials vs mineral hardness. While this graph is, as stated, an idealization it does however illustrate several basic concepts, as follows.

Firstly, it is important to note that a material will suffer only minimal wear loss if the abrasive is softer than the material it is abrading (5). In a case such as this there is no gain from using a significantly harder material than is necessary; for example there would be no advantage in using tungsten carbide over ordinary machine grade steels to resist wear from limestone (5).

In the second case where the abrasive is harder than the metal, there is a sudden steep rise in the wear rate (4,5). In this area of the graph the system becomes very unpredictable and the wear rates experienced can be anything from low to very high. It is also evident that it is this area that provokes the most disagreement between experimentalists, since seemingly insignificant changes in the other factors in a wear system may have a greater effect on the wear rate than expected (7). This unpredictability reduces the emphasis that can be placed on results obtained from small-scale wear tests performed in a laboratory (1), if the complete engineering system is not exactly simulated or reproduced in the test. (Laboratory wear tests are discussed in the next section.)

Eventually the wear rate reaches an upper 'shelf' where a further increase in the hardness of the abrasive has little effect (5). It must be understood however that in this region, the use of a harder material will generally result in a longer wear life. Obviously the final choice of material to be used must be based entirely on economic considerations.

2.2.3 Adhesive Wear

This type of wear occurs when two surfaces slide over one another. It is also often described as either scuffing, galling, seizure or frictional wear (1,2).

The basic mechanism involved is one of local welding and subsequent shearing of minute surface asperities (1).

It must be remembered that even the most finely machined surfaces are very rough on a microscopic scale. Therefore when two nominally flat surfaces are brought into contact they will only touch at a relatively few isolated points (1). This 'effective' contact area is seldom more than 1/1000 of the apparent contact area and will often be as little as 1/10000. These small load bearing areas therefore experience extremely high stresses which usually exceed the yield stress of the material. The high local stresses and resulting plastic deformation give rise to minute welds at each of the local contact points (1). When the surfaces slide relative to one another these small welds are sheared, generally from the softer of the two materials.

Theory predicts that adhesive wear is proportional to the sliding distance and the load (1), is inversely proportional to the hardness and independent of the apparent area of contact. The most effective method of reducing wear of this nature is to eliminate the possibility of asperity welding occuring by the use of surface treatments or lubricants (1).

2.2.4 Fatigue Wear

Fatigue wear occurs where two surfaces are in rolling contact as in bearings and gears. The cyclic stresses caused by this contact give rise to surface fatigue which is characterised by pitting or flaking of the surface (1). The pitting usually occurs suddenly without any prior warning signs and after a relatively long life. The useful life of the component is terminated with the first pitting or flaking (1).

The load on the bearing surfaces is the most important factor to consider in dealing with fatigue wear. It has been shown that a relatively small reduction in the contact stresses can often significantly increase the service life of a component (1,2). Surface fatigue can also be reduced by an increase in the hardness of the materials in contact. Lubrication has little direct influence on fatigue wear but it can eliminate the adhesive wear and corrosion of the surfaces that would tend to increase the local stress concentrations and in turn accelerate the fatigue wear.

2.2.5 Corrosive Wear

Corrosive wear occurs when the products of corrosion (oxides, hydroxides, carbonates, etc) on a surface are removed by the subsequent action of a second surface

(1). Moisture, high temperatures and the chemical reactivity of the lubricant are the factors most likely to cause corrosive wear.

Although corrosive wear is described here as a separate wear type it should be remembered that corrosion plays a part in almost all wear systems, even the simpler ones (9).

### 2.2.6 Wear Tests

The prediction of the wear life of a component in service from the results obtained in a small-scale laboratory test is a difficult task (1,10). This is because there is no quantitative relation for wear, as is the case for, say Hooke's law for elastic bodies, and therefore no wear coefficient comparable to the modulus of elasticity (1). Furthermore, dimensional analysis does not apply.

Although this problem seems to suggest little practical use for small-scale wear tests, they have in fact helped a great deal in the past in the ranking of alloys for the different types of wear resistance and in improving the understanding of wear processes under controlled conditions. Laboratory wear tests will continue to play a significant role in the study of wear, provided that due regard is given to the complete

engineering system under consideration. In general it is possible to simulate all forms of wear (abrasion, adhesion, fatigue and corrosion) in a laboratory test rig and control the most important parameters such as the rubbing surfaces, the load and the speed. The measurements of wear are usually in terms of a volume loss, mass loss (in materials of the same density), or the depth of wear. A detailed examination of the wear surface is also often very important.

Over the years, a multitude of small-scale wear tests have been developed (11), and most manufacturers of wear resistant alloys usually have their own 'in-house' wear testing rigs (12,13,14'.In each case it must be emphasized that these tests are very specific to the type and range of wear process that they test. An engineer must therefore exercise extreme caution in applying the results of these tests in any given wear situation, since even a small difference in some of the parameters involved can give rise to very different (usually disappointing) results in practice. It is for this reason that full-scale wear trials are often preferred (12) although the high costs involved are usually prohibitive, especially if it is required to test a large number of alloys. In these cases it is generally best to narrow the field of choice using a small scale laboratory test and then to 'confirm' these results with a few selected full scale field trials (2).

In conclusion suffice it to say that before a material is placed into service, the wear processes and environment involved should be analysed as completely as possible (12). The suitability of the material in this system can then be judged from past experience and from any wear tests that have been performed. Any haphazardness in this approach will probably result in later difficulties ranging from a shortened wear life to catastrophic failure (5).

## 2.3 Hardfacing

The term "hardfacing" is probably a misnomer since the word conjures up an image of hardness in the mind of most engineers. It is also often thought of as being synonymous with the term "surfacing" which is not entirely correct (2).

Surfacing is defined as "the deposition of material on a (metal) surface to obtain desired properties or dimensions". It is usually employed to extend the life of a part which may have worn or corroded (2). Hardfacing, on the other hand, generally refers to the instances where the overlay contributes to the wear resistance (2). The term "hardfacing" is therefore used to signify wear resistance and not hardness as such. This is because hardness is not an unambiguous

index of wear resistance for the reasons explained in the previous section.

There is, in fact, an ever increasing number of processes used to alter the surface structure of a component (18). These processes are generally divided into three major catagories, namely finishing, treatments and coatings. Finishing and treatments differ from coatings in that they involve no significant change in the dimensions of the component (18). Surfacing and hardfacing are both examples of surface coatings. A classification of the processes most used in industry today is shown in Figure 2.3 (18).

It would seem that hardfacing, as we know it today, probably had its advent in the 1890's or early 1900's (3,15). The first hardfacings were Co-Cr-W (Stellite) alloys which became well known for their resistance to heat, corrosion, abrasion and impact (15). However, some of these alloys are still being used today in applications that are really unsuitable for the properties they exhibit (3).

The correct use of hardfacing in today's industry has a number of advantages, and has more to offer than any other wear preventative technique. The advantages can be summed up as follows (6,16,17) :-

1. Hardfacings are deposited by welding processes. The skills and equipment required are therefore already present in most factories.

2. Most surface treatments usually produce very limited thicknesses of wear resistant material, whereas hardfacings are deposited as a layer or layers and can therefore provide protection in depth which will last longer.

3. A wide range of alloys with varying properties can be deposited. Each of these alloys can be designed to withstand specific service conditions. In many instances it is found that alloys can be weld deposited where it would be impossible to produce them by any other method.

4. It is often only necessary to protect certain areas of a component from wear. Hardfacing is therefore applied (in varying thicknesses) only to the areas that require it and can therefore give the most economic solution of a wear problem.

5. A hard, wear resistant surface can be deposited on a tough backing material. This provides a component having a satisfactory wear life with greater structural integrity than would otherwise be possible.

. . ffecting the Wear Resistance of a

. . . op-

. . . . . rdfacing deposit
. . . . . determined to give an indication of the
. . . ted . . esistance. The main parameters involved
. . . . . e discussed below.

. . . Mic. osstructure.

. . . . . is probably the most important
. . . esistance of a nardfacing deposit
. . . . . microstructure which determines the
. . oughness hardenability and all the other
factors which ensure the deposit's resistance to a
given type or wear.

. . . . . deposit is largely dependent on
. . . . . the wire chemical composition, the
. . . . . procedure and the base metal
. . . . . factors are not independent since,
. . . . . the welding parameters will
. . . . . ent dilution of the electrode by
. . . . . , and can substantially alter the final
. . . . . composition of the deposit (9). For a given
. . . . . composition, the microstructure will depend on
. . . . . which are, in turn, to a large extent
. . . . . the heat input and the other parameters

of the welding process (9). These relationships only serve to make the already difficult process of alloy selection even more complicated. The designer has not only to consider the type of wear involved, but also the welding process and parameters to be used and the composition of the base material, so that he can allow for the effects of dilution and heat input.

Another important factor that must be considered in examining a weld deposit is the heterogeneity of the structure (19,20,21). It has been found (19,21) that a wide scatter in the hardness values and alloy element concentrations can occur in single and multi-pass welds. The electrode coating (or filler in cored wires and strip) does not enter the molten weld pool uniformly and this causes macro-chemical and structural heterogeneity (19). This is also in part due to insufficient agitation at the periphery of the weld pool (19), and the laminar and cellular nature of solidification (21).

Apart from the technical problems discussed above the selection of a satisfactory alloy is often subject to various limitations imposed by the manufacturer, the customer, governments (price controls and security legislation etc), physical phenomena (inc of [illegible] financial resources available (18).

In conclusion it can be indicated that the [illegible]

selecting an alloy for a given application is far from simple. Several authors (6,9,10,12,18,22,23) have discussed the problems of alloy selection and most agree that drawing from the past experience of others with similar problems is invaluable. The detailed study of past, in-house failures can also yield a wealth of information (22).

### 2.3.3 Dilution

The dilution of a deposit is relatively simple to measure when a section of the weld has been polished and etched (25). Figure 2.4 shows the dilution as the ratio of the area of the fused base metal to the total area of the weld deposit (23). This ratio is usually multiplied by 100 to give the dilution as a percentage.

As mentioned in the last section, the dilution of the electrode metal by the base metal is of great importance when considering the deposition of a hardfacing alloy. Hardfacing electrodes generally contain a high percentage of alloying elements which are mostly responsible for the improved wear resistance of the deposit, while the base metal usually has a much smaller percentage of these elements. The dilution of the electrode material with the base metal gives rise to a deposit with a reduced percentage of alloying elements and a generally lower wear resistance

(4,15,16,17,24).

There is some disagreement amongst authors as to which welding parameters have the greatest influence on the dilution of a deposit. Most authors (4,15,16,17,23,26) maintain that the current used in the welding process is most important, with higher currents giving rise to higher dilution. However, current is definitely not the only process parameter that affects the dilution.

The current type (alternating or direct) and polarity (electrode positive or electrode negative) play a significant role in the dilution of the weld deposit (5,15,16).

The electrode stickout (ie. the length of electrode between the current contact and the arc in automatic and semi-automatic welding) also plays a part in the dilution of the weld. There is, however, some disagreement on the extent of stickout that should be used (4,15,16,26).

Other parameters which have an effect on the dilution are the voltage (16,25), the travel speed (17) and even the welding technique, which includes the degree of overlapping of adjacent weld beads (17).

All of the abovementioned welding parameters and their effects on the weld deposit are discussed in greater

detail in the section on flux-cored arc welding (FCAW) to follow. At this stage it should be mentioned that the bulk of the information available on this subject is of a qualitative nature, and in cases where quantitative information is given by one author it is often in conflict with that given by another.

### 2.3.4 Deposit Hardness

The importance of the hardness of a weld deposit for resisting various types of wear was discussed in the section on wear processes. The hardness of a deposit depends on the microstructure, which in turn depends on the chemical composition of both the electrode and base metals and the dilution involved, together with the thermal cycle experienced by the weld metal. The microstructure and dilution and the factors that affect them have been discussed in the previous sections and the same remarks are applicable in any consideration of deposit hardness.

An important point to remember when evaluating the hardness of a deposit containing carbides (eg. chromium and tungsten carbides), is that standard bulk hardness tests no longer show a very meaningful result (5). This is due to the fact that the hard particles (carbides) tend to move away from the indentor, and the hardness measured will generally only be marginally

greater than that of the surrounding matrix. The factors of most concern in such a deposit are the size, quantity, quality (hardness) and the distribution of the carbides (5). Carbide hardness can only be measured on a polished and etched surface with a micro hardness tester (eg. Vickers Micro).

2.3.5 Porosity.

As a weld metal cools during solidification the solubility of gases (mainly nitrogen and hydrogen (27)) in the liquid weld metal decreas s rapidly. When the solidification or cooling process take- place too rapidly or when the volume of dissolved gas is very high, it tends to come out of solution in the form of bubbles. These bubbles cause holes or voids in the solidified weld metal and t is is known as porosity. Porosity can form either on the surface or within the weld metal.

Control of porosity can be achieved by using the correct range of voltage (28), avoiding excessive fluctuations in the voltage (ie within 2V of setting (29)) and ensuring an effective shield of the molten metal from the air (28). These factors are discussed in detail later in this review.

The presence of porosity in a hardfacing deposit is

generally detrimental to its wear life, since once exposed, the edges of a pore are easily worn or fractured and the pore rapidly grows in size. There are however cases where the pore would tend to become filled with abrasive, and this would then become the new wearing surface. The abrasive filling is continually replaced as it is worn away and this can lead to reduced wear of the surrounding hardfacing deposit. This phenomenon is often used to good effect on a much larger scale by depositing hardfacing beads in set patterns to hold the abrasive in small pockets on which the rest of the abrasive then slides (15,16). This and similar techniques are discussed in greater detail in a following section.

### 2.3.6 Deposit Height

The height or thickness of a deposit is important in as much as a thicker deposit will obviously outlast a thinner one, as long as all other factors remain equal. However it will usually be observed that a thicker deposit is narrower than a thinner one made by the same welding process (ie. constant deposition rate) and more runs will therefore be required to cover a surface of a given area. Deposit height must therefore be traded off against the width to give the most economic solution. In a number of cases, it is also necessary to limit the deposit thickness of very hard deposits to

ensure reasonable shock resistance during impact loading (30).

It is generally agreed (25,31) that voltage is the parameter having the greatest effect on the height of the deposit, with the current, travel speed and polarity playing a minor role. This is discussed in detail in the section on the flux-cored welding process.

2.3.7 Deposit Width

A wider deposit will obviously cover a larger area of a component than will a narrower one. However, as described in the previous paragraph on deposit height, a wider deposit will generally be thinner and therefore have a shorter wear life than a narrower one (all other factors being equal). Once again the width and height must be traded off against each other to provide the most economic solution.

A discussion of the effects of process parameters on the width of a deposit can be found in the section on the flux-cored arc welding process.

## 2.4 Welding Process Selection

Modern hardfacings involve a variety of alloys, base materials and applications. Nearly all commercially used arc and flame welding processes are therefore used to deposit hardfacing alloys (32). The selection of a suitable process (15,16,30,32,33,34) for any given application depends on a number of factors, including:-

1. The type of alloy to be deposited. Some processes can only deposit certain alloy types. The maximum allowable dilution can also limit the number of suitable processes.

2. The base metal composition. Certain base metals can only be welded with low heat input processes. For example, a manganese steel cannot be welded with a gas process since the heat input is too high.

3. The size and shape of the component to be hardfaced. Irregularly shaped parts are often difficult to surface with automatic processes while it is uneconomical to hardface large areas with manual processes such as manual metal arc or gas welding.

4. The accessibility of the area to be surfaced. It can be very difficult to manipulate heavy automatic equipment into the correct position for welding in some applications. If out of position welding is required,

the choice of process is limited even further.

5. The condition of the component. Large components that are badly worn are usually best hardfaced with the higher deposition rate welding processes.

6. The number of components. Automatic processes are suited to cases where it is required to hardface a large quantity of similar components.

7. The equipment and expertise available. The cost of equipment and training of operators required to utilize a new hardfacing process will often force a manufacturer to rely on machines and experience already available.

8. The available time. Or occasion it may be necessary to use a high deposition rate process to keep a particular job on schedule, even when a slower process will give a superior result.

9. Site location, ie where the hardfacing is to be performed. Site welding is usually limited to the manual and semi-automatic processes.

## 2.5 Welding Processes

The following is a summary of the major arc welding

processes used for depositing hardfacings including their respective advantages and disadvantages when used in hardfacing applications. Although this project deals entirely with an evalaution involving only the flux-cored arc welding process (FCAW) it was deemed necessary to include both the MMA and SAW processes in this review. This was done in an effort to emphasize both the similarities and the differences between the three major arc welding processes used for hardfacing, and to show the relative importance of the FCAW process. The reasons for the continuously increasing utilization of the FCAW process in the past decades will also become obvious. A more complete discussion of the flux-cored arc welding process can be found in a following section.

### 2.5.1 Manual Metal Arc Welding (MMA)

Manual metal arc welding is started by striking an arc between the work to be welded and a flux covered electrode. The heat generated by the arc melts both the tip of the electrode and the surface of the workpiece near the arc. Small globules of molten metal form on the tip of the electrode and are then transfered (by electrical, magnetic and gravitational forces) through the arc to the weld "pool" or "puddle" on the work surface (35).

The flux shield contains various ingredients which break down in the arc. These ingredients form a dense envelope of gas around the arc to protect the transfering molten metal from contamination by the atmosphere, provide scavengers and deoxidisers to refine the weld metal and form a slag covering over the solidifying metal.

It is also possible to add a limited quantity of alloying elements to the flux. This is very useful when producing electrodes for hardfacing since the addition of these elements to the electrode wire would often make die extrusion impossible and greatly increase the cost of production.

Some manufacturers now produce tubular electrodes with alloying elements contained within the tube and fluxing elements (as usual) bonded to the outside.

Advantages:

1. Equipment used is highly portable. This means that the process is often suitable for site use (16,33).

2. Low cost equipment. As compared to other processes, the equipment required is relatively cheap (16,32).

[illegible] electrode used the process can [illegible] used for out of position welding. Components [illegible] therefore be hardfaced without having to dismantle [illegible] machine (16).

It is the most commonly used process. Most factories generally have the equipment needed for MMA welding and the expertise is often available without the need for extensive training (16).

A large selection of electrodes is available for MMA welding. It is therefore possible to deposit a wide range of hardfacing alloys to protect components from any form of wear (9).

Disadvantages:

Requires a fair degree of skill to obtain the best results (32).

[illegible] deposition rate. A new electrode is usually [illegible]00 to 400mm in length and resistance heating of the electrode can be considerable unless the current is [illegible] low. This in turn limits the [illegible] rate of the process, since excessive heating [illegible] adversely affect its properties. [illegible] deposition rates are from 3 to 6kg/hr (32).

3. Low duty cycle. Only a small percentage (typically 20 to 40%) of the welders time is spent actually depositing weld metal. The bulk of the time is spent aligning workpieces, changing electrodes or removing slag from the deposited weld. The low duty cycle limits effective deposition rates to about 3kg/h (33).

4. Low deposition efficiency. Only a fraction of the electrode purchased is actually deposited as weld metal, the rest being lost as stub ends, slag, vapour and spatter. The deposition efficiency of the MMA process is usually between 40 and 60% (35). This can be a deciding factor in hardfacing because of the high cost of certain electrodes.

5. Excessive dilution. The MMA process can lead to high levels of dilution of the electrode if the current used is not kept to a minimum (24).

All things considered, however, the widespread use of the manual metal arc process has lead to its popularity as a hardfacing process. It has over the years been used in extremely diversified fields of application, and will probably remain very popular for site welding conditions due primarily to its portability and positional welding ability.

2.5.2 Flux Cored Arc Welding (FCAW)

Since this project deals with the effects of process variables in flux-cored arc welding, the FCAW process will be discussed in greater detail in section 2.10 to follow. Flux-cored arc welding offers the greater productivity of the metal inert and active gas processes and can be effectively used for hardfacing.

The MIG and MAG processes are not generally used for hardfacing since this would require high alloy additions to the solid wire used, which would make it virtually impossible to wind it into coil form. With the FCAW process, however, alloying additions can readily be mixed with the fluxing elements in the centre of the tubular wire. The wire itself is usually manufactured from a ductile low alloy steel which is easily wound.

2.5.3 Submerged Arc Welding (SAW)

In submerged arc welding, a bare electrode wire is automatically fed through a layer of granulated flux to the base metal. The flux once again serves to shield the molten and solidifying weld metal from the atmosphere and to supply deoxidizers. In certain cases

the flux also adds alloying elements to the weld pool (35), which is why it can be used as a hardfacing process. Only a portion of the flux actually melts and leaves a solid slag covering over the weld, the balance is usually recovered by a vacuum and recycled. The molten slag is usually electrically conductive and aids in supplying resistance heating to the weld pool. The arc length is automatically controlled by the power supply.

Submerged arc welding is generally considered to be a fully automatic welding process but it is on occasion used in a semi automatic mode where it relies on an operator to correctly manipulate the gun. However, in either case there is no bright flash or spatter and generally only a small amount of smoke or fume produced which is easily extracted from the working area. This means that operators suffer very little fatigue and the duty cycle can be kept very high (generally between 60 and 90%).

The main drawback with this process is that it can usually only be used in the flat position or for horizontal fillet welds, although special equipment and techniques have been developed to facilitate welding in the vertical-up position. The process is totally unsuitable for overhead welding however (35).

Submerged arc welding is widely used as a method of

hardfacing and is particularly useful in applications that are easy to automate as in the surfacing of large cylindrical components (eg. steel mill rolls (20), disc cutters in mining (14), tractor idler wheels (37) and worn railway wheel flanges (38)).

Due to the very high deposition rates that can be maintained with the SAW process it has over the last decade been the subject of many hardfacing research programmes, especially in the USSR.

Electrode diameters of up to 8mm have been used (39) to achieve high deposition rates under stable conditions. It has also been found (40) that metal of almost any chemical composition can be deposited by using the correct alloying elements in the flux. The complete impregnation of the deposited metal by the alloying elements takes place when the molten flux comes into contact with the molten weld pool (40). It has been shown that this alloying process is affected by the relative mass of the flux and the time the metal spends in the molten state (41), and is therefore heavily dependent on the welding parameters used. Uneven mixing of the metal in the weld pool can often give rise to differently alloyed layers which may under certain conditions act as initiation points for cold cracks (40).

By increasing the stickout, the penetration and

dilution of the base metal can be decreased whilst still maintaining a good deposition rate. Marishkin, et al (42) have shown that high quality hardfacing is possible with a 5mm diameter wire at currents of 750-800A and a stickout of up to 250mm.

It has been determined (43) that additional alloying elements can be introduced to the weld metal by using a powder-filled or flux-cored wire and in some cases this is known to give the optimum composition. Mineral additives to cored wires can also make it possible to regulate the processes of reduction of manganese and silicon, and improve the quality of the deposited metal (4 ).

An extension of this process is the use of a strip electrode to increase the deposition rate. Strip electrodes are usually about 0,5 or 0,6mm thick (45,46,47), but experimentation has been done on strip electrodes as thin as 0,3mm and up to 1,0 or 1,2 mm thick (48,49). The width of these electrodes generally varies from 30mm to 60mm (49,50,51). However Mastenko, et al (52) have shown that strip electrodes of up to 200mm wide (deposited at about 5000A) can be used. However, when using electrodes more than 100mm wide and welding currents greater than 1000 A the Lorentz force that develops between the welding current and its magnetic field can cause overlap and undercut along the edges of the beads. This tendency can be overcome by

introducing an additional external compensating magnetic field (52).

Increasing the width of an electrode can also reduce the amount of dilution; for example, in one experiment (52) an increase of electrode width from 20 to 200mm caused a reduction in the dilution from 25 to 8%, while the corresponding deposition rate increased from 8 to about 48 kg/hr. Both of these factors make the process very useful for the hardfacing of large components.

An extension of this process is the use of a flux cored strip (53,54). The electrode is formed into a rectangular box section, and the hollow centre is filled with both alloying and fluxing elements. It has been found that a higher current, arc voltage and travel speed can be used with these cored electrodes giving rise to much higher deposition rates at satisfactory levels of dilution (54).

The bulkweld process can also be considered an extension of submerged-arc welding (55). In bulkwelding however, a carefully metered layer of granular powder metal is deposited under the layer of flux just ahead of a laterally oscillating solid wire electrode. The users of this process (56) claim that it is far more energy efficient than the conventional SAW process, depositing up to four times the amount of weld metal for the same arc current. Bulkwelding also

gives a very low dilution of the deposit and has been used successfully in many hardfacing applications (56).

The following is a summary of the major advantages and disadvantages of submerged-arc welding as applied to hardfacing.

Advantages:

1. High deposition rates. The SAW process is ideal for the hardfacing of large components (16,33).

2. Good control of welding conditions. Extremely precise welds can be deposited which often do not require further machining before being placed in service (30,33).

3. No visible arc. Operators generally experience less fatigue than with other processes (16,33).

4. Moderate heat input. Can be used in applications where a high heat would be detrimental to the properties of the materials used, as in the welding of manganese steels (16).

5. Relatively low dilution of the weld metal. Under certain conditions dilutions as low as 8% can be achieved (16,52).

6. Low operator skill required. Once a system has been set up it often requir-s only a low skill operatcr to maintain a high production rate. This is of particular importance in South Africa where skilled artisans are in short supply.

Disadvantages:

1. Limited portability. For obvious reasons, the equipment required for SAW has only limited portability and cannot generally be used for site welding applications (33).

2. Not generally suited to out of position welding. SAW is usually limited to downhand and horizontal fillet welding. This factor also makes the process unsuitable for many site welding applications (16).

## 2.6 Hardfacing Techniques

There are three main techniques used for depositing hardfacings (16), although som variation w.hin a technique occurs with different applications (33). These techniques can generally be used with all of the arc welding processes discussed so far, although the

limited manoeuvrability of most automatic welding machinery will sometimes be a limitation. The selection of a satisfactory technique depends on a number of factors including the function, service conditions and state of repair of the component.

### 2.6.1 Continuous Coverage

The continuous coverage of a component is generally used in situations where the part has a critical shape and size (16). Examples of these parts are rolls, shafts, t'acks, crusher jaws and cones. Components subjected to severe fine abrasion and erosion (eg. sand chutes, dredge bucket lips, valve seats and pump and fan impellers) are also hardfaced in this manner.

It is important that adjacent weld beads are sufficiently overlapped to provide continuous protection of the base material. Overlapping of the weld beads also gives rise to a reduced dilution, since the weld deposit fuses not only with the base material but also with the adjacent weld bead. When trying to avoid the abrasive wear of fine particles it has been found best to deposit weld runs at right angles to the direction of the flow of abrasive (16).

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2.6.2 Stringer Beads

Due to the high cost of using continuous coverage of a component by hardfacing, methods of only partially covering the surface have been developed and are at present being used to good effect in certain applications (37).

One of these methods is the use of individual stringer beads separated by areas of exposed base metal (16). This method has proved effective in applications such as dragline buckets and teeth, rock chutes and ripper teeth (16,37).

Different patterns of stringer beads have been developed for various service conditions. Examples of these patterns as applied to ripper or shovel teeth are shown in Figure 2.5 (16,37). For teeth working in rocky conditions, the stringer beads are deposited so that they run parallel to the path of the material being handled (Figure 2.5a). The rocky material then rides along the surface of the beads without coming into contact with the base metal.

When the tooth works in an environment of fine abrasive material (eg. sand or clay), it is best to deposit the stringer beads at right angles to the direction of travel (Figure 2.5b). Under these conditions the abrasive particles become compacted into the spaces

and provide protection for the
posed base metal (37).

. Figure 2.5c shows the "waffle" or "checker"
tern used to surface parts subjected to abrasive
rom both large and small particles (16).

. . . . . Next

. . . . . g shovels and buckets are
ear subjected to generally less arduous
conditions (16). It is possible to protect
by depositing on them a series of small
ardfacing dots at about 50mm centres. These dots
hould be approximately 15 to 20mm in diameter and 10mm
g (16) and are deposited in the form of a tight
beginning at the center and working outwards

ests ways of combining the above
echniques to provide wear resistance in a number of
specific applications. One solution to the problem of
resisting wear from a system involving both abrasion
and impact is to use two different electrodes, one with
a high hardness and abrasion resistance and the other
with a good work-hardening ability. The different
electrodes are then deposited alternately to give a

buildup of lines or both [illegible] deposits. The wear resistance of the hardfacing is not greatly affected by the soft lines since the hard layers remain intact and do not spall. This method also allows stress relaxation during welding, and plastic movement is possible under impact. The relative amounts of each electrode that should be applied can be determined from the amounts of impact and abrasion in the wear system (57).

## 2.7 Hardfacing Applications

Due to the variety of alloys and deposition methods available, hardfacings have over the years been used in a vast number of applications that have resulted in considerable savings. A few examples of these are given below to illustrate the diversity of the applications and the savings that can be achieved.

As early as 1972 it was estimated (29) that about 50000 tons of metal were deposited anually in the USSR to restore components to their correct dimensions and improve their wear resistan e. More than 90% of this metal was deposited by arc welding processes.

An automatic welding system using a flux cored wire and a carbon dioxide gas shield was developed by the French

Railways for the repair welding of skid dents and rail ends (58). Before this system was introduced the repair of rail wear was carried out using manual metal arc welding and was limited to very small defects. This meant that rails were generally replaced rather than repaired and often resulted in long delays in rail service. The new automatic system reportedly negates the need for early rail replacement and leads to fewer rail traffic delays.

Belov (59) describes the restoring of worn rotary crusher beaters or hammers. This is a fairly common application for hardfacing and due to the high deposition rates required it is usually performed with either automatic or semi-automatic flux-cored arc welding. Substantial cuts in the time required for hardfacing (and therefore plant downtime) by using FCAW instead of a manual process, have resulted in increased productivity in all cases examined (59,60,61).

Flux-cored arc welding has also been used successfully in applications as varied as:-

1. The hardfacing of rolls of profile bending rolls (62);

2. surfacing crane wheels, crusher mantles, dragline buckets and cement feed screws (63), and

3. the protection of water turbine blades from hydro-abrasive wear in hydro-electric schemes on rivers in Siberia and Eastern Europe (64).

Manual metal arc welding is regularly used to good effect in the hardfacing of smaller components such as forging dies and tools (3). It has been found that under the correct conditions a high quality deposit can be obtained, giving rise to a significant improvement in die and tool life.

Submerged arc hardfacing has resulted in large cost savings in both civil engineering plant (37) and steel works (20,32) where large cylindrical components often require very heavy building-up operations. The surfacing of such components can usually be fully automated and extremely high duty cycles are often achieved.

## 2.8 Economics of Hardfacing

The justification of hardfacing in any application is in most cases based on purely economic considerations (7,30). However, for a number of complex reasons the subject of economics appears to be the least documented and most confusing aspect of surfacing (65).

The following is a list of the more important cost components that must be taken into account when calculating the savings brought about by the introduction of a hardfacing system (16,37,65,66).

1. The service life of a component is increased by hardfacing. The increase is usually between two and twenty times the life of a non-hardfaced part, depending on the service conditions. This saves both the maintenance and downtime costs due to the reduced frequency of repairs.

2. Hardfacing is a very effective reclamation process since a worn component can often be repeatedly hardfaced, extending the life of the part indefinitely. This is of particular importance in a country like South Africa where machine parts are often imported, making them expensive and occasionally very difficult to obtain. There is also no need to tie up large sums of money in stocks of spares.

3. The more sophisticated alloys are usually more expensive and require costly manufacturing processes and heat treatment. However machine parts can often be made from relatively low cost base materials and then hardfaced to give the desired wear resistant surface properties. This can give rise to a lower capital cost

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3. The more sophisticated alloys are usually more expensive and require costly manufacturing processes and heat treatment. However machine parts can often be made from relatively low cost base materials and then hardfaced to give the desired wear resistant surface properties. This can give rise to a lower capital cost

of machinery.

4. The efficiency of a machine often decreases as its components wear. Since hardfaced parts tend to maintain their original dimensions for longer periods the machinery will operate more efficiently and further reduce running costs. The output of a process (production capacity) can also be increased without the usual expense of additional equipment.

5. The cost of acquiring and installing the necessary equipment, together with the cost of hiring or training the personnel to operate it, is also an important economic consideration.

## 2.9 Flux-Cored Arc Welding (FCAW)

### 2.9.1 Introduction

Cored electrodes, where shielding of the arc is provided by the core material, were developed in the 1920's for welding steel. The shielding was however insufficient to produce high quality welds, and the development of the covered electrode (for MMA welding) in the late 1920's and the submerged-arc welding process in 1930, dissipated somewhat the interest in flux-cored electrode welding (68).

The development of metal inert gas (MIG) welding in 1948 provided equipment for continuous wire welding systems, but it was only late in 1956 that flux-cored welding wires became widely available. The process gained rapidly in popularity, and by the early 1960's it had become a major contender for the fabrication of steel weldments (68).

Originally, the process required additional external gas shielding (usually carbon dioxide), but by 1959 wires could be produced with sufficient gas forming elements and deoxidizers in the core materials. This eliminated the need for additional gas shielding and greatly simplified the equipment required, since the gas control components were eliminated.

In 1970, flux-cored arc welding was the fastest growing arc welding process in the USA, and is continuing to gain popularity in modern industry worldwide. The gas-less type electrode wires have over the years been the subject of a considerable amount of research and wires are now available for welding most grades of steel in any welding position (68).

The FCAW process is also widely used for depositing hardfacings, since alloying elements can be added to the core material of an easily formed low alloy tubular wire. Unlike the MIG/MAG gas shielded processes, the FCAW process can be used out of doors since there is no

shielding gas to blow away.

### 2.9.2 The Flux-Cored Arc Welding Process

Flux-cored arc welding has been described as an outgrowth of manual metal arc welding. The fluxing and shielding elements are placed inside a tubular wire that can be coiled and used in a continuous welding process. This process has the manoeuvrability and versatility of MMA welding combined with a much higher deposition efficiency, duty cycle and deposition rate (35). There are no stub end losses, the need for continuous replacment of electrodes is eliminated and slag removal is minimised. Due to an effectively shorter electrode length higher arc currents can be used which in turn give rise to higher deposition rates.

Figure 2.6 is a schematic representation of the principles of the flux-cored arc welding process (35). The cored electrode is fed through a hand-held gun with a copper contact tip (or guide tube) which makes electrical contact with the electrode as it leaves the gun By pulling a trigger on the gun, the operator activates the wire feeder unit and completes the welding circuit. Continuous closed loop arc length control is performed automatically by the wire feeder unit so that an operator needs relatively little

training to become proficient in the use of the process.

The following is a summary of the major advantages and disadvantages of the FCAW process as applied to hardfacing.

Advantages:

1. High deposition rates. One author (32) claims a deposition rate as high as 23kg/hr is possible for the FCAW process. However, most authorities(29,63,67) seem to agree that the practical process deposition rate is limited to about 14 to 15kg/hr. This is still a vast improvement on the deposition rates achieved with the manual metal arc process, however.

2. High duty cycle. Duty cycles between 60 and 70% are typical of the semi-automatic process (32), while the automatic process can achieve a duty cycle as high as 90%.

3. Easy to use. As previously described, this process requires relatively little operator training to achieve satisfactory results (32). This is of particular importance in South Africa where skilled labour is both scarce and expensive.

4. Portability. The wire feeder and power supply can

be separated by long extension leads, which then allows the robust and lightweight feeder unit to be moved into the most suitable position (63). This obviously does not apply to the automati- version of the process.

5. Moderate equipment cost. The wire feeder and gun are the only added expense when compared to the cost of the equipment required for manual metal arc welding.

6. Good control of welding conditions. The process parameters can be controlled to give both low dilution and heat input (16).

7. Low operator fatigue. Once the operator has positioned himself comfortably next to the work he can often continue welding for long periods with much less effort than is required for manual metal arc welding.

8. Excellent shielding of the arc. The core materials give a shielding gas in the centre of the arc that provides good protection even in the windy conditions often experienced on site welding applications (63). This also means that fast flow ventilation systems can be used to remove fumes and smoke from the working area for improved operator comfort.

9. Suitable for production applications and large work (16). The automatic FCAW process is easily adapted to situations where a large number of smaller components

(eg. ripper teeth) are to be surfaced, and is equally suitable in large applications (eg. mill and crusher rolls) where tons of weld metal are deposited in continuous operation.

10. Thin slag crust. The slag crust that forms on the deposit is usually thin and need not be removed before depositing subsequent beads (29). There is also no need for the flux handling equipment used in SAW.

11. Suitable for out of position welding. Although some sources (16,32) maintain that the FCAW process is not suited to out of position welding (ie. other than downhand or flat), more recent developments have led to the production of flux-cored electrode wires that can be used in all positions (64).

Disadvantages:

1. Limited portability of automatic process equipment (16).

2. Smaller range of consumables available in South Africa than for MMA, although this should change as the process becomes more widely used.

### Equipment for FCAW

The three basic components required for gasless flux-cored arc welding are :-

1. The welding machine or power source.

2. The wire feeder and control system.

3. The welding gun and supply cable assembly for semi-automatic welding or the welding torch for automatic welding.

In semi-automatic FCAW the welder is required to move the gun relative to the work, whereas in automatic FCAW this function is performed by a mechanized system. The additional equipment required for automatic welding will not be discussed in this review however. Also, for the purpose of this account the two variations will be discussed as one process, since both have the same operating parameters.

### The Power Source and Wire Feed System

The power source and wire feed system must be discussed together since it is by their interaction that control of the arc length is maintained. There are two types of power source-wire feed systems in use today (68) viz: the constant voltage (flat characteristic)

power supply matched to a constant speed electrode wi
feeder; and the constant current (drooping
characteristic) power supply connected to
voltage sensing electrode wire feeder.

The constant voltage power supply is the most popular
for FCAW and is generally only used for d.c. welding
(68). It has the advantages of simplicity of control,
reliability of arc starting, virtual elimination of
burn back and stubbing, and ease of maintenance.

In the wire feeder, the electrode is usually pulled
from a reel by one or two pairs of drive rolls, and
forced down the length of the supply cable (generally
less than 5m long) to the welding gun (35). The
pressure of the drive rolls on cored electrodes must be
limited to avoid deformation. Drive rolls are
therefore often knurled to give a good grip on the wire
with the minimum of pressure. This practice can,
however, put a rough finish on the electrode surface
which increases the wear rate of the copper contact tube
in the welding gun which therefore needs to be replaced
more frequently. It is also important to note that the
feeder unit be powerful enough to overcome the
additional friction involved in such a situation.

The characteristic arc current vs voltage curve for a
constant voltage welding machine is shown in Figure
(68). This system, in which the machine supplies

nominally constant arc voltage irrespective of the current in the arc, was originally developed for MIG welding. The machine can only be used for automatic or semi-automatic welding, with a continuously fed electrode wire.

In continuous wire welding, the burn-off rate of a given electrode type and size is proportional to the welding current. This means that as the electrode wire is fed at a specific rate into the arc, it will automatically draw a proportional current from a constant voltage power supply. The constant speed wire feeder can be adjusted to give a faster or slower wire feed rate which in turn causes a higher or lower arc current. The voltage of the machine is regulated by an output control on the power source itself.

This system is self regulating, since, should the arc length increase, a small increase in voltage occurs which in turn causes a much lower current to be drawn by the electrode (Figure 2.7). At this lower current there is less electrode burn-off, and the arc length is effectively shortened. The reverse of this process occurs when the arc length becomes too short (68).

Figure 2.8 shows the characteristic curve for a constant current (drooping characteristic) welding machine. The characteristic volt-amp output of this machine produces a maximum voltage at no load, with the

voltage decreasing rapidly as the load increases.

When this system is used for automatic welding (usually SAW) an increase in arc length causes a rise in the voltage which is sensed by the wire feeder mechanism. The wire feeder then increases the electrode feed rate to shorten the arc. The desired welding current is set on the power source.

Welding machines of this type are also used for manual metal arc welding, since the changing arc length causes only minor fluctuations in the arc current.

### 2.9.5 Cored Wires

Flux-cored electrodes are usually produced by forming a thin metal strip into a filled tubular wire (15). This is performed by first forming the flat strip into a V or U section and filling it with a mixture of flux and metal powders, and then drawing it through a die (6,69). Several different methods (Figure 2.9) of crimping or overlapping the seam have been developed in an attempt to improve the current distribution over the cross section of the wire (15,69). These methods have met with varying degrees of success, the biggest problem being the loss of filling when the seam is accidently opened or the wire is crushed or bent (69).

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A relatively new development (1970) in this field is the production of a seamless flux-cored wire (69) for which the manufacturers claim a number of advantages over the conventional seamed wires. Firstly, the wires have a high density fill which can even contain ultra-active ingredients. They can also be surface treated to improve shelf life, electrical conductivity and feeding characteristics. There is also no chance of moisture or water coming into contact with the filling ingredients and baking requirements can be eliminated (69).

### 2.9.6 Deposition Efficiency

The deposition efficiency of a given welding process and procedure is a measure of the percentage of the mass of an electrode that is actually deposited as weld metal, and can have a marked effect on the cost of depositing hardfacing alloys (36). A decrease in deposition efficiency will cause an increase in the cost of the electrodes or consumables and the labour required to complete a job.

Due to the generally higher cost of hardfacing alloys (in some cases the cost exceeds R100/kg. (70!), it is imperative that the deposition efficiency of a welding process is as high as possible when depositing these alloys. It must also be remembered that a lower

deposition efficiency will require more time to deposit a given mass of weld metal (36), and the labour and overhead costs for a job will increase proportionally.

The losses that occur in FCAW are due mainly to the thin layer of unassimilated core materials that forms on the surface of the deposit, the spatter that occurs as the wire is melted and the welding aerosol that forms around the arc (71,72).

There are several factors that affect the deposition efficiency of a welding process, for example, the core elements and composition of the electrode itself can play a significant role (15,73). It has also been shown that an increase in the gas and slag forming components of a flux-cored wire can to a point, improve the deposition efficiency.

The effects of welding parameters on deposition efficiency have been investigated by several authors (eg 4,24,29,71) but the results described are usually of a qualitative rather than a quantitative nature and are often contradictory.

One author (68) states that the larger molten droplets of weld metal that occur when lower welding currents are used cause a greater "splashing action" as they enter the weld pool. This "splashing" gives rise to increased spatter losses and it is therefore best to

use an electrode at higher current levels. Metlitskii et al.(71,72) however, claim that an increase in the current used gives rise to greater losses in the form of spatter and unassimilated core materials.

The role of arc polarity in the deposition efficiency equation also seems to be a point of disagreement. One source (15) states that d.c. electrode negative (straight polarity) causes higher spatter losses, whilst another source (71) claims that using d.c. electrode negative actually gives a smoother deposit surface and improves the deposition efficiency.

A high arc voltage gives rise to excessive spatter losses (15) and a decrease in the deposition efficiency (15).

### 2.9.7 Welding Parameters

There are a number of adjustable welding parameters in flux-cored arc welding which affect the output of the process, and can give wide differences in hardfacing deposit structures and subsequent service life (12). The welder or operator also has a strong influence on the integrity of the deposit (4,5). Not only is he usually responsible for the machine settings of amperage, voltage and electrode polarity but the technique he uses will determine the electrode

stickout, the travel speed (and heat input), the degree of preheat, and the electrode angle, all of which have an effect on the final deposit (74).

There is at present a lack of quantitative information which would enable an engineer to decide on the optimum levels of the process variables to be used, and the selection of the most appropriate hardfacing conditions is at present a virtually impossible task. This situation has been receiving more attention in recent years, and studies on the effects of current, voltage, travel speed and electrode diameter on the penetration, width, height and undercut of weld beads have been performed (75,76,77,78,). These studies included both butt welds (SAW) and fillet welds (FCAW) used in structural welding and whilst they do give an idea of the relative importance of the various parameters, there can however be no direct extrapolation of the results to hardfacing procedures. As with all welding research, this is complicated by the interaction of a number of other process variables. A more sophisticated method of analysis is required (75), and this will be discussed in a following section.

The following is a discussion of the effects that the abovementioned welding parameters have on the various characteristics of a hardfacing deposit.

2.9.8 Arc Current

The arc current used when depositing a hardfacing alloy is of prime importance, since the current affects a number of other process parameters and ultimately the weld deposit itself. A higher current gives higher deposition rates (12,32), which in turn improves the productivity of the surfacing process. To obtain the most economic surfacing rate the operator must therefore use the highest stable arc current. However, high current levels may adversely affect the properties of the deposited weld metal and the subsequent wear life, and will therefore have to be limited.

As mentioned before, the current has a marked effect on the dilution of the deposited weld metal, dilution increasing with increased arc current. Dilutions of between 30 and 60% are typical for continuous arc welding systems (9,23), and the alloy content of a hardfacing weld metal will obviously vary greatly at these different levels of dilution.

The arc current also affects the thermal cycle experienced by the deposit, by altering the heat input to the work. These differing thermal cycles can obviously influence the microstructure of the weld deposit.

The effect that arc current has on the microstructure

of the final weld deposit varies from one alloy type to another. Quaas (12) has shown that only minor changes in microstructure of a martensitic deposit (0,8%C; 1,5%Mn; 6,0%Cr; 1,0%Mo), occur when the metal is deposited at different amperages. In contrast to these findings, Cooksen (23) has shown that the current used can have a significant effect on the structure of carbide forming alloys. It was found that a low current gave a fine dispersion of primary carbide. while the same electrode type produced a microstructure of coarse primary carbide stringers in a eutectic carbide'martensitic matrix at a higher current. These two microstructures would be suited to different wear applications, and this demonstrates how one alloy could be used to provide wear resistance to different wear modes, purely by altering the welding parameters of the deposition process (23).

### 2.9.9 Arc Voltage

Increasing the arc voltage when depositing hardfacings with the FCAW process, tends to decrease the penetration (and hence the dilution) '15,25,28) and increase the width-to-height ratio of the deposit (27). The amount by which this can be done is however limited by the formation of pores in weld metal deposited at higher voltages. The limiting voltage that can be utilized depends on a number of factors including the

type and filling of the cored electrode wire used and will vary from one application to the next.

Merkulov et al. (27) have shown that the deposition voltage can be substantially increased (from 28V to 37V) without the occurrence of porosity by using a pulsating arc. It has also been shown that the use of a pulsating arc can substantially reduce the deptn of penetration at higher voltages (27). Yuzvenko (29) has shown that fluctuations in arc voltage can cause porosity of the deposit. In order to prevent pores from forming the arc voltage should be kept within 2V of the desired setting, and this is why the constant voltage (flat characteristic) power sources are preferred for the FCAW process.

### 2.9.10 Travel Speed

The travel speed is the relative velocity between the welding gun or torch, and the workpiece. It can have a significant effect on the depth and area of weld penetration and the width and reinforcement of the deposit (15,31). There is, however, a specific lack of quantitative information describing the relationship between the travel speed and the weld deposit parameters for the FCAW process under hardfacing conditions.

The heat input of an arc welding process is given by the equation:

$$H.I. = \frac{V \times I \times 60}{\text{Travel Speed} \times 1000} \quad (kJ/mm),$$

where the travel speed is measured in mm/min.

Certain base metals (eg high manganese alloys) experience a reduction in mechanical properties when welded with nigh heat inputs. To maintain a resonably high deposition rate the welder must therefore increase the travel speed, although this is limited by the appearance of undercutting and gas piping (wormholes) at higher travel speeds (15).

The heat input can have a pronounced effect on the cooling rates and hence the microstructure of the weld deposit, although, as already mentioned, some alloy types are more affected by this than others. The size of the component being hardfaced must also be taken into account (9), since heat build up will be far more severe in small components. The comments made in the previous sections on arc current, arc voltage and travel speed of the FCAW process are also of

significance in the discussion [illegible]

2.9.12 Preheat / Interpass Temperature

When hardfacing hardenable steels or particularly heavy sections of material, it is often considered best to preheat the component and maintain this temperature between weld runs (16,26). Base steels with carbon equivalents greater than 0.45% are susceptible to hydrogen (or cold) cracking in the brittle martensitic heat affected zone that forms next to the weld fusion line. Once hydrogen cracks have formed they can cause spalling of the hardfacing deposit and may even, under conditions of fatigue, cause total failure of the base metal component. By preheating the base metal prior to hardfacing the cooling rate is reduced, and a tougher heat affected zone microstructure results.

It is usual to preheat a component to between 100 and 200 degrees C (16,37,59), although this varies depending on the application. Once the correct levels of preheat and interpass temperature have been determined, they must usually be monitored to within close tolerances (67) to achieve a satisfactory deposit.

The effects of preheat in the FCAW process on the wear resistance and geometrical parameters of a hard facing

deposit are not well documented. A supervisor or engineer who is involved with specifying weld procedures will therefore not be able to predict the effects of a change in preheat on the weld deposit. It is also very difficult to determine how to compensate for these effects by altering other process variables.

2.9.13 Electrode Stickout

The electrode stickout is subjected to resistance heating, and a maximum deposition rate is achieved by maintaining a long electrode stickout (68). The heating of the wire also helps to burn off any residual drawing lubricant or other volatile materials which may be on the wire, before it enters the arc (15).

Wahl (4) states that "the use of short electrode stickout represents good hardfacing practice", although no actual figures are quoted. In one case where the FCAW process was used to hardface crankshafts (79), a stickout of 16mm is quoted. Another author, however, (26) claims that a relatively long stickout (30-40mm) is advisable to reduce dilution, and still others (15,16) suggest that electrode stickouts of between 50 and 75mm are best for hardfacing procedures.

It can therefore be seen that the optimum setting of the electrode stickout for hardfacing purposes is a

point on which most authors have their own (and often conflicting) opinions. None of the abovementioned papers quote any figures from research to substantiate the statements made, however, and once again the individual involved with the specification of welding parameters has very little objective data on which to base his decisions.

### 2.9.14 Arc Polarity

Hardfacing with the flux-cored arc welding process is usually performed with a direct current power source. The choice of polarity depends mainly on the composition of the electrode filling, since a number of electrodes are not designed to give stable welding conditions when used in the electrode negative (straight polarity) mode (15,16). The electrode negative mode does, however, cause the least amount of dilution, and is generally the favoured hardfacing mode when stable arc conditions can be achieved (5,71), although this is not always the case (59).

## 2.10 Factorial Design Experiments

### 2.10.1 Introduction

A factorial experiment is one in which the effects of

several factors are investigated at two or more levels of each factor (80). Observations are taken at each one of all possible combinations of the different levels of the factors, with each different combination of factors being known as a treatment combination.

The consideration of an example is probably the best way of discussing the main points at issue when undertaking an experiment of this nature (81). Suppose that a manufacturer intends utilizing a new autoratic welding process to perform the root run weld in a heavy fabrication. Controllable penetration and a high deposition rate would be of prime importance in such an application.

Assuming that nothing is known about the effects of arc current, voltage, polarity, torch stand-off, travel speed or electrode diameter on the penetration and deposition rate for this process, it would then be necessary to perform a number of experiments to determine these effects. The classical approach (81) would then involve setting up a number of separate experiments to determine the optimum ranges for each of the abovementioned process parameters (or factors). However, we unfortunately cannot conduct a set of experiments on the effects of arc current, for example, without first selecting a given arc voltage, travel speed, arc polarity, torch stand-off and electrode diameter. Now it could be that the effects of arc

current on the penetration may be significantly different at different travel speeds, arc voltages or arc polarity or that deposition rate may reach a maximum at a different torch stand-off.

The conclusions reached on the correct amperage level at a particular arc voltage may therefore be inapplicable to the final chosen value of voltage, and the value of voltage actually chosen may in fact be incorrect for the choice of electrode diameter and arc polarity.

Of course none of these misfortunes may occur (81), but even if this were the case an experiment of this nature is extremely inefficient when compared with factorial experiments. In factorial experiments each observation is used a number of times in making estimates of the effects of the different factors.

If the effects of some or all of the factors vary with changes in the other factors, the factors are said to interact (81,82). The estimates of the effects of a factor obtained from a factorial experiment are the average of the effects of each factor measured at different levels of the other factors. At the same time estimates of the actual amount of the variation may be obtained by taking the differences of the effects of one factor at the different levels of the other factors (81).

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2.10.2 Applications for Factorial Experiments

Although factorial experiments were originally used in the study of the effects of fertilizers, plant types and cultivation methods on agricultural yields (81,83), they can in fact be used to study any system where the effect of more than one variable is to be measured. Factorial experiments are therefore ideally suited to the evaluation of the effects of welding process variables on the nature of the weld deposit.

In recent years, several papers have been written on the successful application of factorial design experiments in the study of flux-cored arc welding (78), submerged arc welding (75,76,77), and plasma transferred arc welding (84). All the authors of these papers testify to the efficiency and practicability of using factorial experiments in the evaluation of the effects of welding process variables.

2.10.3 Advantages

There are a number of advantages in using factorial design experiments (80). Firstly, when there are no interactions between factors the factorial design gives the maximum efficiency in the estimation of the

effects. Secondly, if interactions do exist (the nature of which is unknown) a factorial design is essential to avoid misleading conclusions. Finally, in a factorial design the effect of each factor is estimated at several levels of the other factors, and the conclusions therefore hold over a wide range of conditions.

## 2.11 Summary

It must be remembered that the success of any given application of hardfacings depends on a number of factors including the correct alloy and welding process selection. Another important factor that is often overlooked is the dependence of the quality of the deposit on the skill of the welder (4) since any alloy, if deposited under the wrong conditions, will have little chance of success.

Thus, incorrect welding methods and techniques, inexperienced welding operators and incorrect alloy selection have in the past contributed to a large number of failures of hardfacings (67). This has unfortunately caused widespread scepticism amongst potential users of hardfacings (2), and the phrase "necessary evil" is often applied to the use of them (67).

This regrettable (although understandable) attitude will hopefully, with continuing research, education and experience, be replaced by a more rational approach to hardfacing. Such an approach, however, has to be based on more quantitative and objective data than is at present generally available. It is for this reason that further research should be conducted on all aspects of hardfacing.

Perhaps the most pertinent point on the subject comes from Hurricks (2), who has stated that ".....good tribological practice demands discretion".

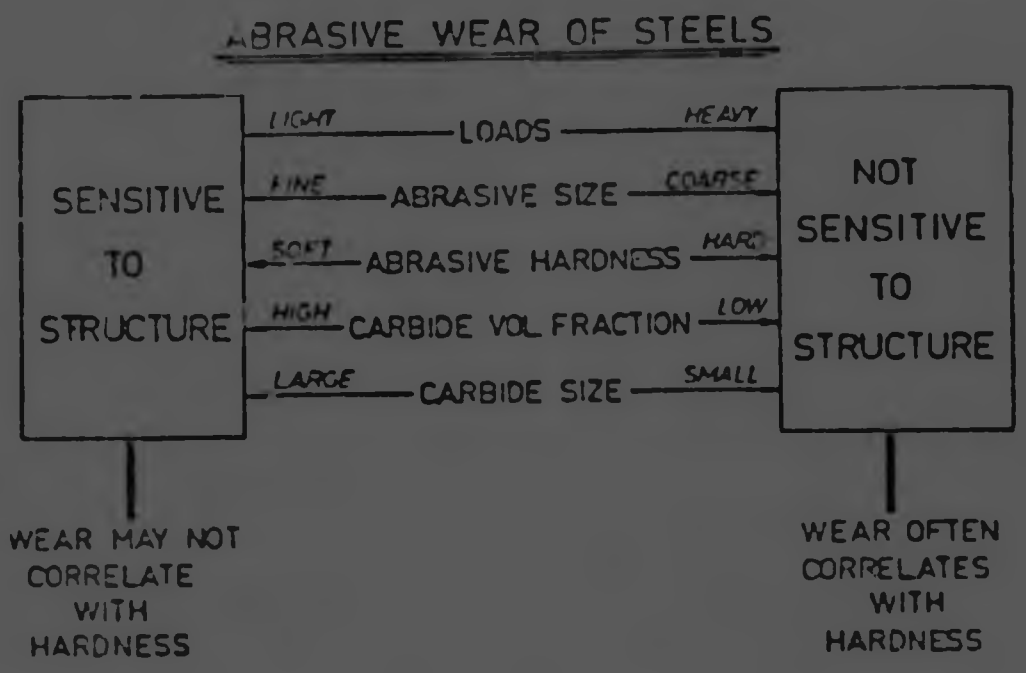



Figure 2.1 Model showing relationship between abrasive wear parameters and microstructure.

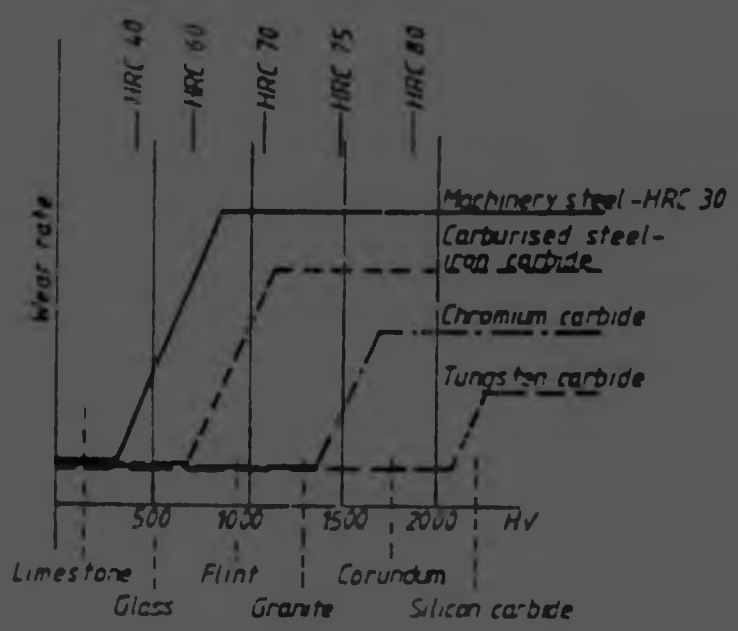



Figure 2.2 Idealized diagram of abrasive wear rate of materials versus mineral hardness.

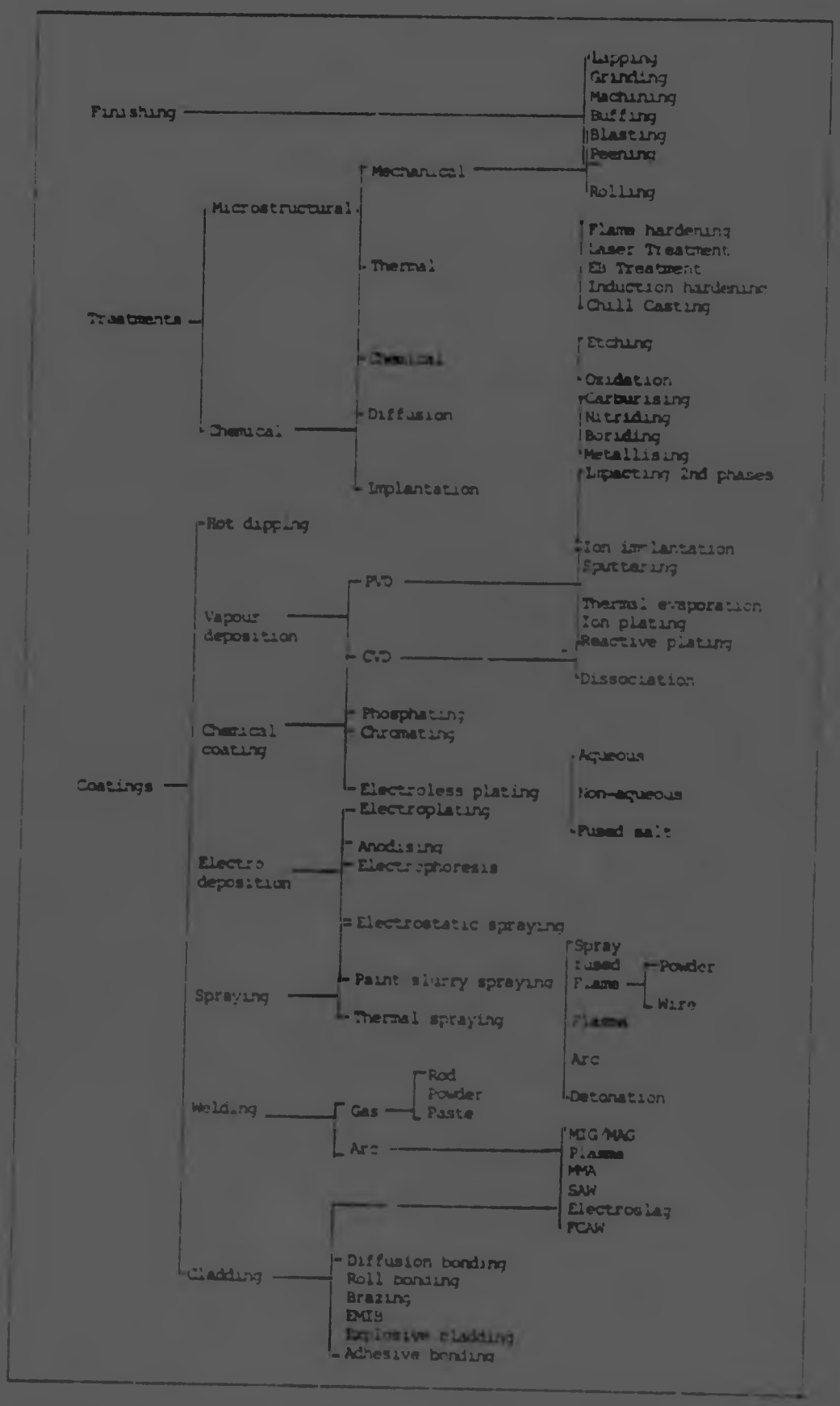



Figure 2.3 Classification of surface modification processes available in industry today.

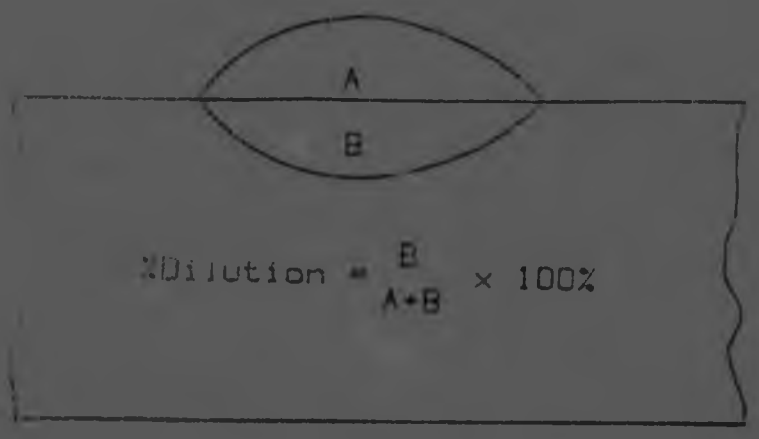



Figure 2.4 Schematic representation of the percentage dilution of a weld deposit.

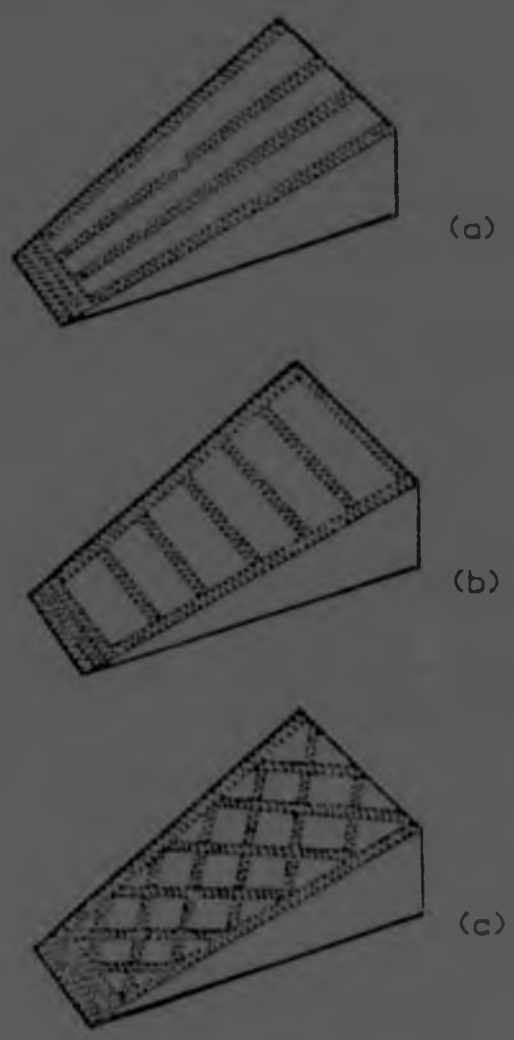



Figure 2.5 Examples of hardfacing patterns as applied to ripper teeth.

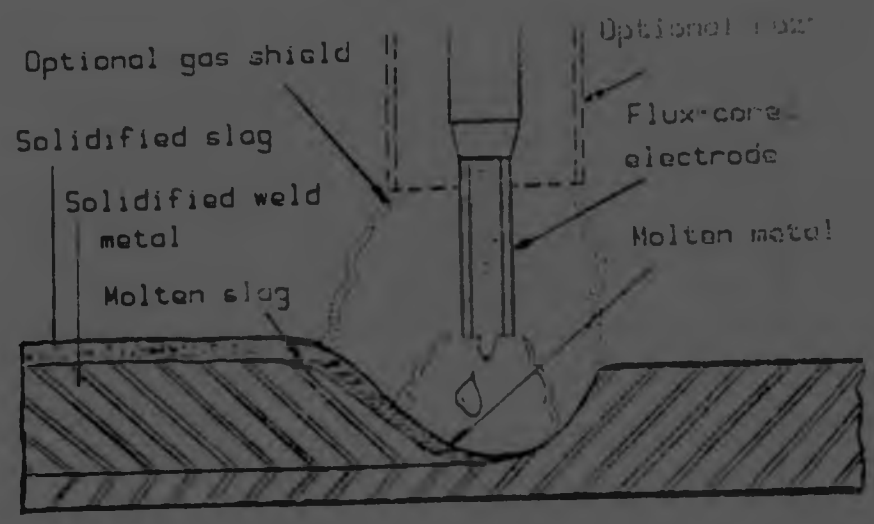



Figure 2.6 Schematic representation of the principles involved in flux-cored arc welding.

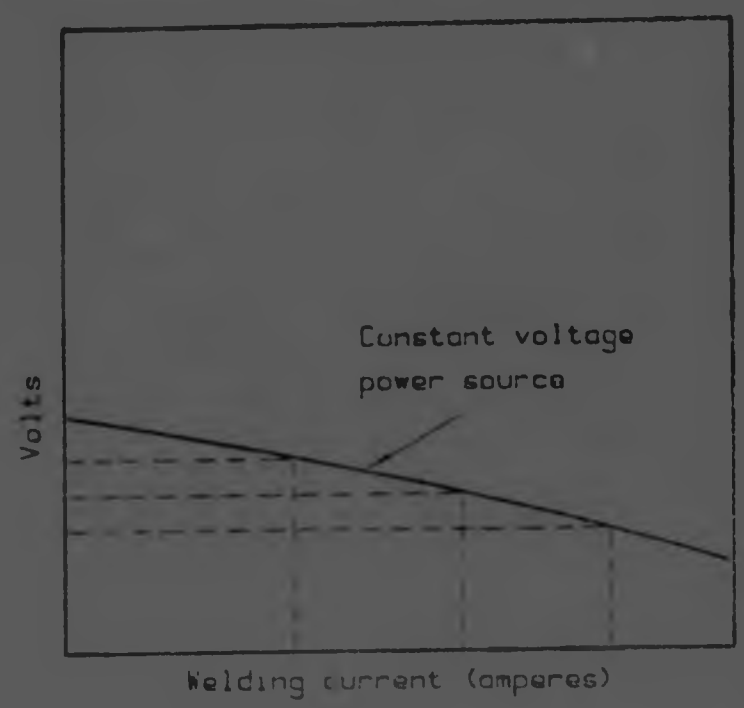



Figure 2.7 Characteristic arc current Versus voltage curve for a constant voltage power supply.

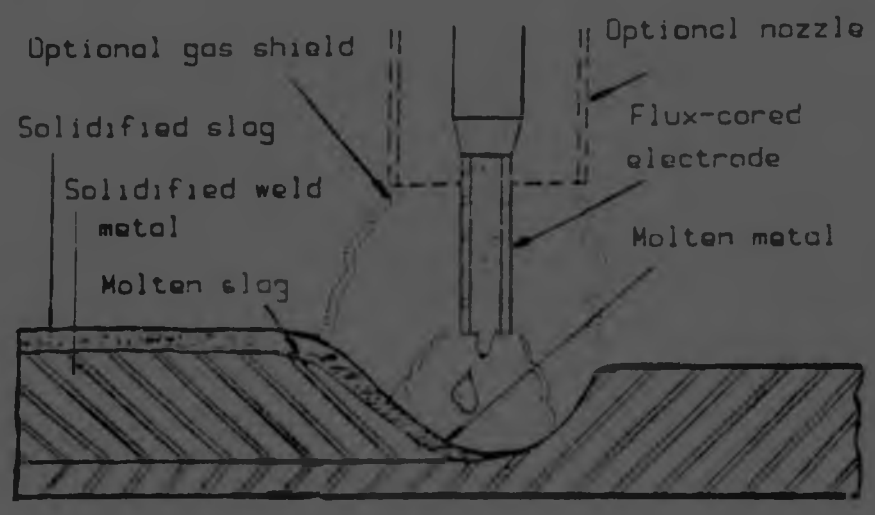



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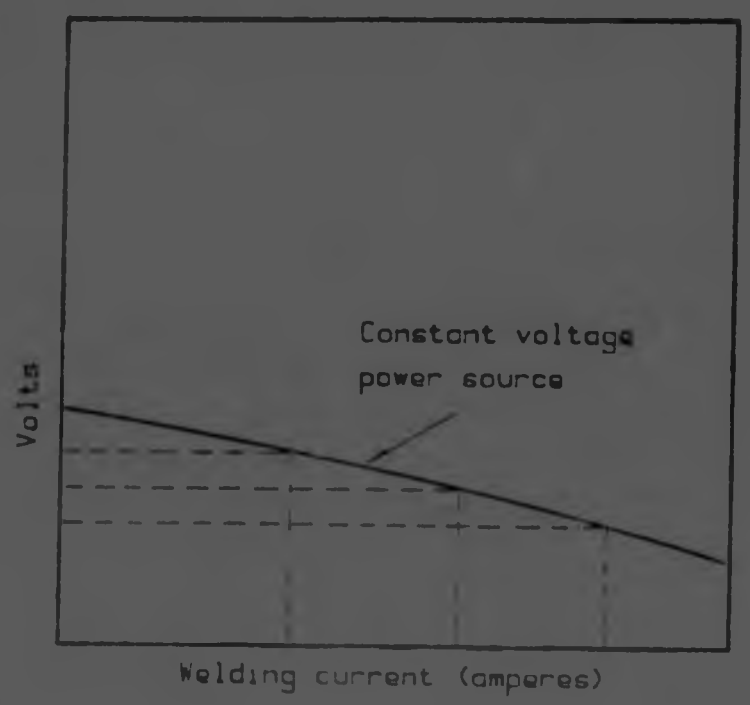



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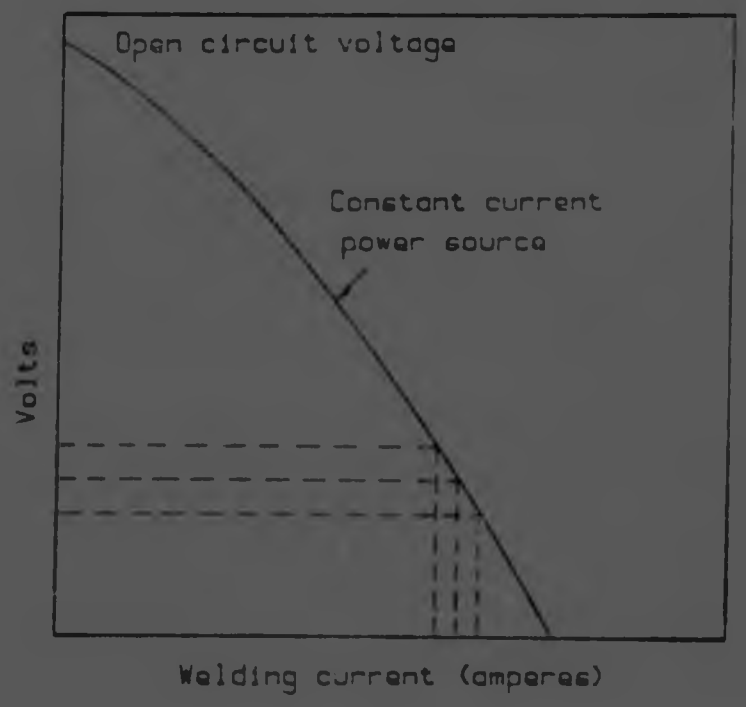



Figure 2.8 Characteristic curve for a constant current (drooping characteristic) power supply.



Figure 2.9 Examples of different methods of crimping the seam in flux-cored welding wires.

# 3 EXPERIMENTAL PROCEDURE

## 3.1 Experimental Design

As mentioned previously, this project was performed as a factorial design experiment. It was established that the factors (process parameters), having the greatest effect on the output of the flux-cored arc welding process are as follows :

1. Arc current (A)
2. Arc voltage (B)
3. Travel speed (C)
4. Torch stand-off (D)
5. Preheat (E)
6. Arc polarity (F)

Letters given in parentheses are the symbols used to denote each of the factors for the purpose of our experiments.

The experimental design involves the setting of each of the factors at two or more levels, as appropriate. To facilitate the selection of suitable levels for the factors given above, a 'working point' (or mean) for

the particular electrode chosen for the experimental programme (Cobolarc 100M, 2,8mm diameter), was decided on from the suppliers recommendations and small-scale preliminary experimentation.

The electrode suppliers recommend an arc cur ent of 250-350 Amps and an arc voltage of 26-34 Volts. It was therefore decided to set the working point at 300 Amps and 30 Volts (ie. the mean of the recommended values). The leve's at which the effects of these factors would be studied was then set at plus and minus 20% from the working point or mean value. Although this range was chosen rather arbitrarily, it corresponded closely with the suppliers recomendations and gave a resonably wide spread of values over which data was then obtained.

Mean settings for both the travel speed and the torch stand-off distance were established by observing an experienced welder. The welding system was set up with the electrode to be used in the experimentation, and the arc current and voltage were set at the mean levels. A number of weld beads were deposited by the welder, and the time taken was recorded in each case giving a measure of the average travel speed used.

The mean travel speed used by the welder was approximately 350mm/min, and a stand-off distance of 30mm was found to be the most controllable and 'comfortable'. These process parameter settings also

produced a well shaped weld bead with no evident lack of fusion or overlap.

Table 3.1 shows the final values chosen for the mean and experimental levels of the six factors. A convenient method for calculating all the possible factor (or treatment) combinations in a factorial experiment is to denote the lower level of a factor with a "1", and the upper level with the lower case letter of the factor symbol. For example, the lower level treatment of arc current would be denoted by a "1", and the upper level treatment by an "a". To list all the possible treatment combinations is then simply a matter of beginning with all the factors at their lower level (ie. treatment combination "1") and then one by one introducing all the other factors. This is done by multiplying the factor by each of the proceding treatment combinations, and will give rise to the following 'standard order' of factor combinations that is required for the Yates method (80) of analysis of an experiment of this type.

| | | |
|---|---|---|
| 1 | All factors at their lower level | |
| a | Only factor A (arc current) at upper level | (axl) |
| b | Only factor B (arc voltage) at upper level | (bxl) |
| ab | Only factors A and B at upper level | (bxa) |
| c | Only factor C at upper level | (cxl) |
| ac | Only factors A and C at upper level | (cxa) |
| bc | Only factors B and C at upper level | (cxb) |
| abc | Factors A,B and C at upper level | (cxab) |
| . | etc | |
| abcdef | All factors at upper level | (fxabcde) |

The project therefore necessitated the production of 64 test welds, one at each treatment combination. Appendix A shows the individual welding parameter settings for each of the welded specimens.

There are a number of weld bead parameters (as discussed in chapter 2) on which the wear resistance of a hardfacing deposit depends, viz: the geometry (including the dilution, height, width and depth of penetration), porosity levels, hardness, and microstructure. Where these parameters can be characterised by a numerical value (ie. all except microstructure), it is possible to perform an analysis of variance to determine which of the process factors have the most effect on these weld bead parameters.

The wear rate of each weld deposit, as determined in a small-scale laboratory abrasive wear test, were also

analysed in this way.

Two other factors of great importance in the economic evaluation of a hardfacing process are the deposition efficiency and deposition rate, both of which depend on the input factors of the process. These were therefore measured for each weld deposit and analysed to show which factors have the greatest effect.

## 3.2 Experimental Equipment

### 3.2.1 Welding Equipment

The power source used for the welding of the test specimens was a Miller Deltaweld 650 CY50 constant potential DC arc welding power source, with a voltage range of 14-46 Volts and a maximum current output of 650 Amps at 100% duty cycle. This was coupled to a Miller S52-A wire feeder and a Bernard (500 Amp) gun with a 10ft feed cable and a lockable trigger. The full specifications of this equipment can be found in Appendix B.

The Bernard gun was mounted on two adjustable brackets which were in turn clamped to a track mounted motorised travel unit (Figure 3.1). The travel unit could be made to travel in both directions along the track and had sufficient power to carry the equipment at a

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The Bernard gun was mounted on two adjustable brackets which were in turn clamped to a track mounted motorised travel unit (Figure 3.1). The travel unit could be made to travel in both directions along the track and had sufficient power to carry the equipment at a

constant travel speed, adjustable between 0 and 600mm/min. Both the stand-off (stickout) distance of the gun tip, and the angle between the electrode and the work piece could be easily adjusted at the holding brackets, although the latter was kept at a constant 70 degrees throughout the experiment.

A jig (Figure 3.1) was also designed and manufactured to hold the specimens and ensure that the surface of the work piece remained parallel to the path of the welding torch during welding. Due to the relative cross sections of the weld beads and the bars on which they were deposited it was assumed that distortion would be minimal, and was therefore ignored.

An Ultrakust "Thermophil" thermocouple was used for measuring the preheat of the base material to be welded. This instrument uses a NiCr-Ni thermocouple and is capable of measuring temperatures from 0 to 1000 Degrees Centigrade, in 200 Degree ranges. To measure the temperature of a surface, the probe is merely placed against the surface and the temperature is read from a dial after sufficient time has elapsed to reach equilibrium conditions. The system was tested and found to give a reading accurate to within 3% for the range required by this experiment.

The mass of the spool of electrode wire and the welded specimen were both measured before and after each weld

was deposited, so that a measure of the deposition efficiency could be made. These mass measurements were carried out on a Mettler PC16 electron. : scale which is capable of measuring a mass of up to 16kg with a resolution of 0,1g.

### 3.2.2 Arc Current and Voltag. Measurement

Initial experimentation showed that a standard tong tester and voltmeter were incapable of giving an accurate reading of either arc current or arc voltage due to the rapid fluctuations in the values of these factors. A system of integrating circuits was therefore adopted since this gave a relatively simple method of accurately determining the average values of arc current and voltage.

To measure the arc current, the voltage drop across a shunt (1000A, 50mV) in the earth cable of the welding circuit was put through a potential divider and then used as the input to one of the integrating circuits mentioned above. The voltage drop across the arc was measured between the copper guide tube (at the tip of the w.lding gun) and the ea.'n clamp on the work piece, and then also sent through a potential divider to the other integrating circuit. Figure 3.2 shows a schematic representation of this measuring system, whilst a full description of the integrating circuits used and their calibration is given in Appendix C.

The outputs from the two integrating circuits were fed into a three channel Bryans XY-Chart Recorder (26000 A3) on which it was possible to set the paper feed rate so that the abscissa gave a reading of time. One Y-channel on the chart recorder was then used to give the integral of arc current with time and the other, the integral of arc voltage with time. The slopes of the straight line graphs drawn by the chart recorder were then proportional to the actual mean values of arc current and arc voltage (Figure 3.3). It was therefore only necessary to multiply each of these slopes by a predetermined constant in order to obtain an accurate value for both arc current and arc voltage.

### Equipment for Abrasive Wear Tests

The apparatus used for the small-scale abrasive wear tests was a modified Abex wet sand machine manufactured by Boart and belonging to Mintek. This machine simulates three body abrasion, and consists of an electric motor which rotates a "T" bar fixed to two sample holders, each of which holds one sample to be tested (Figures 3.4 and 3.5). The samples are rotated on a copper ring (set in a trough filled with a slurry of river sand (particle size in the range 300 to 400 microns) and water (Figure 3.6). The copper ring was 10mm wide and had a mean diameter of 126mm. The load, rotational speed and duration of the test can all be

adjusted.

The mass of each sampl[illegible] the wear tests on a Mettle[illegible] a minimum resolution of 0 1mg

3.2.4 Hardness Testing Equipmen

All the readings of deposit hardness were done on a standard Wilson Rockwell hardness testing machine This type of hardness test was chosen because of the large number of tests (1600 in total) that had to be performed during this experiment. It was used on the Rockwell C scale throughout the tests

3.3 Welded Specimens

The hardfacings studied in this project were all deposited on 710mm long mild steel 40x40mm square bars. The chemical composition of the steel is given in Table 3.2. Two welds of approximately 300mm in length were deposited on each bar, as shown in Figure 3.7.

All of the welds were deposited using a 2,8mm diameter Cobolarc 100M Flux-Cored electrode. This wire (chemical composition in Table 3.3) gives an iron based deposit alloyed with Cr, C and Mn. The total alloy content of the deposit is quoted by the suppliers at

28%, although this will obviously depend on the dilution of the electrode during welding. The deposit type is described as a Chromium Carbide Austenitic Iron that contains Chromium Carbides with a hardness of 1500HV, and is best suited to abrasion (especially large particle types), but can also withstand heavy impact.

The suppliers state that this electrode is ideal for use on 11-14% Mn Steel items such as swing hammers and crusher jaws, as well as on mild and alloy steel parts (eg.dragline buckets and digger teeth). The deposit is not easily machined and can only be finished by grinding.

A 12,5kg spool of electrode wire was obtained for this experiment. Since this was sufficient to produce all of the welded specimens required for the experimentation it was possible to avoid any batch effects that may have occurred had it been necessary to use more than one spool of wire.

## 3.4 Welding Procedure

### 3.4.1 Arc Current and Arc Voltage

The Miller Deltaweld constant potential power source used for the welding of the test specimens has an

ammeter and a voltmeter by which the arc current and arc voltage can be set. Before each weld was deposited, a practice run was made on a scrap plate and the voltage and amperage were set according to the dials on the power source. The arc voltage is set by a knob on the power source whilst the arc current is controlled by setting the wire feed speed on the wire feeder unit, as described in Chapter 2. This would be the standard method of setting these parameters in any practical welding situation. However, the rapid fluctuations in both voltage and amperage make it impossible for the welder to set these with a high degree of accuracy. The electronic system described in section 3.2.2 was therefore designed and manufactured so that an accurate reading of these parameters could be obtained.

It was then possible to analyse the differences between the settings and the actual values for these parameters and thereby establish the effects that these differences can have on the final weld deposit. Newer, computer controlled welding machines with a much higher degree of current and voltage control are now becoming available and these will help to reduce the abovementioned effects in future. However, the cost of this machinery is in most cases not justifiable, and the use of the older equipment described above will no doubt continue for many years to come.

3.4.2 Travel Speed

The travel speed of the welding gun mounted on the travel unit (gear on track type) could be set by a knob on a control board and checked on a dial graduated from 0 to 1000 mm/min. However, the scale of travel speed was marked of in 50mm/min steps, and the accurate setting of travel speed was impossible. It was therefore decided to measure both the length of, and the time taken to deposit each weld bead, so that an independent measure of the travel speed could be made.

Once again, the differences in the set and measured values for travel speed were analysed to give an indication of the effects that these errors would have on a weld deposited under automatic welding conditions.

3.4.3 Torch Stand-off Distance

Torch (or welding gun) stand-off distance was set at the brackets which mounted the welding gun to the travel unit. It was possible to adjust this distance to within 0,5mm of the desired setting, whilst the electrode angle was maintained at a constant 70 degrees (Figure 3.8). Only one value for torch stand-off was therefore recorded for each weld deposit.

### 3.4.4 Minimum Preheat

Since the welding of the test specimens took place during the warm summer months, it was not necessary to preheat the steel bars to ensure the lower level of preheat of 20 Degrees Centigrade. The upper minimum level of preheat (150 Degrees C) was obtained by intermittently heating the surface of the steel bar with a propane torch. Between each heating cycle, the steel was allowed to 'soak' for 5 minutes before the reading of surface temperature was taken with the thermocouple, to ensure that the centre of the bar had reached the minimum preheat temperature. Welding of the specimen was commenced when the temperature of the surface was between 150 and 160 Degrees C.

### 3.4.5 Arc Polarity

All of the test welds were performed with a direct current welding arc, 32 of them with the electrode positive (DCEP) and the other 32 with the electrode negative (DCEN). To change from one arc polarity to the other, it was only necessary to change the cable connections on the output terminals of the power supply.

## 3.5 Measurement of Weld Parameters

### 3.5.1 Deposition Efficiency

The deposition efficiency of a welding process is a measure of the percentage of the electrode wire (by mass) that is actually deposited as weld metal. The balance of the electrode is lost during the welding process due to spatter and flux losses.

To obtain a measure of the deposition efficiency, it was necessary to record the mass of both the electrode wire spool and the steel bar, before and after each weld was deposited. The following symbols were used for the different masses:

Mb = Mass of specimen before welding

Ma = Mass of specimen after welding

Meb = Mass of electrode wire before welding

Mea = Mass of electrode wire after welding

Then :

$$\text{Deposition efficiency} = \frac{Ma - Mb}{Meb - Mea} \times 100\%$$

In each case the welded specimen was thoroughly cleaned of spatter and the small amount of 'slag' before its

mass was recorded. The slag present after welding was a loosely attached powder-like substance that was easily removed with a wire brush, and in no way resembled the thick crust of slag that forms on a MMA weld.

### 3.5.2 Weld Geometry

Once the welding of all the specimens (performed by the author) had been completed, each bar was cut into two pieces with each piece containing one weld deposit approximately 300mm long. Each of these 64 bars was then randomly sectioned at 5 positions to give 5 views of the cross-section of the weld bead, and these sections were then labelled A,B,C,D or E as shown in Figure 3.9. This gave rise to a total of 320 surfaces which were all ground, polished and etched in 10% Nital for 60 seconds. The etching process not only allowed for microstructural studies of the highly alloyed weld metal, but also clearly showed the fusion line between the weld metal and the mild steel base material. No lack of fusion was observed in any of the 320 surfaces.

Due to the relatively small size of the weld beads, it was decided to be best to photograph each surface and take most of the measurements from the greatly magnified (approximately 4 to 5X depending on size) view of the weld bead on the photograph. It was then only necessary to measure one parameter (width of

deposit) on both the actual specimen and the photograph in order to establish the level of magnification, which could then be applied to all of the other parameters measured on the photograph. Figure 3.10 shows a typical example of one of these photographs of two weld beads. The magnification of both welds on each photograph should be the same, and this was used as a check on the accuracy of the measurements.

The total list of measurements taken from each of these photographs (Figure 3.11) included:-

1. Width of weld deposit (W)
2. Height of deposit above surface of steel bar (H1)
3. Depth of penetration in mm (H2)
4. Area of deposit above surface of steel bar (AA)
5. Total area of deposit (AT)

Both of the areas mentioned above were measured with the aid of a planimeter. The actual values for the areas were obtained by dividing the area measured on the photograph by the square of the magnification in each case. It was then possible to calculate the dilution of the deposited weld metal in each case from the formula overleaf.

$$\text{Percentage Dilution} = \frac{AT - AA}{AT} \times 100\%$$

Two estimates of the deposition rate (in cubic mm/sec) could also be calculated from the areas measured above. The first was called the "deposition rate" and is the obtained by multiplying the total deposit area (AT) by the travel speed, whilst the second is called the "effective deposition rate" and was calculated by multiplying only the area of the weld deposit above the surface (AA) by the travel speed. The latter value is probably the most useful in practice since once a hardfacing is worn back to the level of the original surface it is usually replaced before major rebuilding of the component is required.

### 3.5.3 Porosity

Following a study of all 320 polished surfaces, a 5 point numerical scale (from 0 to 4) was adopted in order to characterize the amount of porosity present in each weld. Figure 3.12 shows a typical example of each level of porosity. The level of porosity was estimated for each weld section and these were then averaged to give a mean porosity level for each of the 64 weld deposits.

### 3.5.4 Hardness Tests

The Rockwell C hardness (HRc) of the as-deposited weld metal was measured in 5 places on each weld section (Figure 3.13), giving a total of 25 hardness values for each weld deposit. These values were then averaged to give a mean hardness for each weld that could be used in the subsequent analysis.

### 3.5.5 Wear Tests

Small sections (approximately 20mmx20mm) were cut from each weld and mounted with an epoxy adhesive to shafts of metal (Figure 3.14) that were then placed in the sample holders in the wear testing machine. The following parameters were used for all of the wear tests performed in this experimental programme.

| | |
|---|---|
| Speed: | 54 rpm |
| Load: | 1600g |
| Duration of test: | 35 min |
| Mass of sand per test: | 400g |
| Vol of water per test: | 500ml |

All test samples were cleaned in alcohol and dried in a stream of hot air prior to any mass measurements.

### 3.5.6 Microstructures

Following the complete analysis of the results obtained in this project, selected specimens were chosen for detailed microstructural examination. This was done in an effort to identify trends in the effects of dilution, rather than give a complete analysis of the effects of all of the process parameters on the microstructure. It was felt that this approach was justified, since it was already known which of the process parameters had the most significant effects on the deposit dilution.

Table 3.1 Lower, mean and upper levels chosen for each of the factors or welding parameters.

| Factor | Lower Level | Mean Level | Upper Level |
|---|---|---|---|
| Arc Current (Amps) | 240 (1) | 300 | 360 (a) |
| Arc Voltage (Volts) | 24 (1) | 30 | 36 (b) |
| Travel Speed (mm/min) | 300 (1) | 350 | 400 (c) |
| Stand-off Dist (mm) | 24 (1) | 30 | 36 (d) |
| Min Preheat (Deg C) | 20 (1) | - | 150 (e) |
| Arc Polarity | DCEP (1) | - | DCEN (f) |

Table 3.2 Chemical composition of the mild steel base material onto which the hardfacing welds were deposited.

| Chemical Element | Percentage Composition |
|---|---|
| Carbon | 0,16 % |
| Manganese | 0,87 % |
| Chromium | 0,10 % |
| Nickel | 0,10 % |
| Molybdenum | 0,02 % |
| Aluminium | 0,015 % |
| Silicon | 0,13 % |
| Sulphur | 0,036 % |
| Phosphorous | 0,025 % |

Table 3.3 Chemical composition of electrode wire and flux of the 2,8mm Cobalarc 100M flux-cored electrode used in this experimental program.

| 1. Electrode wire: | |
|---|---|
| Chemical Element | Percentage Composition |
| Carbon | 0,11 % |
| Manganese | 0,35 % |
| Chromium | 84 ppm |
| Nickel | 85 ppm |
| Molybdenum | Trace |
| Iron | Balance |

| 2. Electrode flux: | |
|---|---|
| Chemical Element | Percentage Composition |
| Chromium | 61,6 % |
| Iron | 23,3 % |
| Titanium | 0,35 % |
| Silicon | 2,38 % |
| Aluminium | Less than 0,5 % |
| Calcium | Less than 0,5 % |
| Manganese | Less than 0,5 % |
| Molybdenum | Less than 30 ppm |

Note: The above elements are available mainly as carbonates and oxides which will account for most the balance.



Figure 3.1 Photograph showing Bernard gun mounted on travel unit, with holding jig in the foreground.

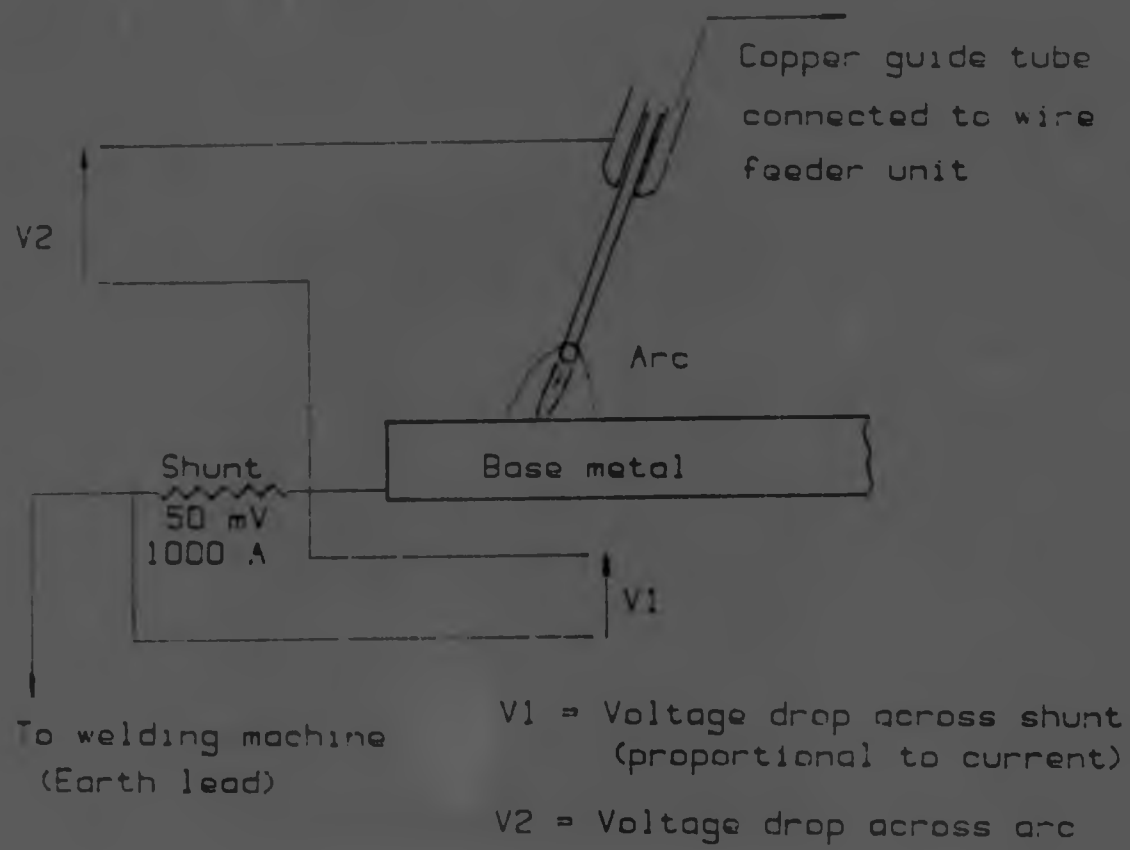
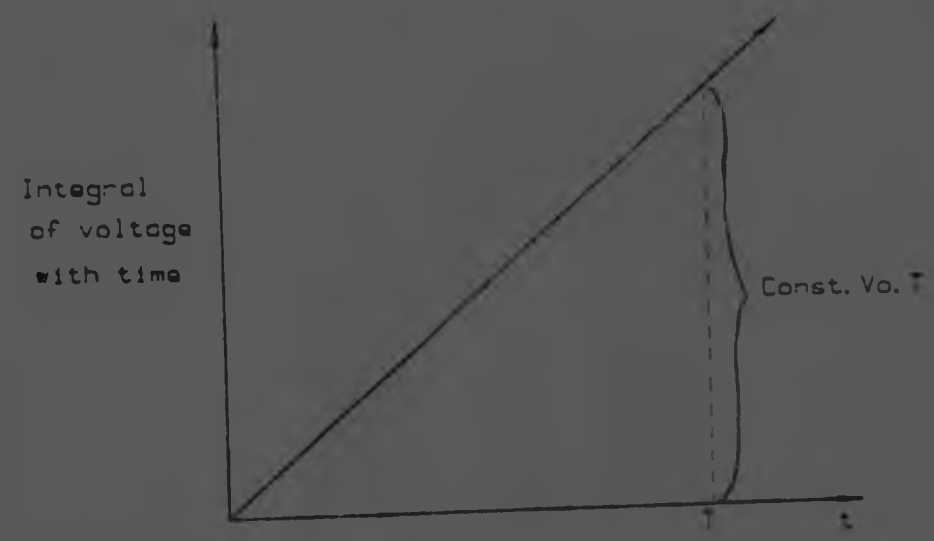



Figure 3.2 Schematic representation of the system used for the measurement of arc current and voltage.




Slope of straight line = $\frac{C.Vo.T}{T}$

= C.Vo

Figure 3.3 Representation of output from ink chart recorder.



Figure 3.4 Photograph of Abrex wet sand abrasion test machine.



Figure 3.5 Close up photograph of the specimen holders of the Abex wet sand abrasion tester.

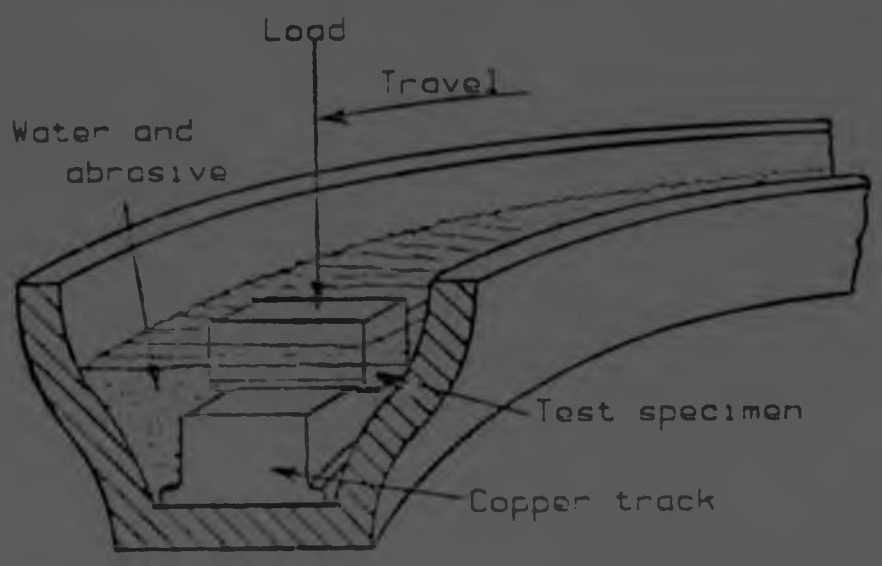



Figure 3.6 Schematic diagram showing the principles of operation of the Abex wet sand abrasion tester.

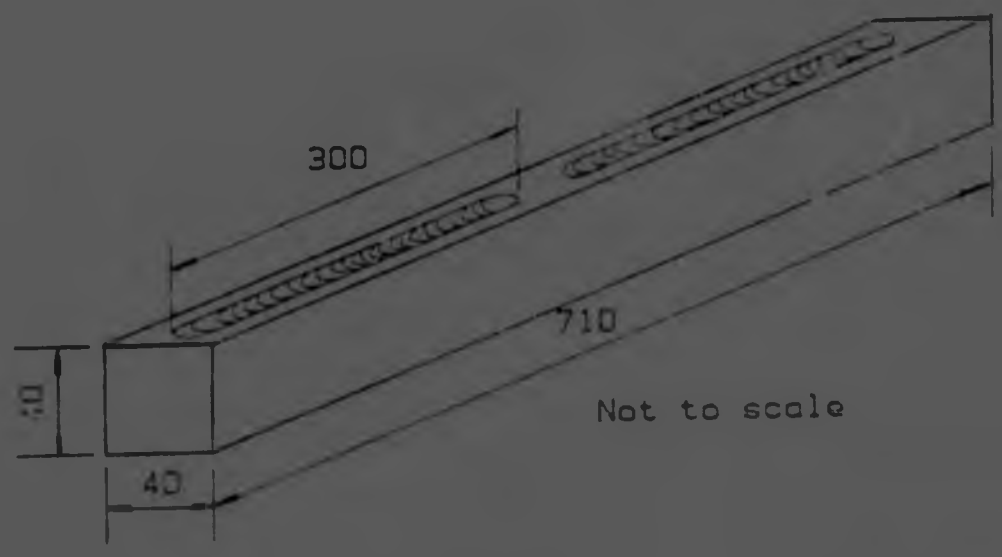



Figure 3.7 Diagram showin~ the relative positions of the test welds on a mild steel bar.

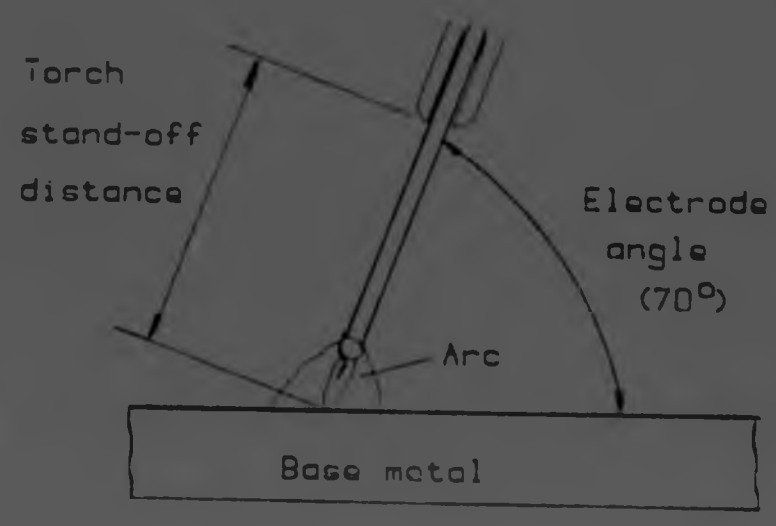



Figure 3.8 Sch matic representation of torch s and-o distance and electrode angle.

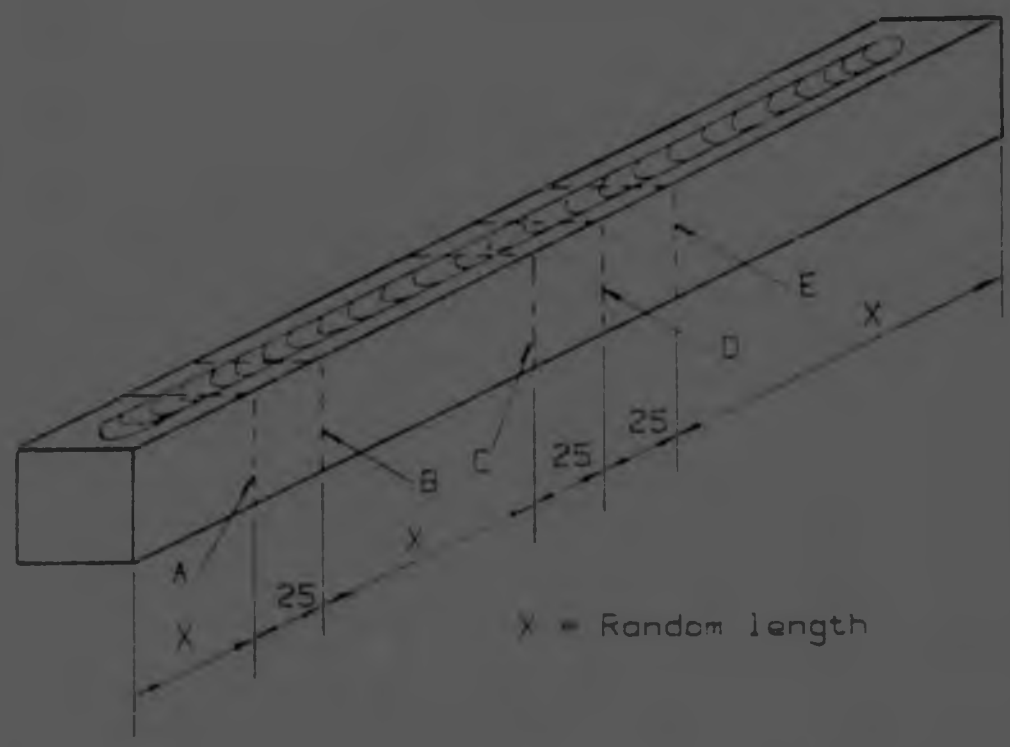
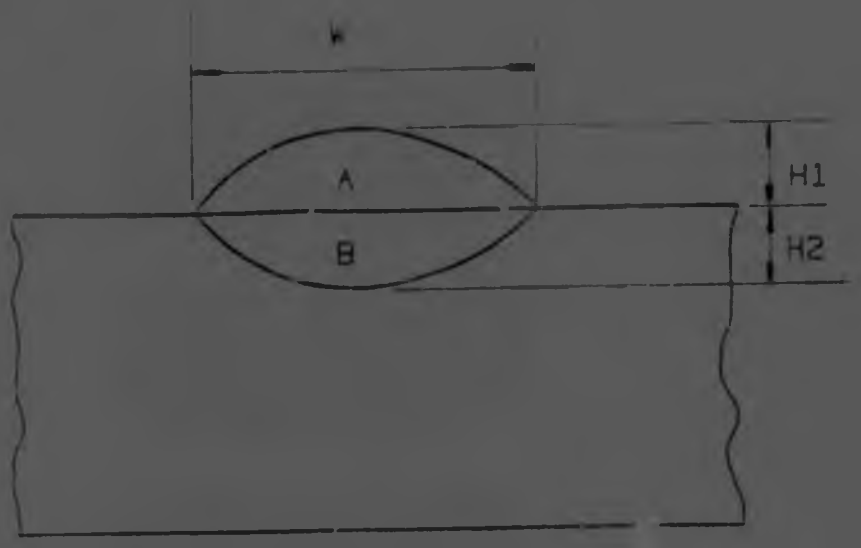



Figure 3.9 Diagram showing the positions of two sectioning cuts made in each weld specimen.



Figure 3.10 Typical example of a photograph of two polished and etched weld deposit cross-sections. These photographs were used for measuring the geometrical weld parameters.




AA = Area of weld metal above surface of base material (A)

AT = Total area of deposit (A+B)

Figure 3.11 Diagram showing the geometrical weld parameters that were measured from the photographs as shown in figure 3.10.



Figure 3.12 Photograph showing examples of the five different levels of porosity on t arbitrary 0 (min) to 4 (max) scale adopted in this experimental programme.

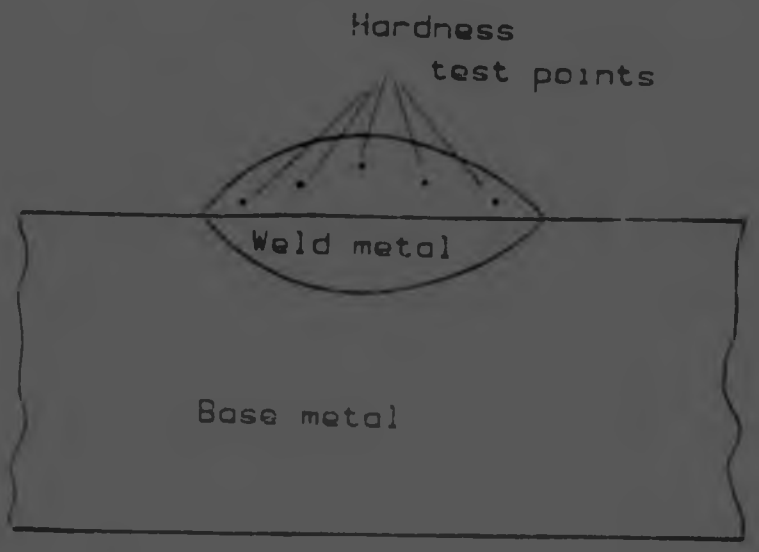



Figure 3.13 Diagram showing the approximate positions of the five hardness done on each sample face.

# 4. RESULTS

## 4.1 Introduction

The results reported in this chapter are presented mainly as a series of tables. These show the relevant data obtained from both the measurement and subsequent analysis procedures. The contents of each of these tables is discussed briefly under relevant headings, whilst the tables themselves are all to be found at the end of the chapter.

## 4.2 Welding Parameters

As previously discussed, a record was kept of both the factor (process parameter) settings and the actual measured values where these differed. This was done in an effort to establish the possible level of accuracy that can be maintained in a welding operation of this nature. It was then possible to relate this level of control to the effects that this would have on the weld deposit in an actual hardfacing operation.

The actual values for arc current, arc voltage and

travel speed were all accurately measured as described in Chapter 3. Table 4.1a records the set and actual values for these three factors for specimens 1 to 32 (electrode positive), whilst Table 4.1b is a listing of the same values for specimens 33 to 64 (electrode positive).

Table 4.2 shows the results of an analysis of the means and standard deviations which were obtained for the measured values of the three ab-vementioned factors. The table is divided into two sections for the different arc polarities.

## 4.3 Weld Bead Parameters

### 4.3.1 General

The deposition efficiency, deposit hardness (HRc) and porosity, together with the results obtained in the wear tests are all listed in Table 4.3.

### 4.3.2 Geometrical Parameters

Appendix D contains a complete listing of the measurements of deposit width, height, depth and areas as obtained from the photographs mentioned in Chapter 3, together with those of actual deposit width measured on the specimens themselves. There are five sets of

measurements for each specimen, each set being obtained on a different polished section (A,B,C,D or E).

From these measurements it was possible to determine the magnification in each of the 160 photographs (two sections per photograph). The actual values of the abovementioned parameters was then determined, and averaged for each of the 64 welded specimens.

These averaged values, together with the calculated values of the dilution, are shown in Table 4.4.

## 4.4 Process Parameters

Values of set and actual heat input and deposition rates for each specimen are given in Table 4.5. These values were calculated as described in Chapters 2 and 3.

## 4.5 Analyses of Variance

An analysis of variance was performed with the aid of the applications packages on the IBM 3083 Model E 08 mainframe computer at the University of the Witwatersrand. In each case, an initial analysis on the first order effects was performed in an effort to establish which of the input factors have a significant

effect on the individual dependent variables. 'cut-off' used was the 5% significance level.

As is usually the case in a factorial analysis of this nature, only the set lower and upper factor values were used as independent variable values in the analysis of variance. In other words, it is assumed that the values given for each dependent variable datum point are recorded at the set factor value, and not at the actual measured factor value. Whilst this method introduces an additional error it does somewhat simplify the analysis, and the errors obtained are not significant when compared to the effects of the factors themselves.

The results of this procedure were then used in a second analysis to identify all significant second and third order interactions of the input factors based only on those factors showing significant first order effects. Only the significant effects and interactions are given in the results below.

These tabulated results include the degrees of freedom, the sum of squares and the mean square for both the model and the error involved, together with the F-value for the model and the root mean square for the error in each case. The value quoted for the R-square is a measure of the percentage of the variation in the dependent variable that can be explained by the

variations in the independent input variables.

The computed values of the individual degrees of freedom, sums of squares, F-value and significance level (1% or 5%) for each independent variable (or interactions between variables) is also shown in the tables. Interactions are depicted with an asterisk between the factor symbols (eg. A*B).

For each dependent variable, a table of the means is also included. These means give an idea of the magnitude of the effect that each of the input factors has on the specified dependent variable. It should be remembered that in no way do these means represent the beginning and end points of an exact linear relationship between the dependent variable and the input factor. The means should rather be seen as a 'guide' to the average effects that each of the factors have on the dependent variable concerned, over a wide range of the other factors.

An examination of these means also highlights the usefulness of performing factorial design experiments and demonstrates the misleading conclusions that could occur in using "one at a time" experimental designs (in which one factor is varied whilst all others are kept constant).

### 4.5.1 Deposition Efficiency

It was found that arc current, voltage and polarity, as well as torch stand-off distance all play a significant role in the deposition efficiency of the welding process used. There is also a significant interaction between the arc current and arc polarity.

Table 4.6 is a complete tabulation of the results from the analysis of variance for deposition efficiency, whilst Table 4.7 shows the mean values of deposition efficiency at each of the factor levels.

### 4.5.2 Deposition Rate

As mentioned before, we define two deposition rates in terms of the volume of weld metal deposited per unit time (Chapter 3) instead of the usual mass per unit time. However, since the deposit density is essentially the same throughout the specimens, it may be assumed that the effects of the factors will remain the same, irrespective of the definition of deposition rate used.

The arc current and preheat are the only two factors which have a significant effect on the total deposition rate. The results of the analysis of variance and the relevant means involved are given in Tables 4.8 and 4.9 respectively.

4.5.1 Deposition Efficiency

It was found that arc current, voltage and polarity, as well as torch stand-off distance all play a significant role in the deposition efficiency of the welding process used. There is also a significant interaction between the arc current and arc polarity.

Table 4.6 is a complete tabulation of the results from the analysis of variance for deposition efficiency, whilst Table 4.7 shows the mean values of deposition efficiency at each of the factor levels.

4.5.2 Deposition Rate

As mentioned before, we define two deposition rates in terms of the volume of weld metal deposited per unit time (Chapter 3) instead of the usual mass per unit time. However, since the deposit density is essentially the same throughout the specimens, it may be assumed that the effects of the factors will remain the same, irrespective of the definition of deposition rate used.

The arc current and preheat are the only two factors which have a significant effect on the total deposition rate. The results of the analysis of variance and the relevant means involved are given in Tables 4.8 and 4.9 respectively.

The effective deposition rate, on the other hand is affected by the arc current, voltage and polarity, as well as the travel speed and the preheat of the substrate. There are also significant interactions between both arc current and voltage, and arc voltage and travel speed. Tables 4.10 and 4.11 detail the results of the analysis of variance and the means for the effective deposition rate.

4.5.3 Porosity

The arc current, voltage and polarity all have a significant effect on the porosity content of the weld metal. A significant interaction between arc voltage and polarity also occurred.

The results of the analysis of variance and the mean levels of porosity are given in Tables 4.12 and 4.13 respectively.

4.5.4 Deposit Geometry

The factors which significantly affect the deposit width are the arc current, voltage and polarity, as well as the travel speed and preheat. There was also a second order interaction between arc current and polarity, and a third order interaction between arc current, voltage and polarity. Tables 4.14 and 4.15

show the results of the analysis of deposit width.

The height of the deposit above the surface of the base material is significantly affected by the arc current, voltage and polarity, as well as the prevailing travel speed. The results of the analysis of deposit height in Tables 4.16 and 4.17 also show second order interactions between arc current and voltage, and arc current and polarity, and a third order interaction between arc current, voltage and polarity.

Arc current, voltage and polarity, together with the substrate preheat, all have a significant effect on the depth of penetration of the weld deposit into the base material. There were however no recorded interactions of the factors in the analysis of depth of penetration, as shown in Tables 4.18 and 4.19.

4.5.5 Dilution

The dilution of the weld deposit is affected by the arc current, voltage and polarity, the travel speed and the degree of preheat, as well as by an interaction between the arc current and polarity.

Tables 4.20 and 4.21 show the results obtained in the analysis of the deposit dilution.

### 4.5.6 Deposit Hardness

The results of the analysis of variance and the calculation of the mean values of the deposit hardness are given in Tables 4.22 and 4.23. It can be seen that the arc voltage and polarity, and the substrate preheat, have the most significant effect on the deposit hardness, whilst there is also an interaction between the arc voltage and arc polarity.

## 4.6 Regression Analyses

The multiple linear regression analyses were performed in two separate groups according to the different arc polarities. This was necessary since it is impossible to characterise the arc polarity in terms of a numerical value which could then be analysed with the other factors.

It should also be noted that the data used for the arc current, arc voltage and travel speed in these analyses were the actual measured values and not the settings assumed in the analyses of variance.

The analysis of variance determined which of the factors had the most significant effect on the dependent variables in each case. It was therefore only necessary to include these factors in the

subsequent multiple regression analyses, the results of which are tabulated below.

The tables document the degrees of freedom, sums of squares and mean squares for both the model and error in each case, together with the F-value for the model and the root mean square of the error involved. The R-square value quoted is a measure of the correlation in each case.

All of the data was analysed to give equations of the form:

$$\text{Log } Y = a\text{Log}A + b\text{Log}B + c\text{Log}C + d\text{Log}D + e\text{Log}E + f$$

where :- Y is the dependent variable in each case,
A to E are the factors as previously defined,
and a to f are constants (parameter estimates).
(the logarithms are all to base 10)

The values for the constants (or parameter estimates) "a" to "f" are also given in subsequent tables, together with the degrees of freedom, standard error and significance level (1% or 5%). In the cases where no value is given for a constant it is assumed to be zero since the factor with which it is associated does not have a significant effect on the dependent variable concerned.

4.6.1 Electrode Positive

The following is a list of the dependent variables on which the regression analyses were performed (on the data obtained from the specimens welded with electrode positive) together with the respective table numbers in which the complete results are given in each case.

| | |
|---|---|
| Deposition efficiency | Table 4.24 |
| Deposition rate | Table 4.25 |
| Effective deposition rate | Table 4.26 |
| Deposit width | Table 4.27 |
| Deposit height | Table 4.28 |
| Penetration depth | Table 4.29 |
| Dilution | Table 4.30 |
| Hardness | Table 4.31 |

4.6.2 Electrode negative

The data obtained from the specimens welded with electrode negative were used for regression analyses on the dependent variables listed below. Once again, the table number in which the complete set of results is tabulated is also given.

| | |
|---|---|
| Deposition efficiency | Table 4.32 |
| Deposition rate | Table 4.33 |
| Effective deposition rate | Table 4.34 |
| Deposit width | Table 4.35 |
| Deposit height | Table 4.36 |
| Penetration depth | Table 4.37 |
| Dilution | Table 4.38 |
| Hardness | Table 4.39 |

## 4.7 Microstructure

A total of six different specimens (three from each arc polarity) were examined for microstructural effects. It was assumed that the major influence on the microstructure of these welds would be the dilution of the deposit, with heat input and preheat playing minor roles. The specimens examined were therefore selected over a range of dilutions, for each of the two arc polarities used, as follows.

Electrode positive:

| Specimen Number | Dilution |
|---|---|
| 9 | 32,5% (minimum) |
| 4 | 44,8% (mean) |
| 24 | 56,8% (maximum) |

Electrode negative:

| Specimen Number | Dilution |
|---|---|
| 46 | 22,3% (minimum) |
| 56 | 34,4% (mean) |
| 63 | 47,6% (maximum) |

This component of the study showed that the dilution of the deposit had a noticeable effect on the microstructures obtained whilst the electrode polarity has little or no effect, other than by virtue of its effect on the dilution.

All of the specimens exhibit a dendritic microstructure, consisting of primary austenite with an inter-dendritic ternary eutectic. With increasing dilution, there is a decrease in the effective chromium content of the deposit and a resultant increase in the proportion of primary austenite. Figures 4.1 and 4.2 show the two extremes in microstructure as found in specimens 46 (minimum dilution) and 24 (maximum dilution) respectively.

## 4.8 Summary

The abovementioned results demonstrate the importance of arc current, arc voltage and current polarity,

Whilst the other factors investigated play only a minor role in the flux-cored arc welding process. The effects of these factors is discussed in detail in the following chapter.

Table 4.1 Set and actual values [illegible], voltage and travel speed, obtained during the welding of the 64 test welds.

| SPECIMEN NUMBER | ARC CURRENT (Amps) | | ARC VOLTAGE (Volts) | | TRAVEL SPEED (mm/min) | |
|---|---|---|---|---|---|---|
| | SETTING | ACTUAL | SETTING | ACTUAL | SETTING | ACTUAL |
| 1 | 240 | 264.9 | 24 | 23.0 | 300 | 281.0 |
| 2 | 360 | 355.0 | 24 | 21.9 | 300 | 311.4 |
| 3 | 240 | 290.5 | 36 | 35.1 | 300 | [illegible] |
| 4 | 360 | 416.1 | 36 | 33.3 | 300 | 305.0 |
| 5 | 240 | 254.5 | 24 | 22.7 | 400 | 410.0 |
| 6 | 360 | 363.1 | 24 | 21.6 | 400 | 391.7 |
| 7 | 240 | 254.3 | 36 | 34.9 | 400 | 413.8 |
| 8 | 360 | 376.8 | 36 | 41.2 | 400 | 407.0 |
| 9 | 240 | 213.8 | 24 | 21.0 | 300 | [illegible] |
| 10 | 360 | 355.9 | 24 | 21.5 | 300 | 298.0 |
| 11 | 240 | 273.9 | 36 | 34.4 | 300 | 311.9 |
| 12 | 360 | 378.7 | 36 | 33.9 | 300 | 302. |
| 13 | 240 | 246.8 | 24 | 22.7 | 400 | 395.8 |
| 14 | 360 | 336.4 | 24 | 21.6 | 400 | 391.0 |
| 15 | 240 | 243.0 | 36 | 33.9 | 400 | 411.4 |
| 16 | 360 | 384.5 | 36 | 34.1 | 400 | 403.1 |
| 17 | 240 | 243.3 | 24 | 32.4 | 300 | 293. |
| 18 | 360 | 351.9 | 24 | 22.6 | 300 | 301.2 |
| 19 | 240 | 271.4 | 36 | 35.4 | 300 | 316.0 |
| 20 | 360 | 359.7 | 36 | 40.8 | 300 | 289.9 |
| 21 | 240 | 259.2 | 24 | 22.9 | 400 | 382.2 |
| 22 | 360 | 369.5 | 24 | 21.2 | 400 | 401.9 |
| 23 | 240 | 274.2 | 36 | 35.5 | 400 | 385.1 |
| 24 | 360 | 368.1 | 36 | 40.2 | 400 | 398.7 |
| 25 | 240 | 252.7 | 24 | 23.2 | 300 | 300.3 |
| 26 | 360 | 344.4 | 24 | 23.1 | 300 | 279.9 |
| 27 | 240 | 241.2 | 36 | 35.5 | 300 | 309.3 |
| 28 | 360 | 404.4 | 36 | 35.0 | 300 | 291.5 |
| 29 | 240 | 266.0 | 24 | 23.4 | 400 | 412.8 |
| 30 | 360 | 340.6 | 24 | 22.0 | 400 | 411.4 |
| 31 | 240 | 242.0 | 36 | 33.5 | 400 | 404.6 |
| 32 | 360 | 383.4 | 36 | 34.0 | 400 | 394.3 |

Table 4.1 Ctd.

| SPECIMEN NUMBER | ARC CURRENT (Amps) | | ARC VOLTAGE (Volts) | | TRAVEL SPEED (mm/min) | |
|---|---|---|---|---|---|---|
| | SETTING | ACTUAL | SETTING | ACTUAL | SETTING | ACTUAL |
| 33 | 240 | 217.1 | 24 | 24.0 | 300 | 306.3 |
| 34 | 360 | 356.7 | 24 | 26.1 | 300 | 302.6 |
| 35 | 240 | 244.0 | 36 | 37.[illegible] | 300 | 287.4 |
| 36 | 360 | 339.2 | 36 | 35.2 | 300 | [illegible] |
| 37 | 240 | 237.8 | 24 | 24.0 | 400 | 402.7 |
| 38 | 360 | 376.8 | 24 | 23.1 | 400 | 402.3 |
| 39 | 240 | 231.6 | 36 | 36.8 | 400 | 400.0 |
| 40 | 360 | 363.5 | 36 | 35.6 | 400 | [illegible] |
| 41 | 240 | 243.1 | 24 | 24.3 | 300 | 313.8 |
| 42 | 360 | 344.7 | 24 | 27.8 | 300 | 300.6 |
| 43 | 240 | 242.7 | 36 | 37.1 | 300 | 293.4 |
| 44 | 360 | 317.0 | 36 | 32.9 | 300 | 298.5 |
| 45 | 240 | 237.8 | 24 | 24.0 | 400 | 388.9 |
| 46 | 360 | 348.5 | 24 | 30.4 | 400 | 387.3 |
| 47 | 240 | 232.4 | 36 | 37.1 | 400 | 395.8 |
| 48 | 360 | [illegible] | 36 | 39.5 | 400 | 395.3 |
| 49 | 240 | 242.0 | 24 | 23.4 | 300 | 308.0 |
| 50 | 360 | 352.7 | 24 | 30.1 | 300 | 303.2 |
| 51 | 240 | 216.7 | 36 | 35.4 | 300 | 296.6 |
| 52 | 360 | 362.0 | 36 | 43.3 | 300 | 303.2 |
| 53 | 240 | 239.5 | 24 | 22.7 | 400 | 409.1 |
| 54 | 360 | 342.8 | 24 | 29.4 | 400 | 401.1 |
| 55 | 240 | 221.6 | 36 | 34.2 | 400 | 405.7 |
| 56 | 360 | [illegible] | 36 | 34.9 | 400 | 398.4 |
| 57 | 240 | 238.8 | 24 | [illegible] | 300 | 300.3 |
| 58 | 360 | 397.0 | 24 | [illegible] | 300 | 304.2 |
| 59 | 240 | 241.5 | 36 | 36.1 | 300 | 308.6 |
| 60 | 360 | 332.8 | 36 | 34.4 | 300 | 301.7 |
| 61 | 240 | 247.9 | 24 | [illegible] | 400 | 411.2 |
| 62 | 360 | 343.7 | 24 | 20.6 | 400 | 401.9 |
| 63 | 240 | 238.7 | 36 | 36.3 | 400 | [illegible] |
| 64 | 360 | 315.0 | 36 | 32.5 | 400 | 402.1 |

Table 4.2 Results of the calculation of the mean and standard deviation of the measured values of arc current, arc voltage and travel speed, for both arc polarities used.

| 1. DCEP: | | | |
|---|---|---|---|
| Factor | Level | Mean | Standard Deviation |
| Arc Current | Lower | 255,7 Amps | 17,49 Amps |
| | Upper | 368,0 Amps | 21,40 Amps |
| Arc Voltage | Lower | 22,93 Volts | 2,56 Volts |
| | Upper | 35,67 Volts | 2,53 Volts |
| Travel Speed | Lower | 299,7 mm/min | 11,08 mm/min |
| | Upper | 401,0 mm/min | 9,80 mm/min |
| 2. DCEN: | | | |
| Factor | Level | Mean | Standard Deviation |
| Arc Current | Lower | 235,8 Amps | 9,25 Amps |
| | Upper | 346,8 Amps | 20,81 Amps |
| Arc Voltage | Lower | 35,40 Volts | 2,99 Volts |
| | Upper | 36,20 Volts | 2,52 Volts |
| Travel Speed | Lower | 301,6 mm/min | 6,1 mm/min |
| | Upper | 399,0 mm/min | 7,2 mm/min |

Table 4.3 Deposition efficiency, hardness, porosity levels and wear test results obtained for the 64 test welds.

| SPECIMEN NUMBER | DEPOSITION EFFICIENCY (%) | AVERAGE HARDNESS (HRc) | AVERAGE POROSITY (0-4) | WEAR TEST MASS LOSS (mg) | | |
|---|---|---|---|---|---|---|
| | | | | TEST1 | TEST2 | AVERAGE |
| 1 | 71.2 | 50.4 | 0.0 | 157.2 | 99.8 | 128.5 |
| 2 | 75.0 | 50.4 | 0.2 | 174.1 | 112.8 | 143.5 |
| 3 | 61.2 | 43.4 | 1.8 | 160.3 | 118.0 | 139.2 |
| 4 | 67.4 | 47.1 | 0.8 | 136.7 | 102.3 | 119.5 |
| 5 | 69.0 | 48.0 | 1.4 | 178.1 | 118.3 | 148.2 |
| 6 | 78.0 | 51.3 | 0.0 | 154.3 | 113.5 | 133.9 |
| 7 | 59.4 | 46.2 | 0.8 | 143.3 | 151.8 | 147.5 |
| 8 | 52.2 | 41.7 | 1.6 | 136.1 | 102.4 | 119.2 |
| 9 | 69.0 | 51.3 | 0.4 | 185.6 | 134.6 | 160.1 |
| 10 | 77.2 | 53.1 | 0.0 | 132.3 | 130.0 | 131.1 |
| 11 | 62.0 | 47.9 | 1.4 | 132.1 | 123.1 | 127.6 |
| 12 | 59.8 | 46.2 | 0.2 | 134.1 | 117.0 | 125.6 |
| 13 | 69.1 | 51.1 | 1.4 | 191.8 | 111.5 | 151.6 |
| 14 | 73.0 | 52.1 | 0.0 | 131.5 | 105.7 | 118.6 |
| 15 | 54.8 | 43.5 | 3.0 | 166.5 | 112.1 | 139.3 |
| 16 | 50.6 | 44.2 | 1.2 | 141.0 | 106.3 | 123.6 |
| 17 | 78.1 | 51.2 | 0.6 | 175.3 | 148.8 | 162.1 |
| 18 | 77.4 | 49.3 | 0.0 | 131.1 | 109.6 | 120.4 |
| 19 | 56.4 | 41.6 | 2.4 | 150.3 | 129.1 | 139.8 |
| 20 | 63.6 | 39.6 | 1.8 | 125.7 | 133.3 | 129.5 |
| 21 | 78.9 | 45.5 | 1.2 | 168.6 | 127.2 | 148.0 |
| 22 | 72.6 | 48.3 | 0.0 | 123.0 | 101.4 | 112.2 |
| 23 | 70.1 | 42.3 | 1.0 | 133.1 | 112.2 | 122.6 |
| 24 | 54.9 | 36.0 | 2.4 | 143.6 | 103.5 | 123.6 |
| 25 | 71.3 | 48.9 | 0.2 | 175.0 | 134.1 | 154.6 |
| 26 | 76.1 | 52.5 | 0.2 | 130.3 | 118.0 | 124.2 |
| 27 | 60.9 | 44.1 | 1.0 | 151.1 | 133.8 | 142.5 |
| 28 | 63.8 | 44.5 | 0.0 | 113.5 | 110.7 | 112.1 |
| 29 | 71.7 | 46.3 | 0.2 | 160.1 | 135.3 | 147.7 |
| 30 | 67.8 | 48.5 | 0.0 | 134.5 | 136.6 | 135.6 |
| 31 | 66.7 | 41.6 | 2.2 | 135.0 | 118.3 | 126.6 |
| 32 | 63.8 | 42.5 | 0.4 | 118.9 | 118.0 | 118.4 |

Table 4.3 Ctd.

| SPECIMEN NUMBER | DEPOSITION EFFICIENCY (%) | AVERAGE HARDNESS (HRc) | AVERAGE POROSITY (0-4) | WEAR TEST MASS LOSS (mg) | | |
|---|---|---|---|---|---|---|
| | | | | TEST1 | TEST2 | AVERAGE |
| 33 | 80.3 | 53.6 | 0.8 | 142.1 | 126.8 | 134.5 |
| 34 | 89.8 | 53.1 | 0.0 | 144.8 | 130.1 | 137.5 |
| 35 | 56.9 | 53.0 | 0.0 | 140.5 | 125.3 | 132.9 |
| 36 | 75.9 | 52.2 | 0.0 | 122.8 | 122.2 | 122.5 |
| 37 | 77.0 | 54.4 | 1.0 | 151.1 | 131.8 | 141.5 |
| 38 | 88.5 | 53.2 | 0.0 | 144.9 | 152.8 | 148.9 |
| 39 | 52.4 | 50.2 | 0.0 | 158.3 | 145.2 | 151.7 |
| 40 | 76.0 | 51.2 | 0.2 | 128.3 | 110.0 | 119.1 |
| 41 | 70.2 | 53.4 | 0.4 | 139.1 | 139.1 | 139.1 |
| 42 | 87.6 | 53.7 | 0.0 | 155.3 | 135.2 | 145.2 |
| 43 | 61.2 | 53.0 | 0.0 | 142.1 | 110.1 | 126.1 |
| 44 | 68.7 | 52.6 | 0.0 | 145.1 | 111.4 | 128.2 |
| 45 | 71.5 | 53.4 | 1.0 | 148.6 | 121.7 | 135.1 |
| 46 | 82.7 | 55.3 | 0.6 | 144.1 | 135.3 | 144.7 |
| 47 | 54.6 | 54.5 | 0.4 | 135.5 | 121.6 | 128.5 |
| 48 | 63.3 | 52.8 | 0.0 | 14 .4 | 126.4 | 136.4 |
| 49 | 76.8 | 50.5 | 0.0 | 1 1.0 | 116.4 | 1 8. |
| 50 | 89.1 | 52.1 | 0.0 | 13 .6 | 1 1.1 | 7 0. |
| 51 | 56.4 | 49.3 | 0.0 | 1 .0 | 106.0 | 1 1. |
| 52 | 78.6 | 50.2 | 0.0 | 13 .6 | 94.9 | 113.2 |
| 53 | 78.6 | 51.2 | 0.0 | 157.2 | 137.8 | 147.5 |
| 54 | 87.8 | 51.6 | 0.0 | 149.5 | 133.9 | 141.7 |
| 55 | 62.2 | 49.2 | 0.0 | 142.3 | 104.8 | 123.5 |
| 56 | 73.8 | 48.9 | 0.0 | 139.3 | 115.1 | 127.2 |
| 57 | 73.9 | 50.8 | 0.6 | 150.1 | 122.2 | 136.1 |
| 58 | 85.6 | 52.4 | 0.0 | 151.6 | 137.8 | 144.7 |
| 59 | 60.7 | 47.5 | 0.0 | 132.1 | 95.7 | 113.9 |
| 60 | 66.7 | 51.7 | 0.2 | 147.5 | 114.9 | 131.1 |
| 61 | 74.4 | 53.5 | 0.2 | 152.7 | 115.7 | 134.2 |
| 62 | 85.3 | 53.2 | 0.0 | 148.3 | 163.5 | 155.9 |
| 63 | 55.3 | 48.8 | 0.2 | 145.3 | 102.7 | 124.0 |
| 64 | 73.8 | 50.6 | 0.0 | 149.1 | 111.8 | 130.5 |

Table 4.4 Geometrical parameters obtained for the 64 test welds.

| SPECIMEN NUMBER | WIDTH (mm) | HEIGHT (mm) | DEPTH (mm) | AREA (Sq. mm) AREA A | AREA B | TOTAL | DILUTION (%) |
|---|---|---|---|---|---|---|---|
| 1 | 9.6 | 3.1 | 1.8 | 21.1 | 12.2 | 33.4 | 36.5 |
| 2 | 14.6 | 3.2 | 2.4 | 37.1 | 23.2 | 60.4 | 38.4 |
| 3 | 13.2 | 2.6 | 2.1 | 24.0 | 19.0 | 43.0 | 44.1 |
| 4 | 17.5 | 3.1 | 2.6 | 37.8 | 30.8 | 68.7 | 44.8 |
| 5 | 9.3 | 2.7 | 1.7 | 17.6 | 11.1 | 28.7 | 38.6 |
| 6 | 14.3 | 3.2 | 2.4 | 34.5 | 24.2 | 58.7 | 41.2 |
| 7 | 10.7 | 2.2 | 1.7 | 14.4 | 12.0 | 26.4 | 45.4 |
| 8 | 12.9 | 1.9 | 1.9 | 16.8 | 17.6 | 34.4 | 51.1 |
| 9 | 9.1 | 3.3 | 2.3 | 21.2 | 12.4 | 33.6 | 36.9 |
| 10 | 14.3 | 3.8 | 2.3 | 41.7 | 20.1 | 61.8 | 32.5 |
| 11 | 10.5 | 2.7 | 2.2 | 18.9 | 12.4 | 31.3 | 39.6 |
| 12 | 15.0 | 2.8 | 2.6 | 29.6 | 25.6 | 55.3 | 46.2 |
| 13 | 8.6 | 2.8 | 1.6 | 17.2 | 9.9 | 27.1 | 36.5 |
| 14 | 12.2 | 2.9 | 2.6 | 28.4 | 16.7 | 45.1 | 37.0 |
| 15 | 10.5 | 1.7 | 2.1 | 11.7 | 14.5 | 26.3 | 55.1 |
| 16 | 13.5 | 2.3 | 2.3 | 20.8 | 21.6 | 42.5 | 50.8 |
| 17 | 8.2 | 3.7 | 2.4 | 21.2 | 12.9 | 34.2 | 37.7 |
| 18 | 15.8 | 3.5 | 2.4 | 42.6 | 25.2 | 67.8 | 37.1 |
| 19 | 13.2 | 2.7 | 2.7 | 24.6 | 22.2 | 46.8 | 47.4 |
| 20 | 16.8 | 2.3 | 2.7 | 27.5 | 31.6 | 59.1 | 53.4 |
| 21 | 8.8 | 2.6 | 2.3 | 16.2 | 11.9 | 28.2 | 42.1 |
| 22 | 14.7 | 3.0 | 2.5 | 33.8 | 27.7 | 61.5 | 45.0 |
| 23 | 12.8 | 2.2 | 2.3 | 19.8 | 19.9 | 39.8 | 50.0 |
| 24 | 15.3 | 2.1 | 2.8 | 21.6 | 28.5 | 50.1 | 56.9 |
| 25 | 9.8 | 2.8 | 2.3 | 19.3 | 14.3 | 33.7 | 42.4 |
| 26 | 15.6 | 3.6 | 2.4 | 43.5 | 25.6 | 69.1 | 37.0 |
| 27 | 13.4 | 2.7 | 2.7 | 25.2 | 23.7 | 48.9 | 48.4 |
| 28 | 18.1 | 3.0 | 2.9 | 39.1 | 34.7 | 73.8 | 47.0 |
| 29 | 10.0 | 2.7 | 2.3 | 20.3 | 16.8 | 37.1 | 45.2 |
| 30 | 12.2 | 2.6 | 2.1 | 23.1 | 18.2 | 41.3 | 44.0 |
| 31 | 9.6 | 2.0 | 1.8 | 12.6 | 11.4 | 24.1 | 47.3 |
| 32 | 16.1 | 2.4 | 2.9 | 27.1 | 29.7 | 56.8 | 52.2 |

Table 4.4 Ctd.

| SPECIMEN NUMBER | WIDTH (mm) | HEIGHT (mm) | DEPTH (mm) | AREAS (Square mm) | | | DILUTION (%) |
|---|---|---|---|---|---|---|---|
| | | | | AREA A | AREA B | TOTAL | |
| 33 | 10.6 | 3.4 | 1.9 | 30.2 | 14.0 | 44.2 | 31.6 |
| 34 | 10.1 | 5.0 | 2.6 | 40.6 | 16.3 | 56.9 | 28.6 |
| 35 | 12.3 | 2.9 | 2.2 | 24.8 | 17.8 | 42.6 | 41.7 |
| 36 | 13.2 | 3.5 | 1.7 | 35.7 | 16.3 | 52.0 | 31.3 |
| 37 | 9.7 | 3.0 | 1.4 | 21.0 | 10.3 | 31.4 | 32.8 |
| 38 | 8.5 | 4.7 | 2.0 | 33.7 | 12.3 | 46.0 | 26.7 |
| 39 | 10.1 | 1.9 | 1.8 | 13.3 | 11.0 | 24.4 | 45.0 |
| 40 | 11.2 | 2.6 | 1.9 | 23.7 | 14.5 | 38.3 | 37.8 |
| 41 | 10.9 | 3.3 | 1.7 | 26.8 | 13.9 | 40.7 | 34.1 |
| 42 | 9.8 | 5.0 | 2.2 | 39.4 | 13.7 | 53.2 | 25.7 |
| 43 | 12.5 | 3.3 | 2.4 | 29.5 | 19.1 | 48.7 | 39.2 |
| 44 | 13.1 | 3.5 | 1.7 | 34.8 | 14.8 | 49.6 | 29.8 |
| 45 | 9.9 | 2.7 | 1.4 | 20.0 | 11.1 | 31.1 | 35.6 |
| 46 | 9.1 | 4.1 | 1.5 | 31.0 | 8.9 | 39.9 | 22.3 |
| 47 | 11.3 | 2.5 | 2.1 | 20.8 | 15.3 | 36.2 | 42.2 |
| 48 | 11.2 | 2.8 | 1.8 | 22.6 | 11.8 | 34.5 | 34.2 |
| 49 | 12.6 | 3.9 | 3.0 | 37.8 | 22.4 | 60.2 | 37.2 |
| 50 | 10.0 | 4.9 | 2.7 | 40.1 | 16.6 | 56.7 | 29.2 |
| 51 | 15.3 | 3.6 | 2.9 | 40.8 | 28.2 | 69.0 | 40.8 |
| 52 | 14.3 | 3.7 | 2.8 | 40.3 | 20.0 | 60.4 | 33.1 |
| 53 | 10.1 | 2.6 | 1.6 | 18.7 | 15.6 | 34.3 | 45.4 |
| 54 | 9.3 | 4.0 | 2.2 | 31.6 | 13.3 | 44.9 | 29.6 |
| 55 | 12.1 | 2.3 | 2.2 | 20.0 | 18.0 | 38.1 | 47.2 |
| 56 | 13.2 | 3.3 | 1.9 | 30.3 | 16.0 | 46.4 | 34.4 |
| 57 | 10.5 | 3.3 | 1.8 | 25.6 | 14.2 | 39.9 | 35.5 |
| 58 | 9.8 | 5.0 | 2.2 | 40.7 | 13.1 | 53.9 | 24.3 |
| 59 | 12.8 | 2.4 | 2.5 | 26.2 | 16.2 | 42.5 | 38.1 |
| 60 | 13.3 | 3.7 | 1.8 | 36.7 | 16.8 | 53.5 | 31.4 |
| 61 | 10.9 | 2.8 | 1.6 | 22.1 | 13.0 | 35.2 | 36.9 |
| 62 | 8.1 | 4.6 | 1.9 | 31.0 | 9.9 | 41.0 | 24.1 |
| 63 | 12.3 | 2.2 | 2.0 | 18.8 | 17.1 | 35.9 | 47.6 |
| 64 | 11.8 | 3.0 | 2.1 | 25.7 | 16.0 | 41.8 | 38.2 |

Table 4.5 Heat input and deposition rates obtained for the 64 test welds.

| SPECIMEN NUMBER | HEAT INPUT (kJ mm) | | DEPOSITION RATE | EFFECTIVE DEPOSITION RATE |
|---|---|---|---|---|
| | SETTING | ACTUAL | (Cubic mm/s) | (Cubic mm/s) |
| 1 | 1.151 | 1.300 | 156.7 | 99.0 |
| 2 | 1.728 | 1.497 | 313.3 | 192.6 |
| 3 | 1.728 | 1.945 | 225.7 | 126.0 |
| 4 | 2.592 | 2.720 | 349.9 | 192.8 |
| 5 | 0.864 | 0.845 | 196.5 | 120.6 |
| 6 | 1.296 | 1.201 | 383.3 | 225.3 |
| 7 | 1.296 | 1.286 | 182.6 | 99.4 |
| 8 | 1.944 | 2.285 | 234.1 | 114.3 |
| 9 | 1.151 | 0.931 | 162.0 | 102.0 |
| 10 | 1.728 | 1.540 | 307.0 | 207.1 |
| 11 | 1.728 | 1.812 | 163.0 | 98.5 |
| 12 | 2.592 | 2.548 | 278.8 | 149.2 |
| 13 | 0.864 | 0.849 | 179.1 | 113.4 |
| 14 | 1.296 | 1.115 | 294.0 | 184.9 |
| 15 | 1.296 | 1.201 | 180.3 | 80.2 |
| 16 | 1.944 | 1.949 | 285.8 | 140.3 |
| 17 | 1.151 | 1.611 | 167.0 | 103.7 |
| 18 | 1.728 | 1.584 | 340.6 | 213.9 |
| 19 | 1.728 | 1.824 | 246.4 | 129.5 |
| 20 | 2.592 | 3.037 | 285.6 | 132.9 |
| 21 | 0.864 | 0.931 | 179.9 | 103.5 |
| 22 | 1.296 | 1.169 | 412.3 | 226.4 |
| 23 | 1.296 | 1.516 | 255.3 | 127.2 |
| 24 | 1.944 | 2.226 | 333.1 | 143.7 |
| 25 | 1.151 | 1.171 | 168.7 | 96.8 |
| 26 | 1.728 | 1.705 | 322.3 | 202.8 |
| 27 | 1.728 | 1.661 | 252.3 | 129.8 |
| 28 | 2.592 | 2.913 | 358.6 | 189.8 |
| 29 | 0.864 | 0.904 | 255.6 | 140.0 |
| 30 | 1.296 | 1.092 | 283.3 | 158.3 |
| 31 | 1.296 | 1.202 | 162.6 | 85.3 |
| 32 | 1.944 | 1.983 | 373.7 | 178.0 |

Table 4.5 Ctd.

| SPECIMEN NUMBER | HEAT INPUT (kJ/mm) | | DEPOSITION RATE (Cubic mm/s) | EFFECTIVE DEPOSITION RATE (Cubic mm/s) |
|---|---|---|---|---|
| | SETTING | ACTUAL | | |
| 33 | 1.151 | 1.020 | 225.8 | 154.1 |
| 34 | 1.728 | 1.845 | 287.1 | 204.7 |
| 35 | 1.728 | 1.930 | 204.2 | 118.7 |
| 36 | 2.592 | 2.407 | 258.1 | 177.0 |
| 37 | 0.864 | 0.850 | 210.8 | 141.2 |
| 38 | 1.296 | 1.298 | 308.3 | 225.8 |
| 39 | 1.296 | 1.278 | 162.6 | 88.9 |
| 40 | 1.944 | 1.945 | 254.5 | 157.6 |
| 41 | 1.151 | 1.129 | 213.1 | 140.2 |
| 42 | 1.728 | 1.912 | 266.4 | 197.3 |
| 43 | 1.728 | 1.841 | 238.0 | 144.4 |
| 44 | 2.592 | 2.096 | 247.1 | 173.2 |
| 45 | 0.864 | 0.880 | 201.9 | 129.9 |
| 46 | 1.296 | 1.641 | 258.0 | 199.9 |
| 47 | 1.296 | 1.307 | 238.7 | 137.4 |
| 48 | 1.944 | 1.964 | 227.2 | 149.2 |
| 49 | 1.151 | 1.103 | 309.1 | 194.0 |
| 50 | 1.728 | 2.100 | 286.6 | 202.5 |
| 51 | 1.728 | 1.551 | 341.0 | 201.5 |
| 52 | 2.592 | 3.101 | 305.3 | 204.0 |
| 53 | 0.864 | 0.797 | 234.0 | 127.3 |
| 54 | 1.296 | 1.507 | 300.2 | 211.1 |
| 55 | 1.296 | 1.120 | 257.9 | 137.5 |
| 56 | 1.944 | 1.729 | 308.0 | 201.4 |
| 57 | 1.151 | 1.130 | 199.6 | 128.1 |
| 58 | 1.728 | 2.341 | 273.3 | 206.6 |
| 59 | 1.728 | 1.695 | 218.7 | 134.9 |
| 60 | 2.592 | 2.276 | 269.3 | 184.6 |
| 61 | 0.864 | 0.846 | 241.1 | 151.8 |
| 62 | 1.296 | 1.057 | 274.9 | 207.9 |
| 63 | 1.296 | 1.354 | 229.9 | 120.1 |
| 64 | 1.944 | 1.527 | 280.1 | 172.3 |

Table 4.6 Results of the analysis of variance for deposition efficiency.

| Dependant Variable: Deposition Efficiency | | | | |
|---|---|---|---|---|
| Source | Deg of Freedom | Sum of Squares | Mean Square | |
| Model | 5 | 5559,454 | 1111,891 | |
| Error | 58 | 1012,995 | 17,465 | |
| F-Value | | 63,660 | | |
| Root Mean Square | | 4,179 | | |
| R-Square | | 0,846 | | |
| Source | Deg of Freedom | Sum of Squares | F-Value | Significance Level |
| A | 1 | 716,901 | 41,05 | 1% |
| B | 1 | 3457,440 | 197,96 | 1% |
| D | 1 | 133,403 | 7,64 | 1% |
| F | 1 | 579,606 | 33,19 | 1% |
| A*F | 1 | 672,106 | 38,48 | 1% |

Table 4.7 Mean values of deposition efficiency at the different levels of the significant factors.

| Dependent Variable: Deposition Efficiency (%) | |
|---|---|
| Factor Levels | Mean of Dependent Variable |
| A | |
| 240 | 66,63 |
| 360 | 73,33 |
| B | |
| 24 | 77,33 |
| 36 | 62,63 |
| D | |
| 24 | 71,42 |
| 36 | 68,53 |
| F | |
| DCEN | 72,99 |
| DCEP | 66,97 |
| A B | |
| 240 DCEN | 66,40 |
| 240 DCEP | 66,86 |
| 360 DCEN | 79,58 |
| 360 DCEP | 67,08 |

Table 4.8 Results of the analysis of variance for deposition rate.

| Dependant Variable: Deposition Rate | | | |
|---|---|---|---|
| Source | Deg of Freedom | Sum of Squares | Mean Square |
| Model | 2 | 130993,76 | 65496,88 |
| Error | 61 | 101383,26 | 1662,02 |
| F-Value | | 39,410 | |
| Root Mean Square | | 40,767 | |
| R-Square | | 0,564 | |

| Source | Deg of Freedom | Sum of Squares | F-Value | Significance Level |
|---|---|---|---|---|
| A | 1 | 114572,9 | 69,94 | 1% |
| E | 1 | 16420,8 | 9,88 | 1% |

Table 4.9 Mean values of deposition rate at the different levels of the significant factors.

| Dependent Variable: Deposition Rate | |
|---|---|
| Factor Levels | Mean of Dependent Variable |
| A | |
| 240 | 214,18 |
| 360 | 298,80 |
| E | |
| 20 | 240,18 |
| 150 | 271,99 |

Table 4 10 Results of the analysis of variance for the effective deposition rate.

| Dependant Variable: Effective Deposition Rate | | | |
|---|---|---|---|
| Source | Deg of Freedom | Sum of Squares | Mean Square |
| Model | 7 | 83596,27 | 11942,32 |
| Error | 56 | 23362,38 | 417,19 |
| F-Value | | 28,63 | |
| Root Mean Square | | 20,425 | |
| R-Square | | 0,782 | |

| Source | Deg of Freedom | Sum of Squares | F-Value | Significance Level |
|---|---|---|---|---|
| A | 1 | 57831,8 | 138,62 | 1% |
| B | 1 | 7552,0 | 18,10 | 1% |
| C | 1 | 1744,5 | 4,18 | 5% |
| E | 1 | 2027,7 | 4,86 | 5% |
| F | 1 | 8004,8 | 19,20 | 1% |
| A*B | 1 | 4199,7 | 10,07 | 1% |
| A*C | 1 | 2230,7 | 5,35 | 5% |

Table 4.11 Mean values of the effective deposition rat. at the different levels of the significant factors.

| Dependent Variable: Effective Deposition Rate | |
|---|---|
| Factor Levels | Mean of Dependent Variable |
| A | |
| 210 | 123,15 |
| 360 | 185,27 |
| B | |
| 24 | 166,07 |
| 36 | 144,34 |
| C | |
| 300 | 160,42 |
| 400 | 149,99 |
| E | |
| 20 | 149,58 |
| 150 | 160,84 |
| P | |
| DCEN | 166,39 |
| DCEP | 144,02 |
| A B | |
| 240 24 | 127,91 |
| 240 36 | 122,39 |
| 360 24 | 204,23 |
| 360 36 | 166,30 |
| B C | |
| 24 300 | 165,39 |
| 24 400 | 166,75 |
| 36 300 | 155,47 |
| 36 400 | 133,22 |

Table 4.12 Results of the analysis of variance on the average porosity.

| Dependant Variable: Average Porosity | | | |
|---|---|---|---|
| Source | Deg of Freedom | Sum of Squares | Mean Square |
| Model | 4 | 19,283 | 4,821 |
| Error | 59 | 14,447 | 0,245 |
| F-Value | | 19,690 | |
| Root Mean Square | | 0,495 | |
| R-Square | | 0,572 | |

| Source | Deg of Freedom | Sum of Squares | F-Value | Significance Level |
|---|---|---|---|---|
| A | 1 | 2,976 | 12,15 | 1% |
| B | 1 | 2,481 | 10,13 | 1% |
| F | 1 | 7,701 | 31,45 | 1% |
| B*F | 1 | 6,126 | 25,02 | 1% |

Table 4.13 Mean values of the average porosity at the different levels of the significant factors.

| Dependent Variable: Average Porosity | |
|---|---|
| Factor Levels | Mean of Dependent Variable |
| A | |
| 240 | 0,7375 |
| 360 | 0,5063 |
| B | |
| 24 | 0,3250 |
| 36 | 0,7188 |
| F | |
| DCEN | 0,1750 |
| DCEP | 0,8688 |
| B F | |
| 24 DCEN | 0,2875 |
| 24 DCEP | 0,3625 |
| 36 DCEN | 0,0625 |
| 36 DCEP | 1,3750 |

Table 4.14 Results of the analysis of variance for deposit width.

| Dependant Variable: Deposit Width | | | | |
|---|---|---|---|---|
| Source | Deg of Freedom | Sum of Squares | Mean Square | |
| Model | 9 | 328,847 | 36,538 | |
| Error | 54 | 45,058 | 0,834 | |
| F-Value | | 43,790 | | |
| Root Mean Square | | 0,913 | | |
| R-Square | | 0,879 | | |
| Source | Deg of Freedom | Sum of Squares | F-Value | Significance Level |
| A | 1 | 62,420 | 74,81 | 1% |
| B | 1 | 81,002 | 97,08 | 1% |
| C | 1 | 32,626 | 39,10 | 1% |
| E | 1 | 11,614 | 13,92 | 1% |
| F | 1 | 33,315 | 39,93 | 1% |
| A*F | 1 | 98,821 | 118,43 | 1% |
| A*B*F | 3 | 9,050 | 3,62 | 5% |

Table 4.15 Mean values of deposit width at the different levels of the significant factors.

| Dependent Variable: Deposit Width | | | |
|---|---|---|---|
| Factor Levels | | | Mean of Dependent Variable |
| A | | | |
| 240 | | | 11,031 |
| 360 | | | 13,006 |
| B | | | |
| 24 | | | 10,893 |
| 36 | | | 13,143 |
| C | | | |
| 300 | | | 12,732 |
| 400 | | | 11,304 |
| E | | | |
| 20 | | | 11,592 |
| 150 | | | 12,444 |
| F | | | |
| DCEN | | | 11,297 |
| DCEP | | | 12,740 |
| A | E | | |
| 240 | DCEN | | 11,552 |
| 240 | DCEP | | 10,510 |
| 360 | DCEN | | 11,042 |
| 360 | DCEP | | 14,970 |
| A | B | F | |
| 240 | 24 | DCEN | 10,717 |
| 240 | 24 | DCEP | 9,235 |
| 240 | 36 | DCEN | 12,387 |
| 240 | 36 | DCEP | 11,785 |
| 360 | 24 | DCEN | 9,373 |
| 360 | 24 | DCEP | 14,249 |
| 360 | 36 | DCEN | 12,711 |
| 360 | 36 | DCEP | 15,691 |

Table 4.16 Results of the analysis of variance for the deposit height.

| Dependant Variable: Deposit Height | | | |
|---|---|---|---|
| Source | Deg of Freedom | Sum of Squares | Mean Square |
| Model | 8 | 36,191 | 4,524 |
| Error | 55 | 3,645 | 0,066 |
| F-Value | | 68,260 | |
| Root Mean Square | | 0,257 | |
| R-Square | | 0,908 | |

| Source | Deg of Freedom | Sum of Squares | F-Value | Significance Level |
|---|---|---|---|---|
| A | 1 | 6,867 | 103,62 | 1% |
| B | 1 | 10,435 | 157,45 | 1% |
| C | 1 | 6,595 | 99,53 | 1% |
| F | 1 | 7,054 | 106,44 | 1% |
| A*B | 1 | 1,104 | 16,65 | 1% |
| A*F | 1 | 3,128 | 47,21 | 1% |
| A*B*F | 2 | 1,007 | 7,60 | 1% |

Table 4.17 Mean values of deposit height at the different levels of the significant factors.

| Dependent Variable: Deposit Height | | | |
|---|---|---|---|
| Factor Levels | | | Mean of Dependent Variable |
| A | | | |
| 240 | | | 2,816 |
| 360 | | | 3,471 |
| B | | | |
| 24 | | | 3,547 |
| 36 | | | 2,740 |
| C | | | |
| 300 | | | 3,464 |
| 400 | | | 2,822 |
| F | | | |
| DCEN | | | 3,475 |
| DCEP | | | 2,811 |
| A | B | | |
| 240 | 24 | | 3,088 |
| 240 | 36 | | 2,543 |
| 360 | 24 | | 4,006 |
| 360 | 36 | | 2,936 |
| A | F | | |
| 240 | DCEN | | 2,927 |
| 240 | DCEP | | 2,705 |
| 360 | DCEN | | 4,024 |
| 360 | DCEP | | 2,918 |
| A | B | F | |
| 240 | 24 | DCEN | 3,156 |
| 240 | 24 | DCEP | 3,021 |
| 240 | 36 | DCEN | 2,697 |
| 240 | 36 | DCEP | 2,389 |
| 360 | 24 | DCEN | 4,731 |
| 360 | 24 | DCEP | 3,281 |
| 360 | 36 | DCEN | 3,317 |
| 360 | 36 | DCEP | 2,555 |

Table 4.18 Results of the analysis of variance for the depth of penetration.

| Dependant Variable: Depth of Penetration | | | | |
|---|---|---|---|---|
| Source | Deg of Freedom | Sum of Squares | Mean Square | |
| Model | 4 | 4,927 | 1,232 | |
| Error | 59 | 5,866 | 0,099 | |
| F-Value | | 12,390 | | |
| Root Mean Square | | 0,315 | | |
| R-Square | | 0,456 | | |
| Source | Deg of Freedom | Sum of Squares | F-Value | Significance Level |
| A | 1 | 0,5395 | 5,43 | 5% |
| C | 1 | 1,7213 | 17,31 | 1% |
| E | 1 | 1,5203 | 15,29 | 1% |
| F | 1 | 1,1454 | 11,52 | 1% |

Table 4.19 Mean values of the depth of penetration at the different levels of the significant factors.

| Dependent Variable: Depth of Penetration | |
|---|---|
| Factor Levels | Mean of Dependent Variable |
| A | |
| 240 | 2,138 |
| 360 | 2,321 |
| C | |
| 300 | 2,393 |
| 400 | 2,065 |
| E | |
| 20 | 2,075 |
| 150 | 2,383 |
| F | |
| DCEN | 2,096 |
| DCEP | 2,363 |

Table 4.20 Results of the analysis of variance for deposit dilution.

| Dependant Variable: Deposit Dilution | | | |
|---|---|---|---|
| Source | Deg of Freedom | Sum of Squares | Mean Square |
| Model | 7 | 3605,41 | 515,06 |
| Error | 56 | 415,96 | 7,43 |
| F-Value | | 63,340 | |
| Root Mean Square | | 2,725 | |
| R-Square | | 0,897 | |

| Source | Deg of Freedom | Sum of Squares | F-Value | Significance Level |
|---|---|---|---|---|
| A | 1 | 274,77 | 36,99 | 1% |
| B | 1 | 1112,97 | 149,84 | 1% |
| C | 1 | 217,75 | 29,31 | 1% |
| E | 1 | 129,31 | 17,41 | 1% |
| F | 1 | 1402,03 | 188,75 | 1% |
| A*F | 1 | 452,47 | 60,91 | 1% |

Table 4.21 Mean values of deposit dilution at the different levels of the significant factors.

| Dependent Variable: Deposit Dilution | | |
|---|---|---|
| Factor Levels | | Mean of Dependent Variable |
| A | | |
| 240 | | 41,607 |
| 360 | | 37,463 |
| B | | |
| 24 | | 35,365 |
| 36 | | 43,705 |
| C | | |
| 300 | | 37,691 |
| 400 | | 41,380 |
| E | | |
| 20 | | 38,114 |
| 150 | | 40,957 |
| F | | |
| DCEN | | 34,855 |
| DCEP | | 44,216 |
| A | F | |
| 240 | DCEN | 39,586 |
| 240 | DCEP | 43,629 |
| 360 | DCEN | 30,124 |
| 360 | DCEP | 44,803 |

Table 4.22 Results of the analysis of variance for deposit hardness.

| Dependant Variable: Deposit Hardness (HRc) | | | |
|---|---|---|---|
| Source | Deg of Freedom | Sum of Squares | Mean Square |
| Model | 4 | 940,009 | 235,00 |
| Error | 59 | 177,969 | 3,02 |
| F-Value | | 77,910 | |
| Root Mean Square | | 1,737 | |
| R-Square | | 0,841 | |

| Source | Deg of Freedom | Sum of Squares | F-Value | Significance Level |
|---|---|---|---|---|
| B | 1 | 286,88 | 95,11 | 1% |
| E | 1 | 108,42 | 35,94 | 1% |
| F | 1 | 454,22 | 150,58 | 1% |
| B*F | 1 | 90,49 | 30,00 | 1% |

Table 4.23 Mean values of deposit hardness at the different levels of the significant factors.

| Dependent Variable: Deposit Hardness (HRc) | | |
|---|---|---|
| Factor Levels | | Mean of Dependent Variable |
| B | | |
| 24 | | 51,363 |
| 36 | | 47,128 |
| E | | |
| 20 | | 50,547 |
| 150 | | 47,944 |
| F | | |
| DCEN | | 51,909 |
| DCEP | | 46,581 |
| B | F | |
| 24 | DCEN | 52,838 |
| 24 | DCEP | 49,888 |
| 36 | DCEN | 50,981 |
| 36 | DCEP | 43,275 |

Table 4.24 Results of the regression analysis for deposition efficiency with electrode positive.

| Dependant Variable: Deposition Efficiency (DCEP) | | | | |
|---|---|---|---|---|
| Source | Deg of Freedom | Sum of Squares | Mean Square | |
| Model | 1 | 0,05260 | 0,052560 | |
| Error | 30 | 0,03817 | 0,001272 | |
| F-Value | | 41,342 | | |
| Root Mean Square | | 0,036 | | |
| R-Square | | 0,580 | | |
| Variable | Deg of Freedom | Parameter Estimate | Standard Error | Significance Level |
| Intercept | 1 | 2,394 | 0,0891 | 1% |
| Log(B) | 1 | -0,393 | 0,0611 | 1% |

Table 4.25 Results of the regression analysis for deposition rate with electrode positive.

| Dependant Variable: Deposition Rate (DCEP) | | | | |
|---|---|---|---|---|
| Source | Deg of Freedom | Sum of Squares | Mean Square | |
| Model | 2 | 0,4247 | 0,2123 | |
| Error | 29 | 0,1188 | 0,0041 | |
| F-Value | | 51,814 | | |
| Root Mean Square | | 0,064 | | |
| R-Square | | 0,781 | | |
| Variable | Deg of Freedom | Parameter Estimate | Standard Error | Significance Level |
| Intercept | 1 | -1,0395 | 0,3390 | 1% |
| Log(A) | 1 | 1,3375 | 0,1349 | 1% |
| Log(E) | 1 | 0,0623 | 0,0259 | 5% |

Table 4.26 Results of the regression analysis for effective deposition rate with electrode positive.

| Dependant Variable: Effective Deposition Rate (DCEP) | | | | |
|---|---|---|---|---|
| Source | Deg of Freedom | Sum of Squares | | Mean Square |
| Model | 2 | 0,4188 | | 0,2094 |
| Error | 29 | 0,1177 | | 0,0041 |
| F-Value | | 51,620 | | |
| Root Mean Square | | 0,064 | | |
| R-Square | | 0,781 | | |
| Variable | Deg of Freedom | Parameter Estimate | Standard Error | Significance Level |
| Intercept | 1 | -0,3033 | 0,3543 | -- |
| Log(A) | 1 | 1,2861 | 0,1352 | 1% |
| Log(B) | 1 | -0,518º | 0,1100 | 1% |

Table 4.27 Results of the regression analysis for deposit width with electrode positive.

| Dependant Variable: Deposit Width (DCEP) | | | | |
|---|---|---|---|---|
| Source | Freedom | Sum of Squares | | Mean Square |
| Model | | 0,2477 | | 0,0826 |
| Error | 3 | 0,0580 | | 0,0021 |
| F-Value | | 39,835 | | |
| Root Mean Square | | 0,046 | | |
| R-Square | | 0,810 | | |
| Variable | Deg of Freedom | Parameter Estimate | Standard Error | Significance Level |
| Intercept | 1 | -0,7844 | 0,4096 | -- |
| Log(A) | 1 | 0,9671 | 0,0967 | 1% |
| Log(B) | 1 | 0,1724 | 0,0786 | 5% |
| Log(C) | 1 | -0,3056 | 0,1244 | 5% |

Table 4.26 Results of [illegible]
effective deposition rate with electrode po[illegible]

| Dependant Variable: Effective Deposition Rate (DCEP) | | | | |
|---|---|---|---|---|
| Source | Deg of Freedom | Sum of Squa[illegible] | Mean Squa[illegible] | |
| Model | 2 | 0,4188 | 0,2094 | |
| Error | 29 | 0,1177 | 0,004[illegible] | |
| F-Value | | 51,620 | | |
| Root Mean Square | | 0,064 | | |
| R-Square | | 0,781 | | |
| Variable | Deg of Freedom | Parameter Estimate | Standard Error | Signi[illegible] Level |
| Intercept | 1 | -0,3033 | 0,354[illegible] | |
| Log(A) | 1 | 1,2861 | 0,1352 | 1% |
| Log(B) | 1 | -0,5189 | 0,1100 | 1% |

Table 4.27 Results of the regression analys[illegible]
deposit width with electrode positive.

| Dependant Variable: Deposit Width (DCEP) | | | | |
|---|---|---|---|---|
| Source | Deg of Freedom | Sum of Squares | Mean Square | |
| Model | 3 | 0,2477 | 0,0826 | |
| Error | 28 | 0,0580 | 0,0021 | |
| F-Value | | 39,835 | | |
| Root Mean Square | | 0,046 | | |
| R-Square | | 0,810 | | |
| Variable | Deg of Freedom | Parameter Estimate | Standard Error | Significanc[illegible] Level |
| Intercept | 1 | -0,7844 | 0,4096 | -- |
| Log(A) | 1 | 0,9671 | 0,0967 | 1% |
| Log(B) | 1 | 0,1724 | 0,0786 | 5% |
| Log(C) | 1 | -0,3056 | 0,1244 | 5% |

Table 4.28 Results of the regression analysis for deposit height with electrode positive.

| Dependant Variable: Deposit Height (DCEP) | | | | |
|---|---|---|---|---|
| Source | Deg of Freedom | Sum of Squares | Mean Square | |
| Model | 3 | 0,1699 | 0,05665 | |
| Error | 28 | 0,0449 | 0,00160 | |
| F-Value | | 35,341 | | |
| Root Mean Square | | 0,040 | | |
| R-Square | | 0,791 | | |
| Variable | Deg of Freedom | Parameter Estimate | Standard Error | Significance Level |
| Intercept | 1 | 2,663 | 0,3602 | 1% |
| Log(A) | 1 | 0,182 | 0.0851 | 5% |
| Log(B) | 1 | -0,501 | 0,0691 | 1% |
| Log(C) | 1 | -0,766 | 0,1094 | 1% |

Table 4.29 Results of the regression analysis for depth of penetration with electrode positive.

| Dependant Variable: Depth of Penetration (DCEP) | | | | |
|---|---|---|---|---|
| Source | Deg of Freedom | Sum of Squares | Mean Square | |
| Model | 3 | 0,0717 | 0,0239 | |
| Error | 28 | 0.0668 | 0,0024 | |
| F-Value | | 10,014 | | |
| Root Mean Square | | 0,049 | | |
| R-Square | | 0,518 | | |
| Variable | Deg of Freedom | Parameter Estimate | Standard Error | Significance Level |
| Intercept | 1 | 0,1019 | 0,4346 | -- |
| Log(A) | 1 | 0,3804 | 0,1030 | 1% |
| Log(C) | 1 | -0,3101 | 0,1335 | 5% |
| Log(E) | 1 | 0,0626 | 0,0198 | 1% |

Table 4.30 Results of the regression analysis for deposit dilution with electrode positive.

| Dependant Variable: Deposit Dilution (DCEP) | | | | |
|---|---|---|---|---|
| Source | Deg of Freedom | Sum of Squares | Mean Square | |
| Model | 3 | 0,0910 | 0,03064 | |
| Error | 28 | 0,0245 | 0,00088 | |
| F-Value | | 34,984 | | |
| Root Mean Square | | 0,030 | | |
| R-Square | | 0,789 | | |
| Variable | Deg of Freedom | Parameter Estimate | Standard Error | Significance Level |
| Intercept | 1 | 0,0165 | 0,2179 | -- |
| Log(B) | 1 | 0,4262 | 0,0510 | 1% |
| Log(C) | 1 | 0,3733 | 0,0809 | 1% |
| Log(E) | 1 | 0,0328 | 0,0120 | 5% |

Table 4.31 Results of the regression analysis for deposit hardness with electrode positive.

| Dependant Variable: Deposit Hardness (HRc) (DCEP) | | | | |
|---|---|---|---|---|
| Source | Deg of Freedom | Sum of Squares | Mean Square | |
| Model | 2 | 0,0363 | 0,01816 | |
| Error | 29 | 0,0144 | 0,00050 | |
| F-Value | | 36,566 | | |
| Root Mean Square | | 0,022 | | |
| R-Square | | 0,716 | | |
| Variable | Deg of Freedom | Parameter Estimate | Standard Error | Significance Level |
| Intercept | 1 | 2,1441 | 0,0565 | 1% |
| Log(B) | 1 | -0,3004 | 0,0384 | 1% |
| Log(E) | 1 | -0,0234 | 0,0091 | 5% |

Table 4.32 Results of the regression analysis for deposition efficiency with electrode negative.

| Dependent Variable: Deposition Efficiency (DCEN) | | | |
|---|---|---|---|
| Source | Deg of Freedom | Sum of Squares | Mean Square |
| Model | 3 | 0,1309 | 0,04363 |
| Error | 28 | 0,0203 | 0,00072 |
| F-Value | | 60,250 | |
| Root Mean Square | | 0,027 | |
| R-Square | | 0,866 | |

| Variable | Deg of Freedom | Parameter Estimate | Standard Error | Significance Level |
|---|---|---|---|---|
| Intercept | 1 | 1,4567 | 0,1721 | 1% |
| Log(A) | 1 | 0,5572 | 0,0553 | 1% |
| Log(B) | 1 | -0,5098 | 0,0544 | 1% |
| Log(D) | 1 | -0,1449 | 0,0541 | 1% |

Table 4.33 Results of the regression analysis for deposition rate with electrode negative.

| Dependant Variable: Deposition Rate (DCEN) | | | |
|---|---|---|---|
| Source | Deg of Freedom | Sum of Squares | Mean Square |
| Model | 2 | 0,3962 | 0,1981 |
| Error | 29 | 0,1489 | 0,0050 |
| F-Value | | 39,918 | |
| Root Mean Square | | 0,070 | |
| R-Square | | 0,727 | |

| Variable | Deg of Freedom | Parameter Estimate | Standard Error | Significance Level |
|---|---|---|---|---|
| Intercept | 1 | -0,7477 | 0,3537 | 5% |
| Log(A) | 1 | 1,2303 | 0,1412 | 1% |
| Log(E) | 1 | 0,0506 | 0,0281 | 5% |

Table 4.32 Results of the regression analysis for deposition efficiency with electrode negative.

| Dependent Variable: Deposition Efficiency (DCEN) | | | | |
|---|---|---|---|---|
| Source | Deg of Freedom | Sum of Squares | Mean Square | |
| Model | 3 | 0,1309 | 0,04363 | |
| Error | 28 | 0,0203 | 0,00072 | |
| F-Value | | 60,250 | | |
| Root Mean Square | | 0,027 | | |
| R-Square | | 0,866 | | |
| Variable | Deg of Freedom | Parameter Estimate | Standard Error | Significance Level |
| Intercept | 1 | 1,4567 | 0,1721 | 1% |
| Log(A) | 1 | 0,5572 | 0,0553 | 1% |
| Log(B) | 1 | -0,5098 | 0,0544 | 1% |
| Log(D) | 1 | -0,1449 | 0,0541 | 1% |

Table 4.33 Results of the regression analysis for deposition rate with electrode negative.

| Dependant Variable: Deposition Rate (DCEN) | | | | |
|---|---|---|---|---|
| Source | Deg of Freedom | Sum of Squares | Mean Square | |
| Model | 2 | 0,3962 | 0,1981 | |
| Error | 29 | 0,1489 | 0,0050 | |
| F-Value | | 39,918 | | |
| Root Mean Square | | 0,070 | | |
| R-Square | | 0,727 | | |
| Variable | Deg of Freedom | Parameter Estimate | Standard Error | Significance Level |
| Intercept | 1 | -0,7477 | 0,3537 | 5% |
| Log(A) | 1 | 1,2303 | 0,1412 | 1% |
| Log(E) | 1 | 0,0506 | 0,0281 | 5% |

Table 4.34 Results of the regression analysis for effective deposition rate with electrode negative.

| Dependant Variable: Effective Deposition Rate (DCEN) | | | | |
|---|---|---|---|---|
| Source | Deg of Freedom | Sum of Squares | Mean Square | |
| Model | 2 | 0,3852 | 0,1926 | |
| Error | 29 | 0,1536 | 0,0051 | |
| F-Value | | 37,615 | | |
| Root Mean Square | | 0,072 | | |
| R-Square | | 0,715 | | |
| Variable | Deg of Freedom | Parameter Estimate | Standard Error | Significance Level |
| Intercept | 1 | 0,0248 | 0,3782 | -- |
| Log(A) | 1 | 1,1725 | 0,1457 | 1% |
| Log(B) | 1 | -0,5464 | 0,1231 | 1% |

Table 4.35 Results of the regression analysis for deposit width with electrode negative.

| Dependant Variable: Deposit Width (DCEN) | | | | |
|---|---|---|---|---|
| Source | Deg of Freedom | Sum of Squares | Mean Square | |
| Model | 3 | 0,0863 | 0.02877 | |
| Error | 28 | 0,0484 | 0,00173 | |
| F-Value | | 16,634 | | |
| Root Mean Square | | 0,042 | | |
| R-Square | | 0,641 | | |
| Variable | Deg of Freedom | Parameter Estimate | Standard Error | Significance Level |
| Intercept | 1 | 1,8758 | 0,4055 | 1% |
| Log(A) | 1 | -0,2431 | 0,0854 | 1% |
| Log(B) | 1 | 0,4624 | 0,0851 | 1% |
| Log(C) | 1 | -0,3602 | 0,1213 | 1% |

Table 4.36 Results of the regression analysis for deposit height with electrode negative.

| Dependent Variable: Deposit Height (DCEN) | | | | |
|---|---|---|---|---|
| Source | Deg of Freedom | Sum of Squares | Mean Square | |
| Model | 3 | 0,3113 | 0,10377 | |
| Error | 28 | 0,0688 | 0,00246 | |
| F-Value | | 42,241 | | |
| Root Mean Square | | 0,050 | | |
| R-Square | | 0,819 | | |
| Variable | Deg of Freedom | Parameter Estimate | Standard Error | Significance Level |
| Intercept | 1 | 1,3504 | 0,4832 | 1% |
| Log(A) | 1 | 0,8786 | 0,1018 | 1% |
| Log(B) | 1 | -0,5865 | 0,1014 | 1% |
| Log(C) | 1 | -0,8316 | 0,1446 | 1% |

Table 4.37 Results of the regression analysis for depth of penetration with electrode negative.

| Dependant Variable: Depth of Penetration (DCEN) | | | | |
|---|---|---|---|---|
| Source | Deg of Freedom | Sum of Squares | Mean Square | |
| Model | 2 | 0,0978 | 0,04891 | |
| Error | 29 | 0,1457 | 0,00502 | |
| F-Value | | 9,736 | | |
| Root Mean Square | | 0,071 | | |
| R-Square | | 0,402 | | |
| Variable | Deg of Freedom | Parameter Estimate | Standard Error | Significance Level |
| Intercept | 1 | 2,0227 | 0,5196 | 1% |
| Log(C) | 1 | -0,7273 | 0,2044 | 1% |
| Log(E) | 1 | 0,0790 | 0,0287 | 1% |

Table 4.38 Results of the regression analysis for deposit dilution with electrode negative.

| Dependant Variable: Deposit Dilution (DCEN) | | | | |
|---|---|---|---|---|
| Source | Deg of Freedom | Sum of Squares | Mean Square | |
| Model | 1 | 0,1079 | 0,10790 | |
| Error | 30 | 0,1568 | 0,00523 | |
| F-Value | | 20,643 | | |
| Root Mean Square | | 0,072 | | |
| R-Square | | 0,408 | | |
| Variable | Deg of Freedom | Parameter Estimate | Standard Error | Significance Level |
| Intercept | 1 | 3,1720 | 0,3636 | 1% |
| Log(A) | 1 | -0,6722 | 0,1480 | 1% |

Table 4.39 Results of the regression analysis for deposit hardness with electrode negative.

| Dependant Variable: Deposit Hardness (HRc) (DCEN) | | | | |
|---|---|---|---|---|
| Source | Deg of Freedom | Sum of Squares | Mean Square | |
| Model | 2 | 0,00458 | 0,00229 | |
| Error | 29 | 0,00330 | 0,00011 | |
| F-Value | | 20,166 | | |
| Root Mean Square | | 0,011 | | |
| R-Square | | 0,582 | | |
| Variable | Deg of Freedom | Parameter Estimate | Standard Error | Significance Level |
| Intercept | 1 | 1,8660 | 0,0330 | 1% |
| Log(B) | 1 | -0,0746 | 0,0215 | 1% |
| Log(E) | 1 | -0,0234 | 0,0043 | 1% |

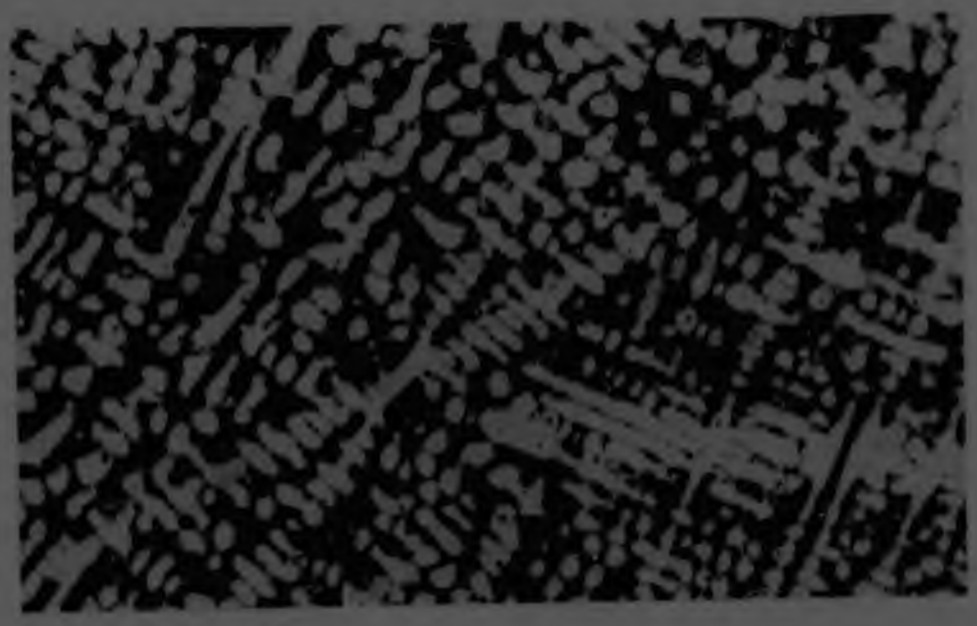


Figure 4.1 Photomicrograph of the dendritic microstructure of the weld bead with the lowest percentage dilution. Magnification 500X.

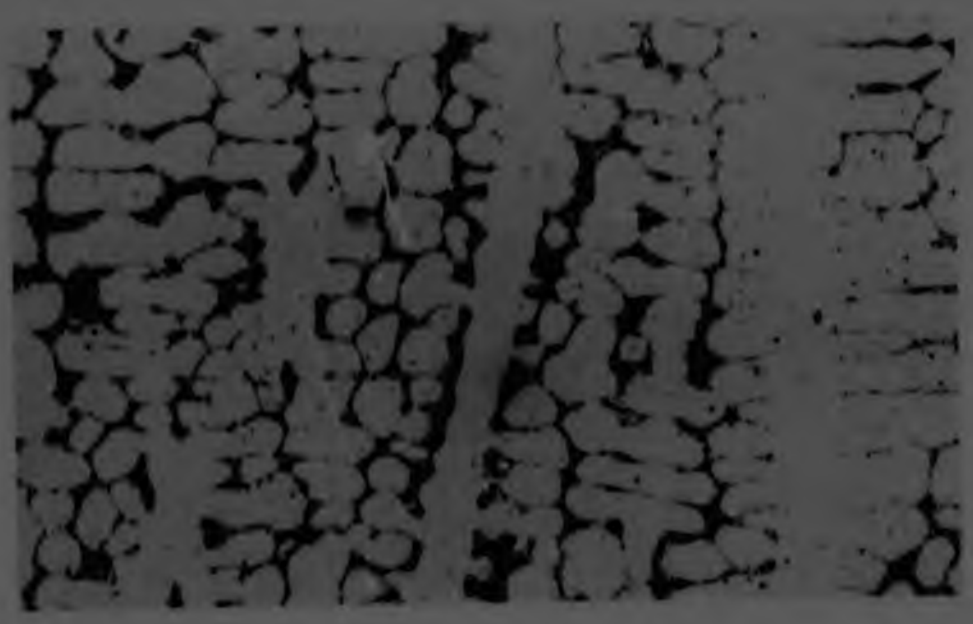


Figure 4.2 Photomicrograph of the dendritic microstructure of the weld deposit with the highest percentage dilution. Magnification 500X.

# 5. DISCUSSION

## 5.1 Introduction

This chapter includes a detailed discussion of the results obtained from the analyses of variance and regression described in the previous chapter. It must first be emphasized that the figures (graphs) included in this chapter show the average effects of the factors (process parameters) on each of the dependent variables discussed. These graphs are therefore drawn using the data given in the tables of the means in Chapter 4. The means of the dependent variables are calculated for a number of points at each factor level, and since the other factor combinations vary at all of these points, there is usually a fair degree of scatter involved. It would therefore be unwise to assume that the graphs show an exact linear relationship between the variables as depicted in each figure, but rather represent the 'average effect' that the factor will have on the dependent variable over a wide range of operating conditions.

This phenomenon is best explained by an example using the data available for deposition efficiency in Table 4.3. Figure 5.1 shows the values for deposition

efficiency plotted against the actual values of arc voltage for both arc polarities. It can be seen that there is a fair degree of scatter over the voltage ranges used due to the impossibility of accurately setting the welding machine to a given voltage as described before. The greatest amount of scatter however occurs across the range of deposition efficiency. The main reason for this scatter is that the graph in fact represents 32 pairs of data points, (one point at each level of arc voltage), each of these pairs being obtained at a different combination of the other factor levels.

In the analysis of this data, the difference (effect) in deposition efficiency between the two levels of arc voltage is calculated for each pair of data points (ie. at 32 different treatment combinations of the other factors). In the case of arc voltage these differences do not vary significantly for any of the other input factors, and thus no interaction is assumed to occur. The average effect of arc voltage over the range of experimentation can therefore be represented by the single solid line drawn in figure 5.1, and repeated for completeness in figure 5.4.

Figure 5.2 shows a graph of all the data points for deposition efficiency versus arc current. The reasons for the degree of scatter present are the same as for the scatter in Figure 5.1 discussed above. The main

[illegible] however, is that at higher amperages the average deposition efficiency is higher [illegible] as for electrode [illegible]. The effects of arc current and [illegible] interact on the [illegible].

[illegible] interactions that are not demonstrated by [illegible] experiments, and therefore reduces the [illegible] of these experiments in research of this [illegible]. This point will be discussed in greater detail [illegible] later in this chapter. Also, [illegible] in which the effects of the factors are [illegible] greater than those of the errors (or [illegible], are included in this report.

The results obtained from the regression analyses give [illegible] idea of the influence that each of the factors has [illegible] weld deposit. This is also discussed in [illegible] sections that follow.

[illegible] important to realise that the results discussed below are only valid for the ranges of the factors used in this experimental program. Any attempts at extrapolation should therefore be [illegible] with extreme caution, and preferably [illegible] additional experimentation.

## 5.2 Variations in Process Parameters

The coefficient of variation in the arc current ranged from 3,92 to 6,84% and in the arc voltage from 5,81 to 11,77%, for the four different settings shown in Table 4.2. From the results obtained in the other analyses it is apparent that these variations in current and voltage could have an effect on the 'quality' of the weld deposit. Special attention should therefore be given to the setting of these parameters in an industrial situation since any additional variation introduced by the welder or operator may significantly alter the physical properties of the deposit. The magnitude of these effects will become apparent in this chapter.

## 5.3 Deposition Efficiency

From Table 4.6 it can be seen that the factors which have the most effect on the deposition efficiency include the arc current (A) and voltage (B) as well as the torch stand-off (D) distance and the arc polarity (F). There is also a significant interaction between the arc current and the arc polarity.

This is a good example to use in a discussion of the importance of considering interactions of factors. It also serves to emphasize the inappropriateness of

describing the effect of one factor in isolation, when an interaction involving this factor occurs.

Consider first the means of the deposition efficiency for the different levels of arc current in Table 4.7. The average deposition efficiency increases from 66,63% at 240 Amps, to 73,33% at 360 Amps. This would suggest that an increase in the arc current will, on average, cause a substantial increase in the deposition efficiency (approximately 0,06% per Amp). However, a closer inspection of the interaction that occurs between arc current and polarity shows a very different relationship in practice.

There is in fact little to be gained (in deposition efficiency) by increasing the arc current, if the arc polarity is electrode positive (66,86% at 240 Amps to 67,08% at 360 Amps). On the other hand however, if electrode negative is used, an increase in arc current can give rise to a marked average increase in deposition efficiency (approximately 0,11% per Amp on average). These effects are shown clearly in Figure 5.1.

An increase in arc voltage causes a substantial drop (approximately -1,23% per Volt) in the deposition efficiency (Figure 5.2). This is probably due to an increase in the amount of spatter which occurs at higher voltages.

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An increase in arc voltage causes a substantial drop (approximately -1,23% per Volt) in the deposition efficiency (Figure 5.2). This is probably due to an increase in the amount of spatter which occurs at higher voltages.

The deposition efficiency is also the only dependent variable on which the torch stand-off distance has a significant effect. An increase in torch stand-off causes a small decrease (approximately -0,24% per mm) in deposition efficiency, as shown in Figure 5.3. The reasons for this phenomenon are not fully understood.

The results of the regression analyses performed on the deposition efficiency support the above discussion. Firstly, the regression results for the data obtained using electrode positive show that in this case only the arc voltage is of importance. The equation is given below.

$$Log(Dep\ Eff) = bLog(B) + f$$

where: $b = -0,393$

$f = 2,394$

The regression results for the electrode negative case were also as expected from the analysis of variance and are shown overleaf.

$$Log(Dep\ Eff) = aLog(A) + bLog(B) + dLog(D) + f$$

where: a = 0,557

b = -0,510

d = -0,145

f = 1.457

5.4 Deposition Rates

As mentioned previously, there were two different volumetric deposition rates that were investigated. The results obtained are discussed below.

Firstly, the total deposition rate which was calculated from the total area of the weld deposit (called the 'deposition rate') was analysed. The two factors having a significant influence on this parameter are the arc current and the preheat of the base material. This is as expected, since an increase in the arc current causes a higher burn-off rate of the electrode. An increase in the preheat means that a greater amount of the base material is melted with all other factors being equal, and increase the total area of the weld deposit. This also gives rise to a higher dilution and will be discussed elsewhere in this chapter.

These effects are represented graphically in Figures 5.4 and 5.5.

The calculated value for R-square (0,564) would seem to indicate that there are other factors which significantly affect the deposition rate, that have not been included in this study. Therefore, although the results discussed in this section do show trends in the deposition rate with differing values of arc current and preheat, it must be remembered that this is not an exhaustive analysis and further experimentation would be necessary if more detailed information or confirmation is required.

The results of the two regression analyses for deposition rate are given below, and show that the deposition rate depends more on the arc current than it does on the preheat. As expected, the results for the different arc polarities do not differ significantly.

$$\text{Log(Dep Rate)} = a\,\text{Log(A)} + e\,\text{Log(E)} + f$$

where, for electrode positive: $a = 1,338$

$e = 0.062$

$f = -1,040$

and for electrode negative: $a = 1,230$

$e = 0,051$

$f = -0,748$

From Table 4.10, it can be seen that the arc current,

arc voltage, travel speed, preheat and the arc polarity all have a significant effect on the effective deposition rate. The 'effective deposition rate' is calculated using only the area of weld metal above the surface of the base material. As discussed previously this is probably a more useful measure of deposition rate, since once a hardfaced component is worn down to this level it is usually hardfaced again to avoid the need for excessive build-up.

There are two significant interactions of the factors mentioned above. The first interaction is between arc current and arc voltage, and the second between arc voltage and travel speed. These interactions are represented graphically in Figures 5.6 and 5.7, and show some interesting relationships between the factors and the dependent variable.

Although an increase in the voltage gives rise to an increase in the heat input of the process, it is interesting to note that this does not necessarily mean an increased effective deposition rate. In both Figures 5.6 and 5.7 it is in fact shown that an increase in the arc voltage actually causes a decrease in the effective deposition rate. This is probably due to the increased dilution that occurs at higher voltages (see section 5.7 to follow=), together with the decrease in deposition efficiency as voltage increases.

At higher arc currents the increased electrode burn-off rate gives rise to a higher effective deposition rate as discussed before. This effect is enhanced by the reduced dilution and increased deposition efficiency at lower arc voltages and causes the interaction shown in Figure 5.6.

A decrease in the travel speed causes a drop in the level of dilution (see section 5.7) and gives rise to the interaction with arc voltage shown in Figure 5.7.

An increase in the minimum preheat once again gives rise to a small (approximately 7,5%) increase in the effective deposition rate as shown in Figure 5.8. The reason for this increase is not fully understood, but is thought to be due to a slight improvement in arc stability which in turn improves the deposition efficiency.

Perhaps the most interesting effect on the effective deposition rate is that caused by changing the arc polarity, since the theory which explains this effect has repercussions throughout the rest of this discussion. To fully understand this effect it is necessary to first consider the nature of the arc (35).

An arc is produced when an electric current flows through an ionized column of gas (or "plasma") between

two electrodes, The positive electrode (anode) is deficient in electrons, whilst the negative electrode (cathode) has an excess of electrons. An electric current is caused by the excess electrons of the cathode that move through the plasma to the anode in an effort to correct the imbalance. This in effect creates an excess of positive gas ions in the plasma which move to the cathode.

Most of the heat generated in the cathode area is caused by the positive ions striking the surface of the cathode, whilst the heat at the anode is generated mainly by the electrons which are accelerated through the plasma by the arc voltage.

The hottest part of the plasma is the central portion where the accelerated motion and constant colliding of the excited gas atoms is the most intense. The outer portion, or arc flame, is somewhat cooler and consists of recombining gas molecules that were disassociated in the central column.

The distribution of heat in the three zones (anode, cathode and centre) can be altered. A change in the arc length has the greatest effect on the arc plasma. Changing the plasma gas (ie. shielding gas or flux) can change the heat balance between the anode and the cathode. For example, when welding aluminium with TIG and argon gas, for a given electrode size, the arc

current can be increased by a factor of ten without melting the electrode when electrode negative is used instead of electrode positive. This indicates that more heat is generated at the anode than at the cathode. However, the opposite is known to be the case for both SAW and MMA (35), and this gives rise to a higher burn-off rate when the electrode is negative.

From the results obtained in these experiments it would seem as if most of the heat is generated at the cathode with this particular electrode type (this is probably also the case for most other flux-cored wires). Since the burn-off rate is increased in the electrode negative mode. the wire feed rate set on the wire feeder unit must be increased (when compared with electrode positive) to achieve the desired arc current. Thus this explains the reason for the increased effective deposition rate when the electrode is negative.

The regression analyses gave the following results which are consistant with the above discussion, although the effects of travel speed and preheat were not large enough to be significant in these analyses.

Log(Eff dep rate) = aLog(A) + bLog(B) + f

where, for electrode positive: a = 1,286
b = -0,519
f = -0,303

and for electrode negative: a = 1,173
b = -0,546
f = -0,025

5.5 Level of Porosity

The factors which have the most significant effect on the average level of porosity in the welds are the arc current, arc voltage and the arc polarity (Table 4.12). There is also an interaction between the arc voltage and the arc polarity. However, the value of R-square for this analysis (0,572) shows once again that there are obviously other unknown factors that have a significant effect on the level of porosity. The regression analyses performed also failed to show any reliably definitive relationships between porosity and the factors considered. The results discussed below must therefore be seen rather as merely guidelines which should aid in reducing the porosity levels of weld deposits of this nature.

Figure 5.9 shows an average decrease in the level of

porosity with an increase in arc current from 0,738 at 240 Amps to 0,306 at 360 Amps. The reason for this is not fully understood but it may be due to the increased heat input, which lengthens the solidification time of the deposit and gives the gas bubbles more time to escape. Also, since the electrode burn-off rate is increased there should be more shielding gas in the region of the arc caused by the vapourising of flux materials. This in turn would give a better shield of the arc from the atmosphere, and possibly decrease the level of porosity.

The interaction between arc voltage and arc polarity shown in Figure 5..0. indicates that the use of DCEN results in a much reduced level of porosity (especially at higher voltages) than with DCEP, whilst the influence of arc voltage on porosity depends on the arc polarity used. It is of note that an increase in voltage causes a marked increase in the porosity level when DCEP is used, but that an increase in voltage causes a slight decrease in the amount of porosity present when DCEN is used. It seems reasonable to suggest that this phenomenon is caused by a difference in shielding conditions and heat distribution in the arc when different arc polarities are used.

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The interaction between arc voltage and arc polarity shown in Figure 5.10, indicates that the use of DCEN results in a much reduced level of porosity (especially at higher voltages) than with DCEP, whilst the influence of arc voltage on porosity depends on the arc polarity used. It is of note that an increase in voltage causes a marked increase in the porosity level when DCEP is used, but that an increase in voltage causes a slight decrease in the amount of porosity present when DCEN is used. It seems reasonable to suggest that this phenomenon is caused by a difference in shielding conditions and heat distribution in the arc when different arc polarities are used.

## 5.6 Deposit Geometry

### 5.6.1 Deposit Width

The factors having the most significant effect on the width of the weld deposit include the arc current, arc voltage, travel speed,preheat and the arc polarity (Table 4.14). There is also a significant second order interaction between arc current and polarity, and a third order interaction between arc current, arc voltage and polarity.

This third order interaction is represented graphically in Figure 5.11, and shows that higher voltages generally give rise to wider deposits irrespective of the arc current. Also evident is that increasing current has a greater effect on the deposit width when using DCEP, than with DCEN. This seems due once again, to the cathode (in this case the base material) being the region where the most heat is generated, and this in turn melts a wider 'strip' of the base material. The effect is enhanced at higher arc voltages as shown in Figure 5.11. With the electrode negative, most of the heat is generated at the electrode, and increasing the arc current has a far smaller effect on the deposit width. In fact it can be seen that at lower arc voltages (24V), the deposit width actually decreases with increased arc current, although the reason for this occurrence is unknown.

The deposit width decreases slightly with an increase in the travel speed (Figure 5.12). The reasons for this decrease are self evident.

Figure 5.13 shows that a small increase in the deposit width is caused by increasing the preheat from 20 to 150 degrees Centigrade. Once again, this is due to a higher proportion of the 'hot' base material being melted, giving rise to a wider weld pool. This is a small effect when compared with the other factors, however.

The results obtained in the regression analyses support the above discussion, and yield the following relationships between the variables.

$$Log(Width) = aLog(A) + bLog(B) + cLog(C) + f$$

where, for electrode positive: a = 0,967
b = 0,172
c = -0,306
f = -0,784

and for electrode negative: a = -0,243
b = 0,462
c = -0,360
f = 1,876

5.6.2 Deposit Height

The arc current, arc voltage,travel speed and arc polarity all have a significant effect on the height of the deposit above the surface of the base material (Table 4.16). There are also two second order interactions, one between arc current and arc voltage and the other between arc current and polarity; a third order interaction also exists between arc current, arc voltage and polarity.

It is interesting to note that the graphical representation of this third order interaction (Figure 5.14) shows almost exactly the opposite effects of the factors on deposit height to those shown in Figure 5.11 for deposit width. Increasing arc current has a far greater effect on the deposit height when DCEN is used. Also, the use of lower voltages gives a generally much higher deposit.

The reason for the arc current having more of an effect on the deposit height when DCEN is used is probably once again due to the heat generated at the cathode (electrode wire). The burn-off rate increases with an increase in the arc current. This molten metal falls as droplets onto the weld pool, and the surface tension keeps them from 'spreading out' on the surface of the base material before they solidify, giving rise to a higher deposit.

The reasons for the small decrease in deposit height with increasing travel speed (Figure 5.15) are self evident.

The results of the regression analyses given below show quite different results for the different arc polarities, especially as regards the intercept and amperage coefficients.

$$Log(Height) = aLog(A) + bLog(B) - cLog(C) + f$$

where, for electrode positive: a = 0,182
b = -0,501
c = -0,766
f = 2,663

and for electrode positive: a = 0,879
b = -0,587
c = -0,832
f = 1,350

5.6.3 Depth of Penetration

The analysis of variance for the depth of penetration has an R-square value of only 0,456 which indicates that the major factor(s) affecting the penetration was not considered in this analysis. The results of this analysis are nevertheless included in this discussion

since they do reveal a few trends in the effects of some factors.

The factors having a significant effect on the depth of penetration are the arc current, travel speed, preheat and the arc polarity. Figure 5.16 shows that on average an increase in the arc current causes a corresponding increase in the depth of penetration. It is thought that this is due to the increased heat input which melts the base material to a greater depth. An increase in the travel speed decreases the heat input, and this would explain the decrease in the depth of penetration shown in Figure 5.17. As expected, an increase in the preheat also gives rise to an increase in the penetration depth as shown in Figure 5.18.

Changing the arc polarity from DCEN to DCEP also causes an increase in the average depth of penetration from 2,10mm to 2,36mm. This is once again thought to be due to the differing heat distributions that occur with different arc polarities as explained in section 5.4.

The results of the regression analyses performed on the depth of penetration are given in Tables 4.29 and 4.37. However, due to the low R-square values obtained in these analyses and their relative unimportance, they are not discussed in this section.

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## 5.7 Dilution

As discussed previously in this thesis, the dilution of the deposit is of great importance in any hardfacing operation, and for maximum wear resistance the dilution should be kept to a minimum for any given electrode. From Table 4.20, the factors having the most significant effect on the dilution include the arc current, arc voltage, travel speed, preheat and the arc polarity. There is also a second order interaction between the arc current and polarity.

Figure 5.19 is a graphical representation of the interaction between the arc current and the arc polarity. This is probably the most important result obtained during this entire experimental programme, since it shows that an increase in the arc current can actually significantly decrease the dilution if electrode negative arc polarity is used. This in turn means that if DCEN is used, it is possible to maintain a high level of deposition efficiency and deposition rate whilst still keeping the dilution to a minimum. All of these factors help to improve the economic feasibility of a hardfacing process.

The limits to this improvement in deposition rate and efficiency, as well as dilution will only be determined through further research in this field. The maximum practical setting of arc current will however be

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limited by arc stability and heat input considerarions which are important when hardfacing small components or susceptible materials (eg. high manganese steels).

When DCEP is used, Figure 5.19 shows that, as expected, the dilution of the weld metal is increased by an increase in the arc current, although the magnitude of this increase is small when compared to the changes that occur with DCEN. This interaction between arc current and polarity is also thought to be due to the distribution of heat between the anode and cathode as described in section 5.4.

As expected, an increase in the arc voltage causes a marked increase in the dilution of the weld metal. This effect is shown in Figure 5.20.

An increase in the travel speed gives rise to a small increase in the average dilution as shown graphically in Figure 5.21. A decrease in the travel speed means that a higher proportion of the arc energy is directed onto the already molten weld pool, and less onto the 'exposed' base material. This means that less of the base material is actually melted, and the dilution decreases.

The percentage dilution increases with an increase in the preheat (Figure 5.22). The reason for this is obviously due to the increase in the amount of 'hot'

base metal that is melted for the same energy input from the arc.

The regression analyses performed on the dilution data show two very different sets of results for the different arc polarities. These results show which of the factors are the most important in determining the expected level of dilution. However, the values of R-square (or the correlation) for the two cases also differ substantially (0,789 for DCEP and 0,408 for DCEN). This would suggest that only the regression results obtained for the DCEP process can be relied on with any degree of certainty, although the regression results for the DCEN process do show the inversely proportional relationship between arc current and dilution.

For electrode positive,

$$Log(Dilution) = bLog(B) + cLog(C) + eLog(E) + f$$

where: b = 0,426

c = 0,373

e = 0,033

f = 0,017

gative,

aLog(A, + f

-0,672

3,172

.8 Deposit Hardness

The anal_sis of variance (Table 4.22) shows that the arc voltage, preheat and arc polarity are the factors having the greatest effect on the deposit hardness. There is also an interaction between the arc voltage and the polarity, as depicted in Figure 5.23. These results show that the hardness of the deposit is related to the dilution, although not as directly as was first thought, since the analysis of variance results do not correlate completely with those obtained for dilution.

The interaction obtained is between arc voltage and polarity (Figure 5.23), and not as expected between arc current and polarity as in the case of dilution. This is probobly due to the reduced efficiency in the transfer of the various alloying elements across the arc when the arc voltage is increased. This would in

turn reduce the percentage alloy cont[illegible] metal, and thereby decrease the depos[illegible]

The deposit hardness is increased sub[illegible] changing from electrode positive to electrod[illegible] This is thought to be mostly due to the reduce[illegible] dilution which occurs when using the DCEN pro[illegible]

As expected, an increase in the preheat of the substrate causes a small but significant decrea[illegible] the deposit hardness (Figure 5.24). This is probabl[illegible] due to the combined effects of an increase in dilutio[illegible] and a decrease in the cooling rate experienced b[illegible] preheated sample.

The results from the regression analyses performed al[illegible] agree with the above discussion and serve to highligh[illegible] the most important factors in estimating the deposit hardness.

$$Log(HRc) = bLog(B) + eLog(E) + f$$

where, for electrode positive: b = -0,300
e = -0,023
f = 2,144

and for electrode negative: b = -0,075
e = -0,023
f = 1,866

Figures 5.25 and 5.26 show the results of linear regression analyses that were performed on the hardness (HRc) versus dilution data for the DCEP and DCEN processes respectively. The linear equations obtained from these analyses are as follows.

For electrode positive,

Hardness = -0,672 x (% Dilution) + 76,54

(Correlation coefficient = 0,881)

whilst for electrode negative,

Hardness = -0,147 x (% Dilution) + 57,02

(correlation coefficient = 0,528)

It would seem from the above correlation coefficients

that the deposit hardness for the DCEN process is less predictable than for the DCEP process. However, it should be noted that the range of deposit hardness for the DCEN process is a lot smaller than the range for the DCEP process (47,5 to 55,3 for DCEN and 36,0 to 53,1 for DCEP), and the average deposit hardness is also significantly greater for the DCEN process (51,9 for DCEN and 46,6 for DCEP). Also, the variation in hardness is much less for the DCEN process when compared to the DCEP process. The standard deviation of the hardness values for DCEN is 1,89, whilst for DCEP it is as high as 4,22.

5.9 Microstructure

The results given in Chapter 4 were obtained from a study of the differing microstructures that occur with increased dilution of the weld deposit. Figures 4.4 and 4.5 show the vastly different microstructures that occur at the opposite ends of the dilution scale. The dendrite size increases greatly with an increase in dilution, and this is accompanied by a marked decrease in the proportion of the inter-dendritic ternary eutectic present in the weld.

From the hardness results obtained (on unworked samples), it can be shown that this more dilute weld metal is significantly softer and will probably be more

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From the hardness results obtained (on unworked samples), it can be shown that this more dilute weld metal is significantly softer and will probably be more

resistant to impact but less resistant to abrasion than the harder, less dilute weld metal. This phenomenon highlights the possibility of using one electrode type to resist differing wear conditions, purely by adjusting the welding process parameters.

However, great care should be exercised if this approach is adopted, since, for example, it may not prove economically viable to 'over dilute' an alloy merely to improve its impact resistance. In this instance, it would probably be preferable to obtain a cheaper electrode wire (with a lower alloy composition), and deposit it under the optimum welding conditions for that electrode type. Also, from the experience gained in this experimental programme, it would seem that the level of control of the welding parameters required for such an approach would be beyond the ability of a lot of welding equipment combinations.

## 5.10 Wear Results

The abrasive wear test described before, gave the results (mass losses) listed in Table 4.3. The analysis of these results showed no correlation between the wear rate and any of the welding input variables, deposit hardness or the dilution. The reasons for this lack of correlation are not fully understood, but it is

thought to be due mainly to the variability introduced by the wear test itself, although this was controlled as accurately as possible.

These results serve to emphasize, once again, the care that should be exercised in applying data obtained from small scale laboratory wear tests to any field wear situation.

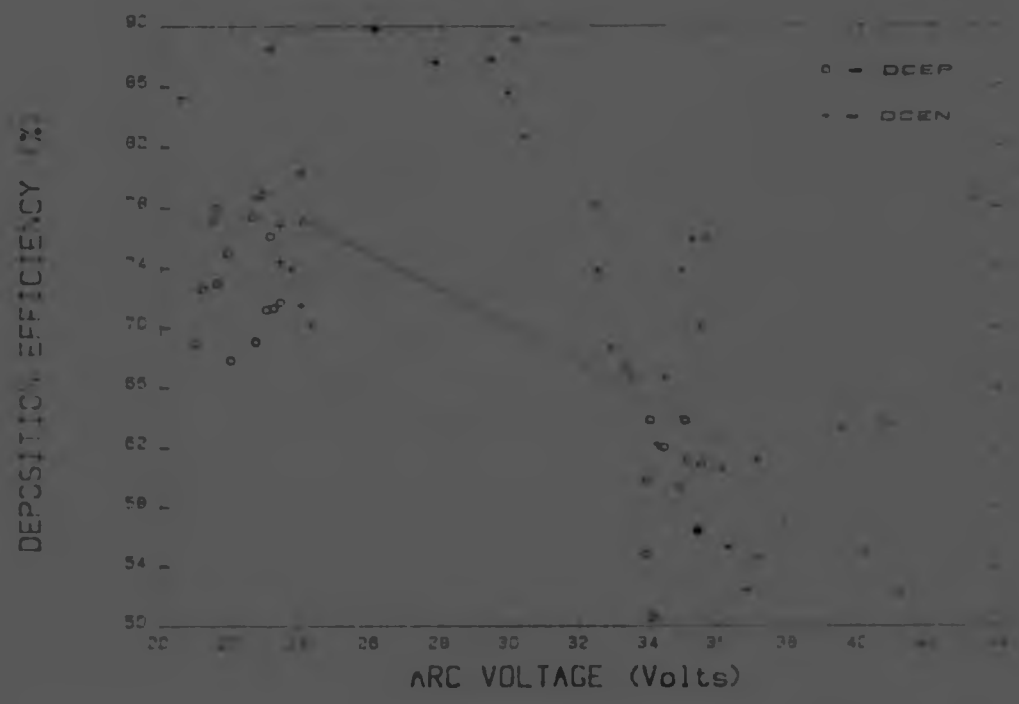



Figure 5.1 Graph showing all data points of deposition efficiency vs arc voltage for the discussion of factorial experiments.

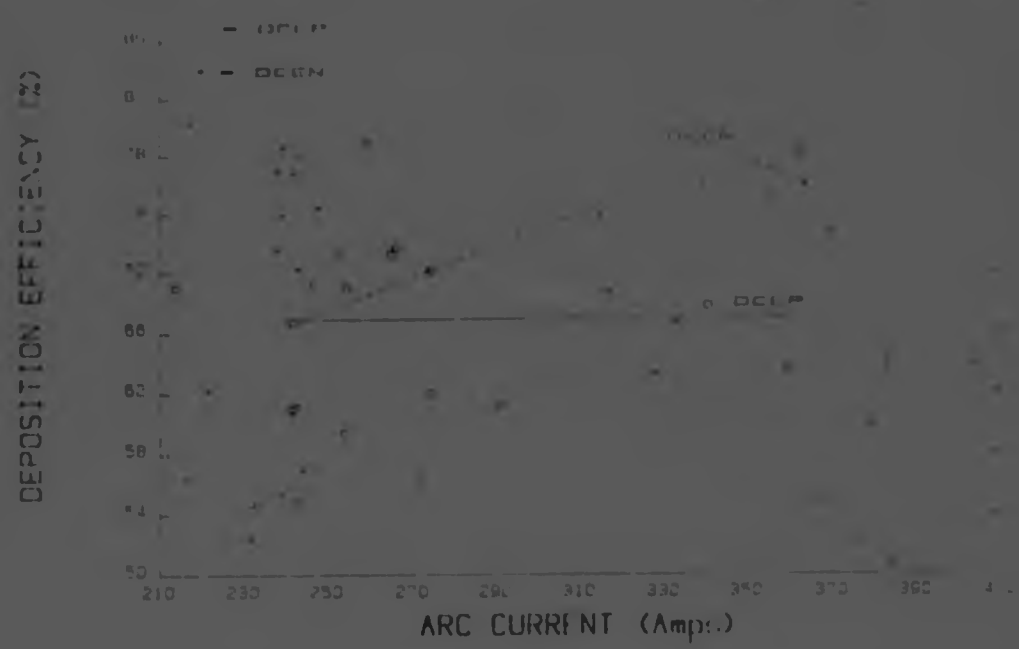



Figure 5.2 Graph showing all data points of deposition efficiency vs arc current and polarity for the discussion of interactions in factorial experiments.

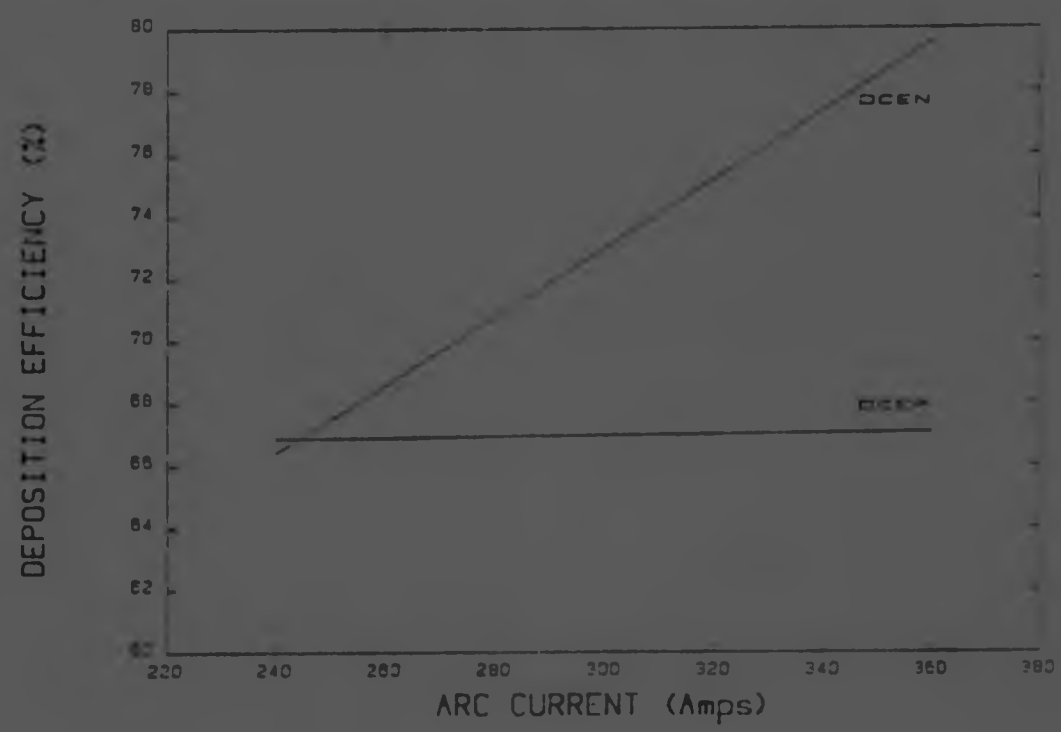



Figure 5.3 Graphical representation of deposition efficiency vs arc current and polarity.

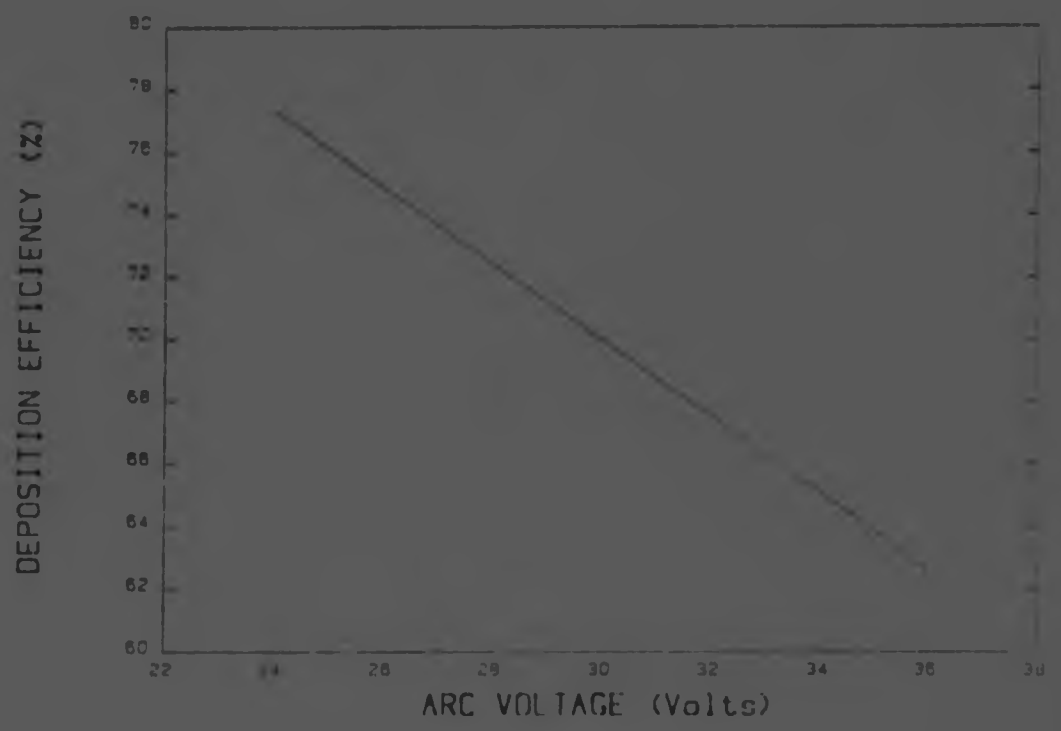



Figure 5.4 Graphical representation of deposition efficiency vs arc voltage.

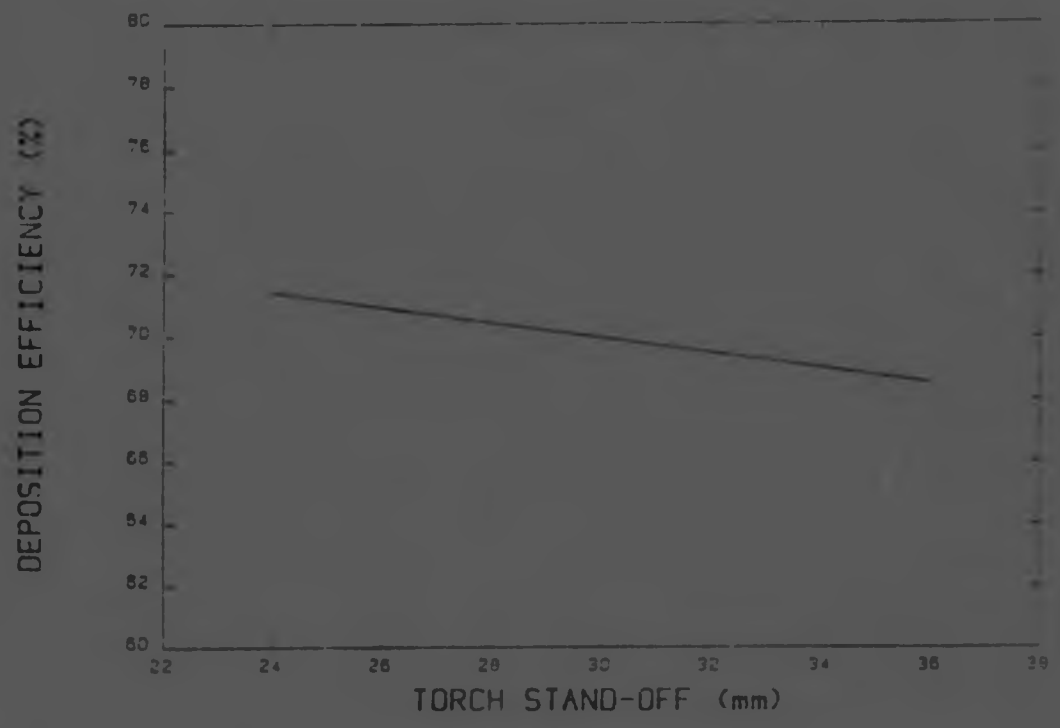



Figure 5.5 Graphical representation of deposition efficiency vs torch stand-off.

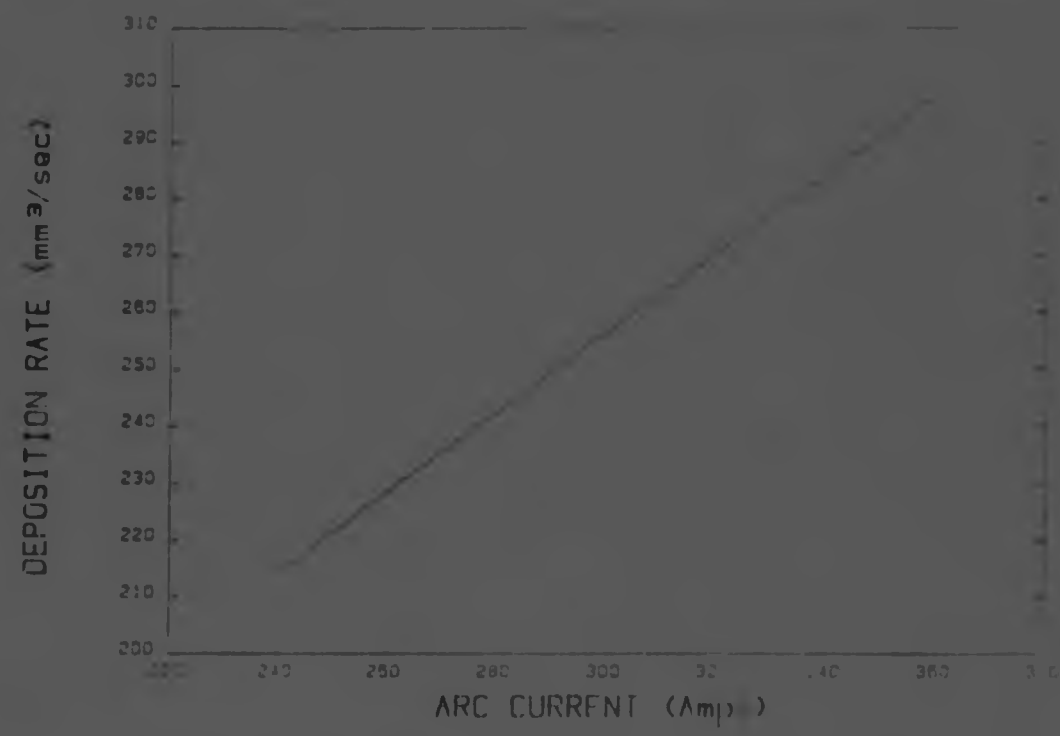



Figure 5.6 Graphical representation of deposition rate vs arc current.

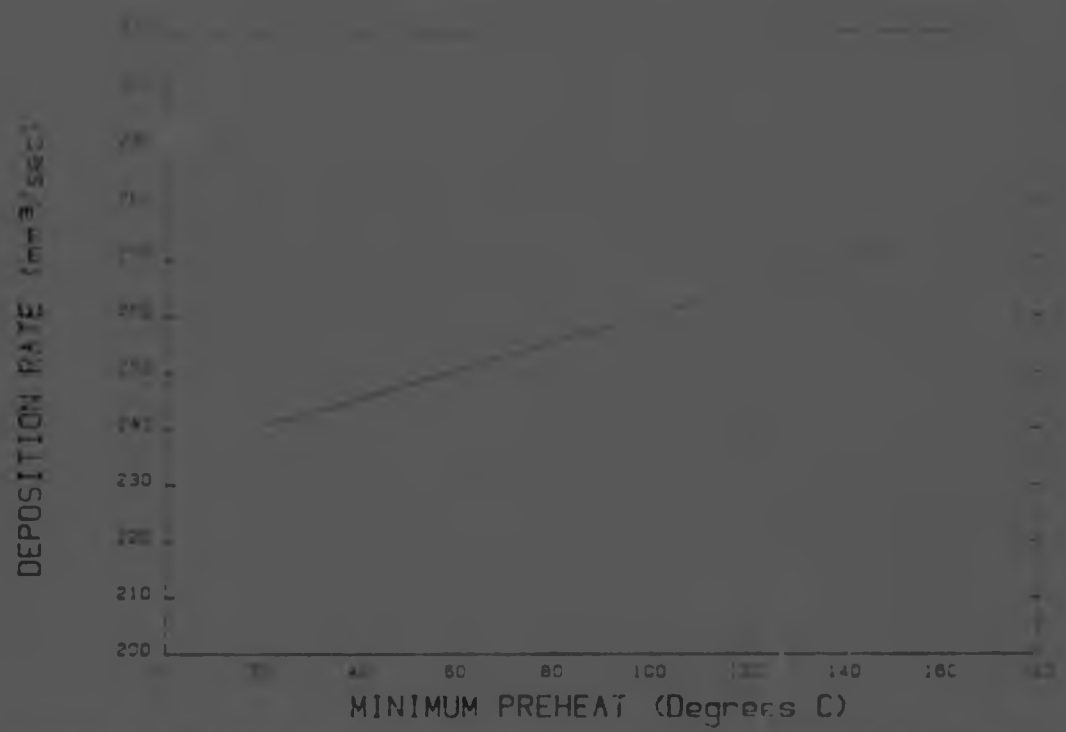



Figure 5.7 Graphical representation of deposition rate vs minimum pre-heat.

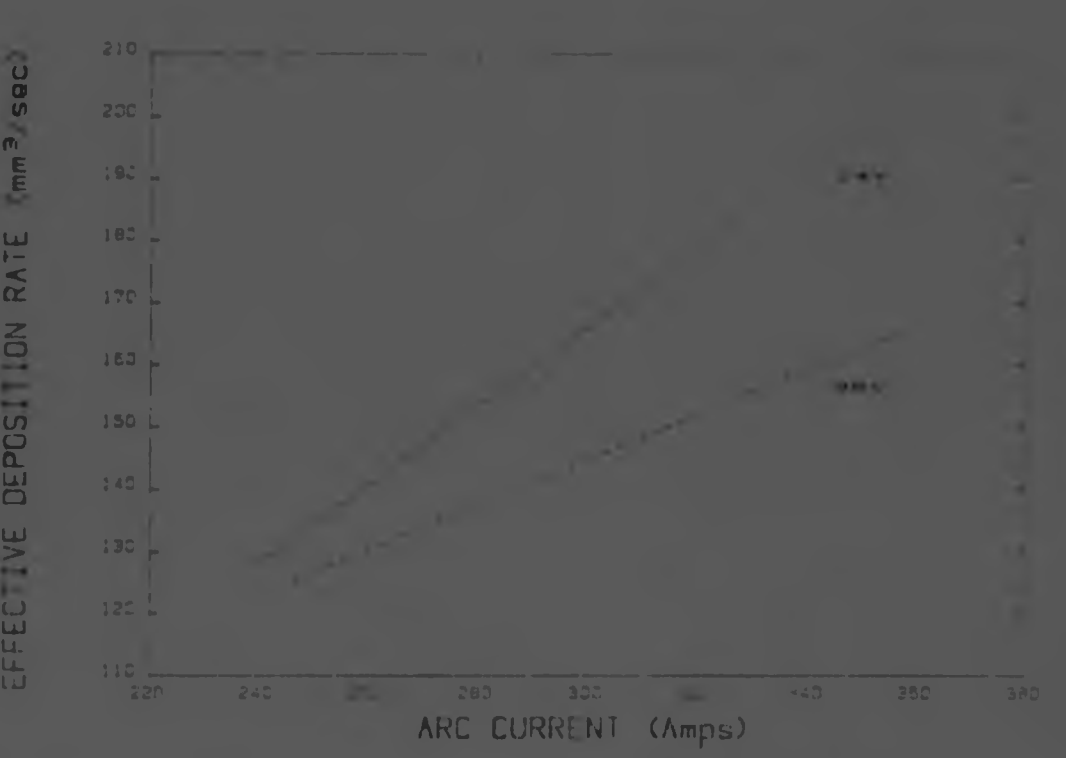



Figure 5.8 Graphical representation of effective deposition rate vs arc current for various

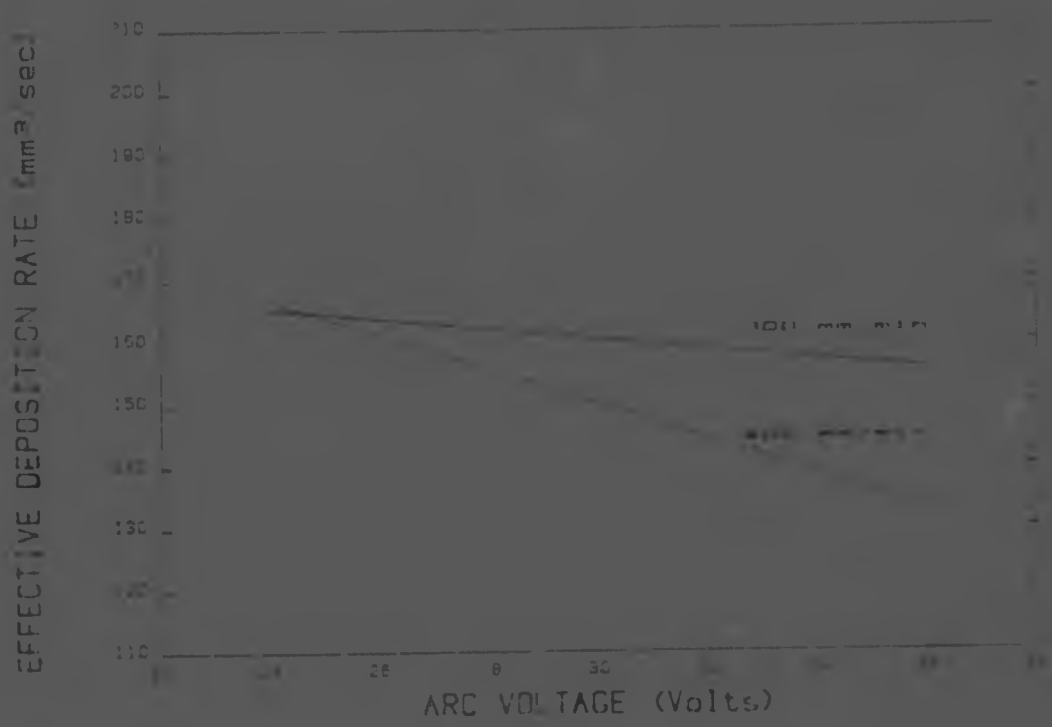



Figure 7.9 Graphical representation of effective deposition rate vs arc voltage and travel speed.

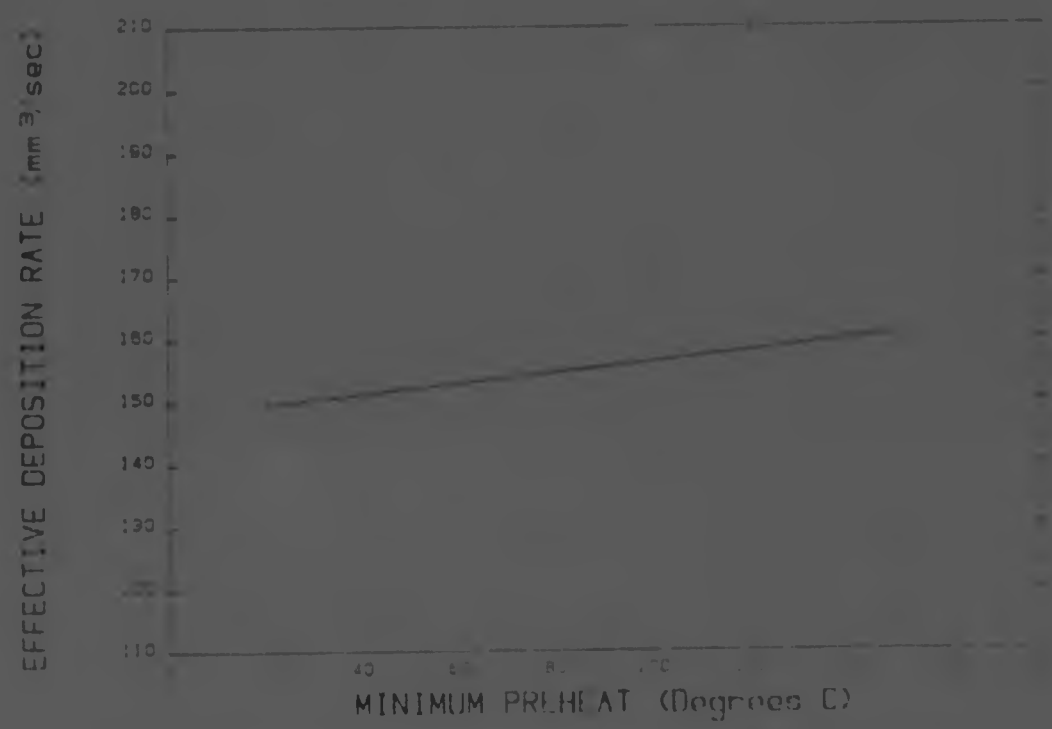
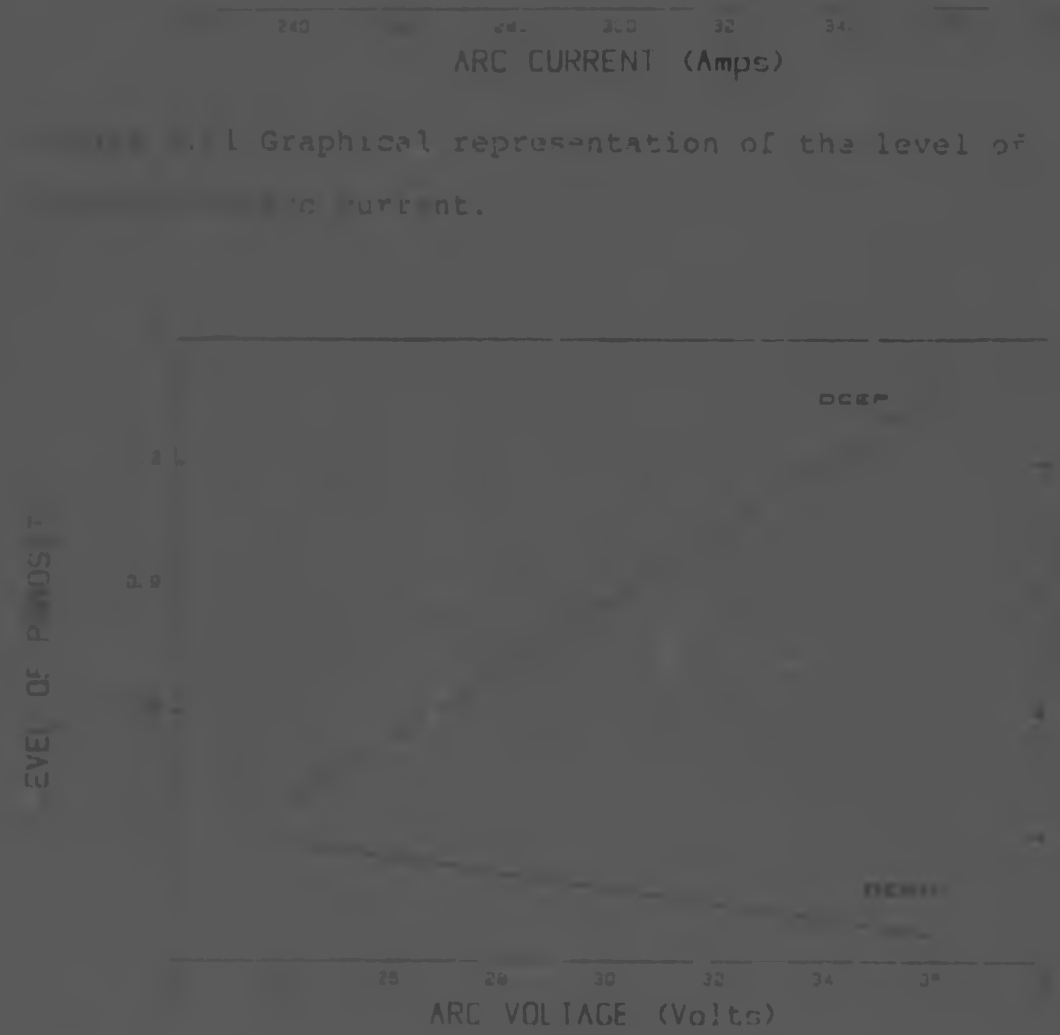
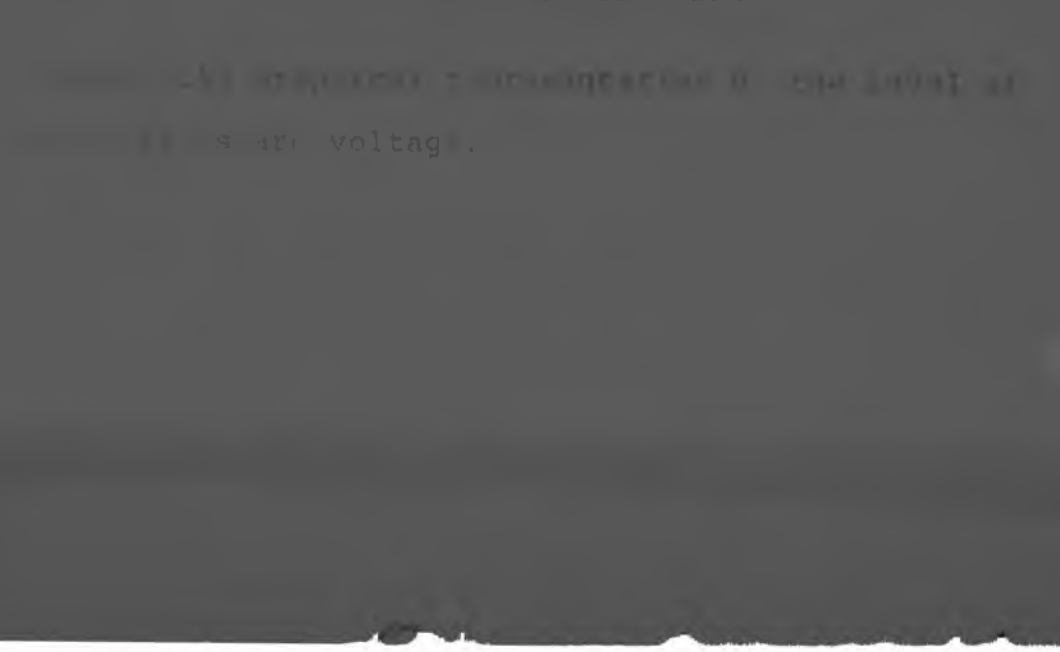



Figure 7.10 Graphical representation of effective deposition rate vs minimum preheat.




Graphical representation of the level of
c current.




s arc voltage.

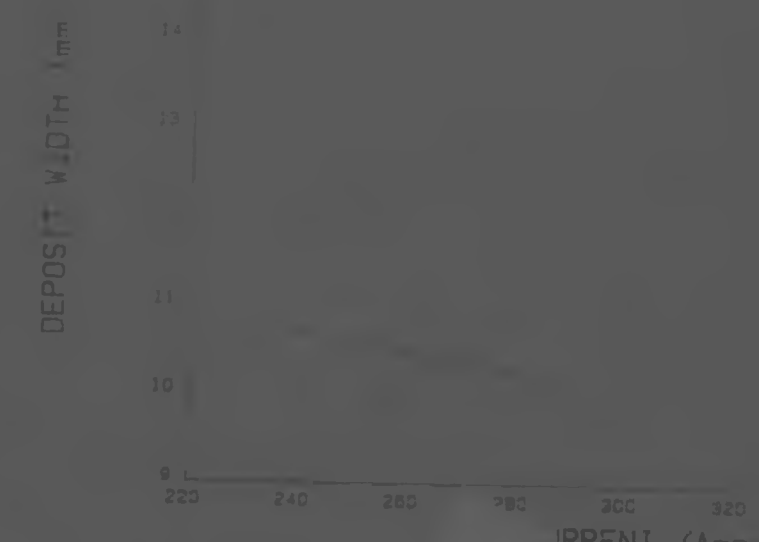
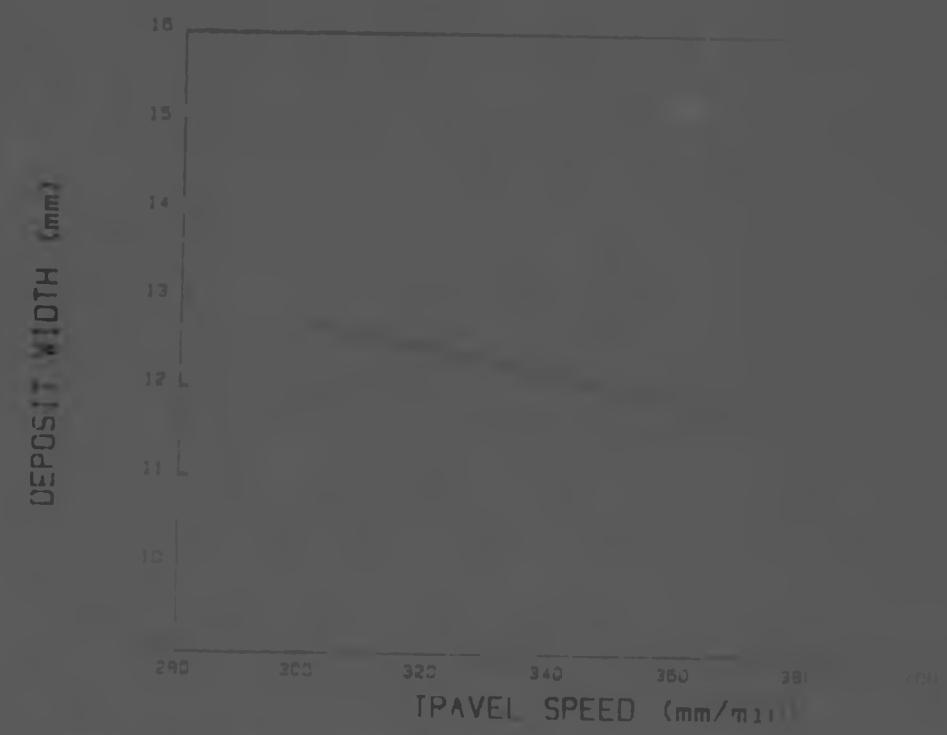



Figure [illegible]

vs arc current, [illegible] c voltag and pola[illegible]




[illegible]

vs travel speed.

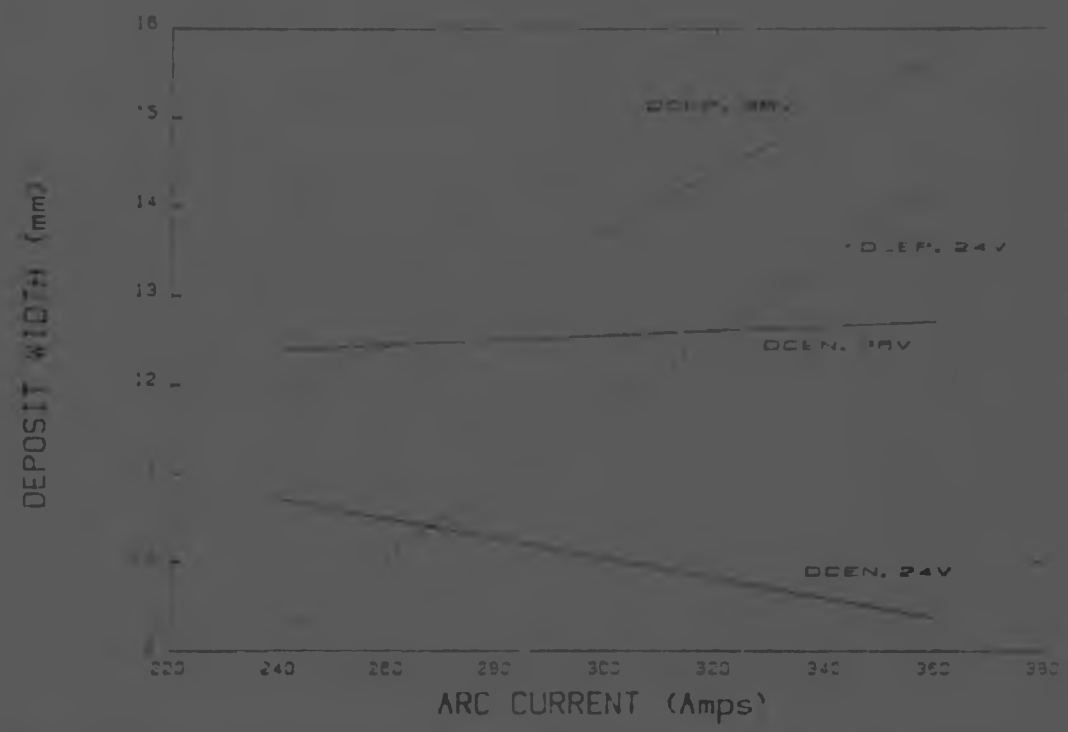



Figure 5.13 Graphical representation of deposit width vs arc current, arc voltage and polarity.

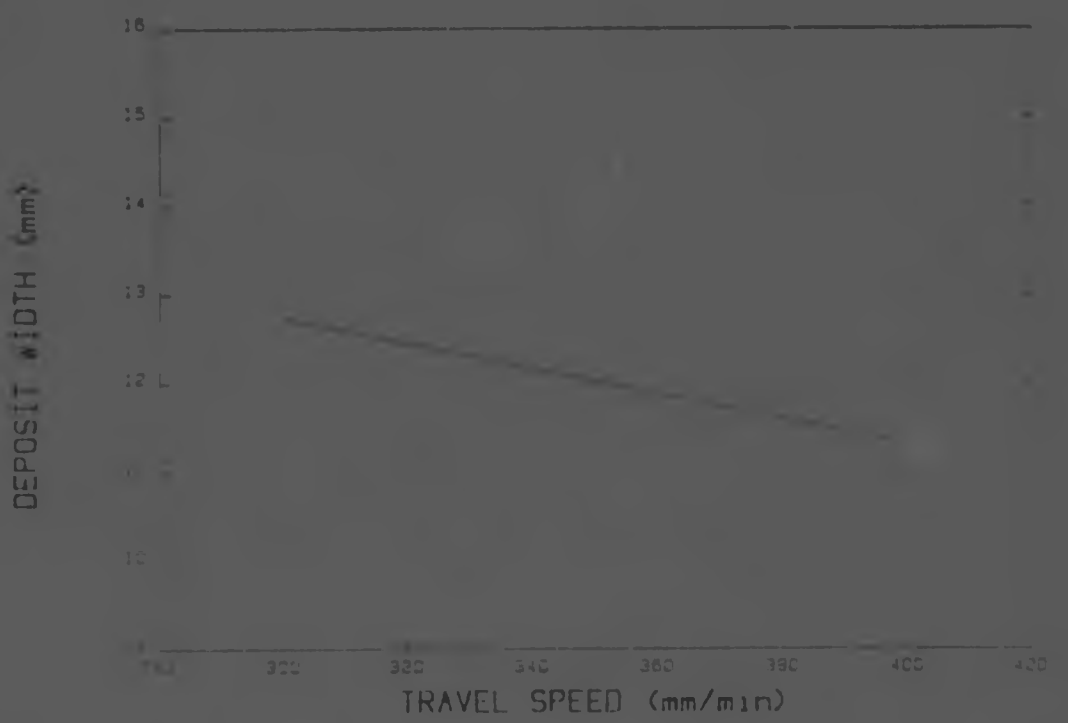



Figure 5.14 Graphical representation of deposit width vs travel speed.

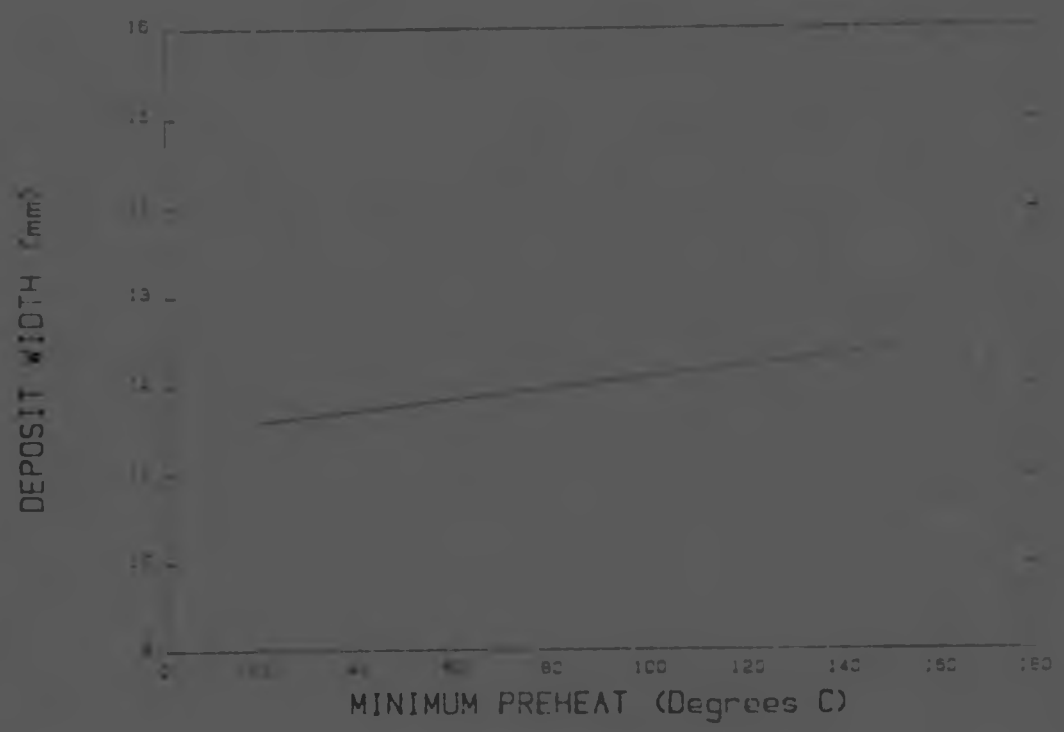



Figure 5.15 Graphical representation of deposit width vs minimum preheat.

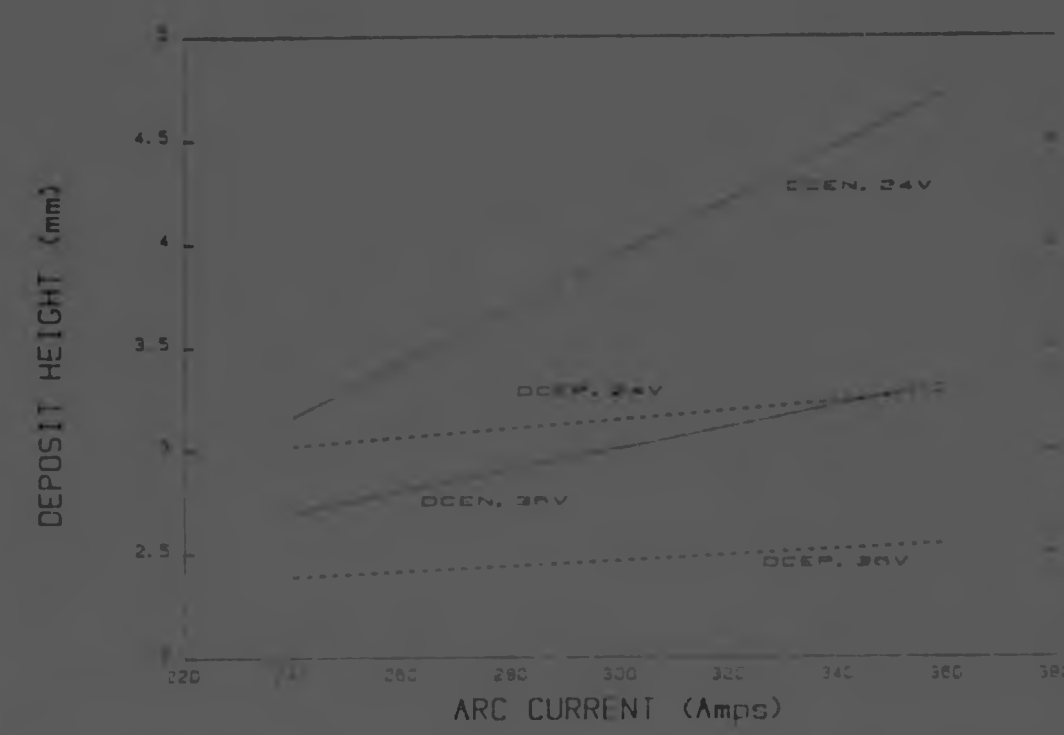



Figure 5.16 Graphical representation of deposit height vs arc current, arc voltage and polarity.

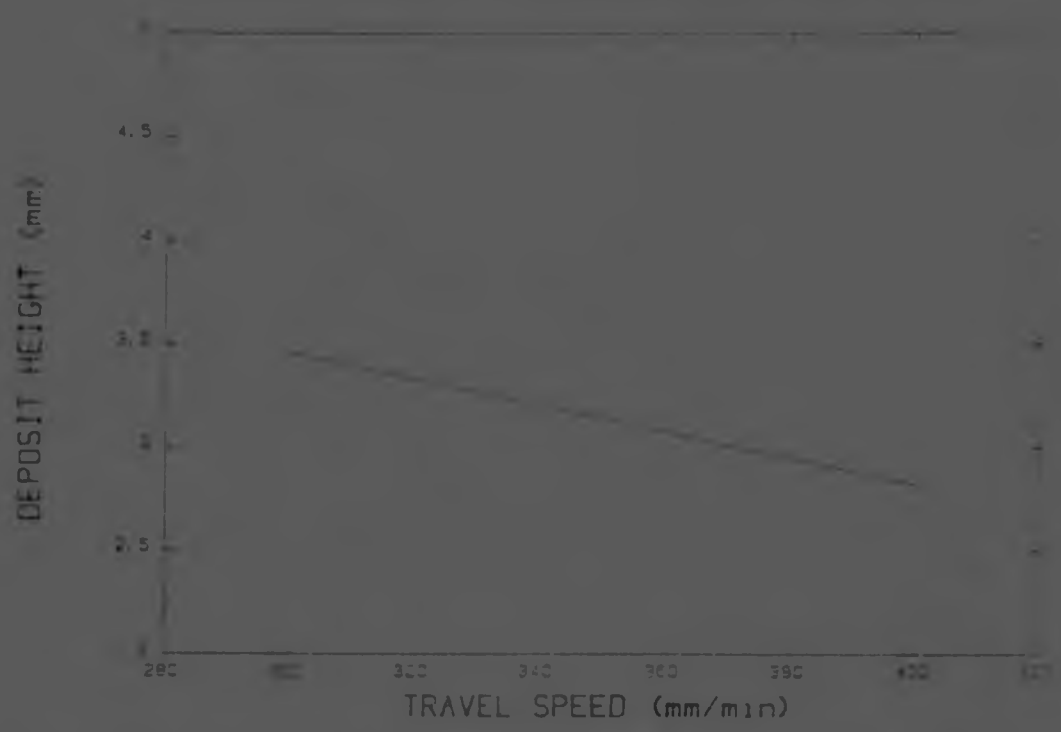



Figure 7.17 Graphical representation of deposit height travel speed.

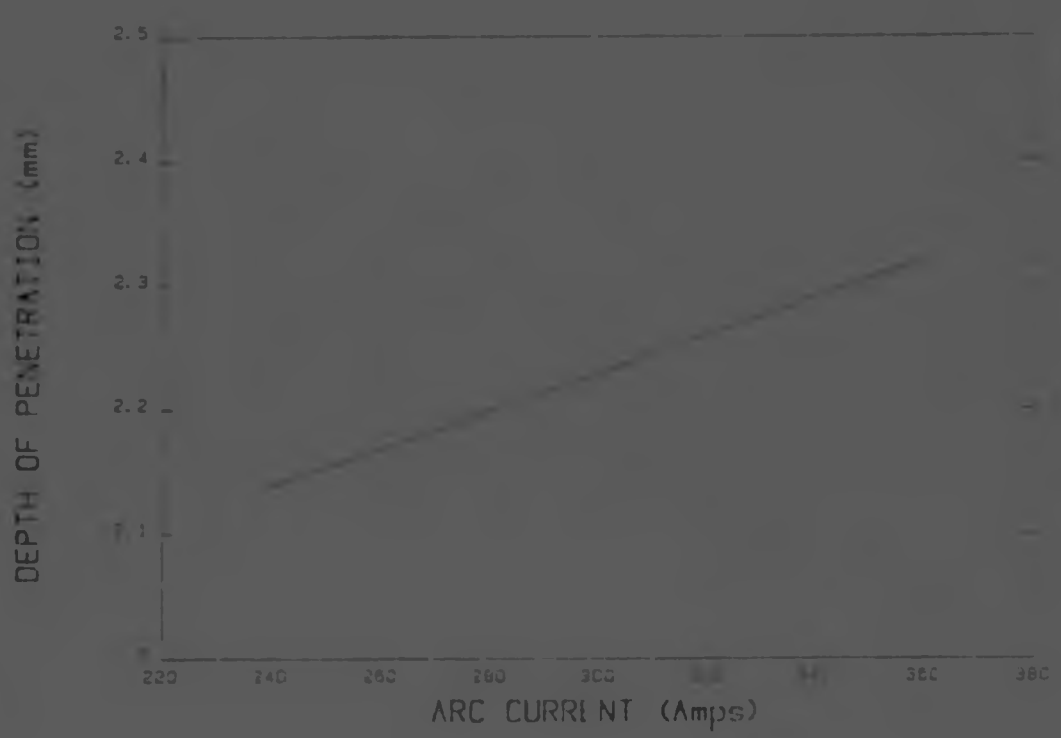



Figure 7.18 Graphical representation of depth of penetration vs arc current.

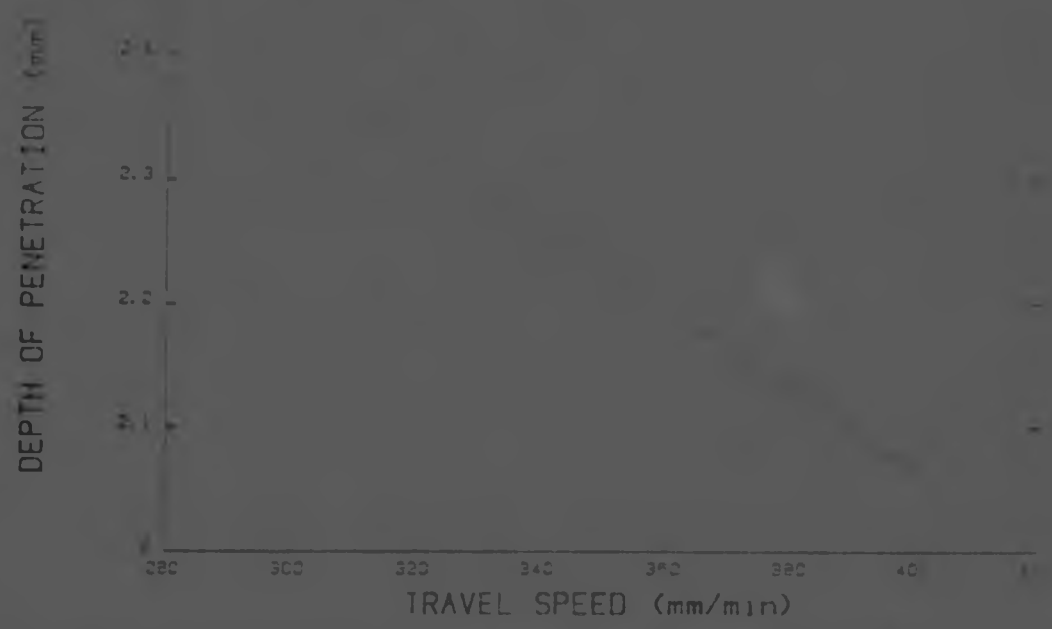



Figure 5.19 Graphical representation of depth of penetration vs travel speed

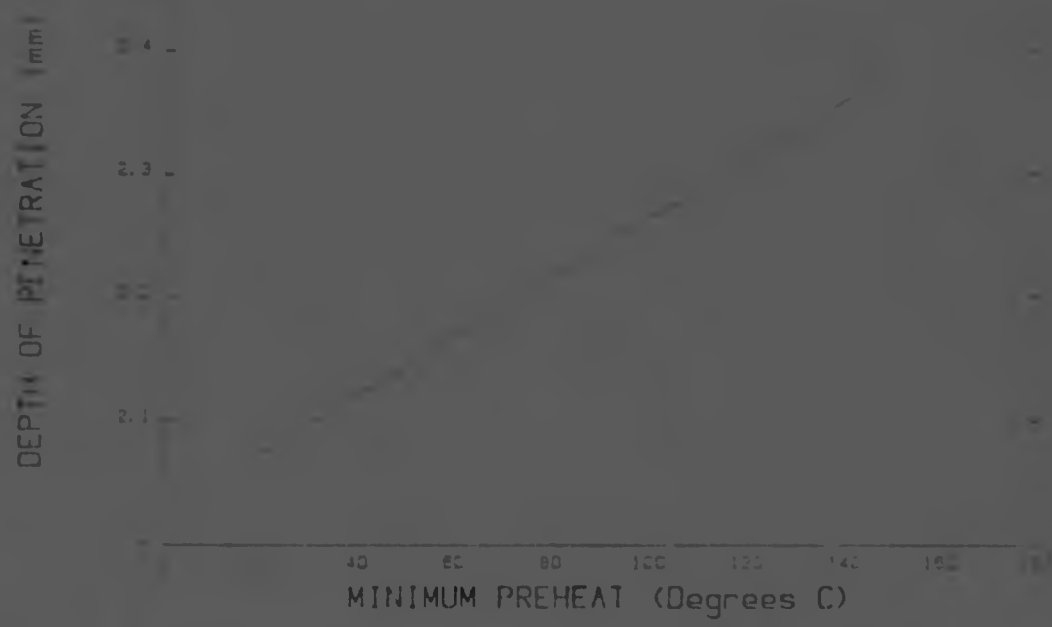



Figure 5.20 Graphical representation of depth of penetration vs minimum preheat

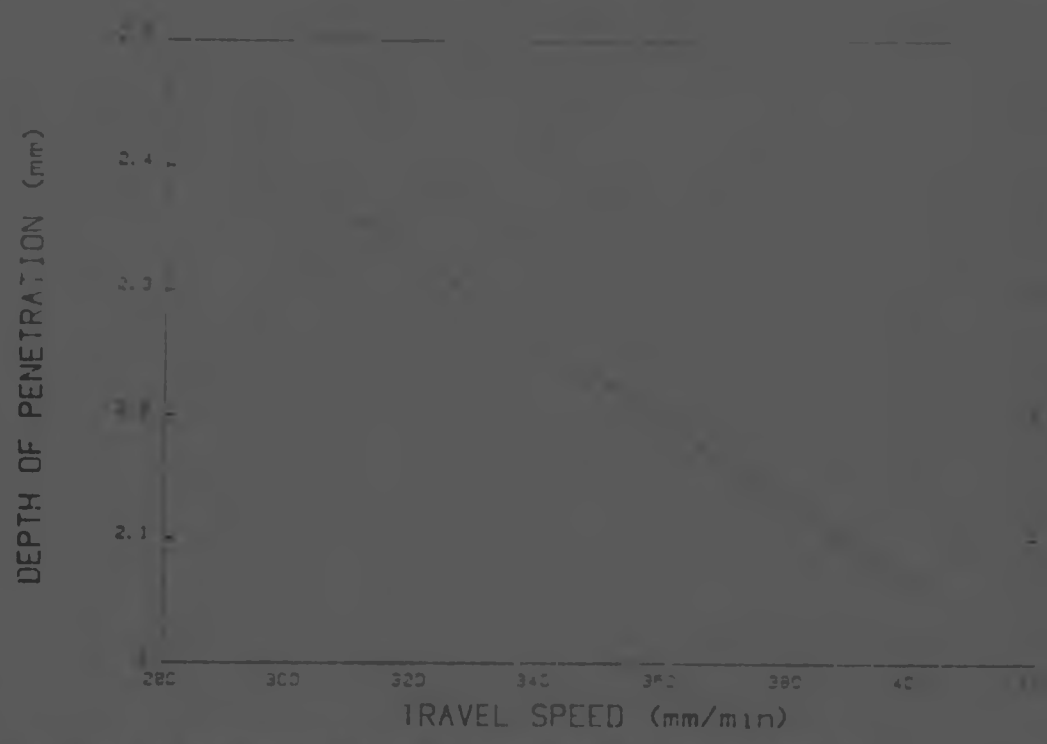



Figure 7.19 [illegible] depth of penetration vs travel [illegible].

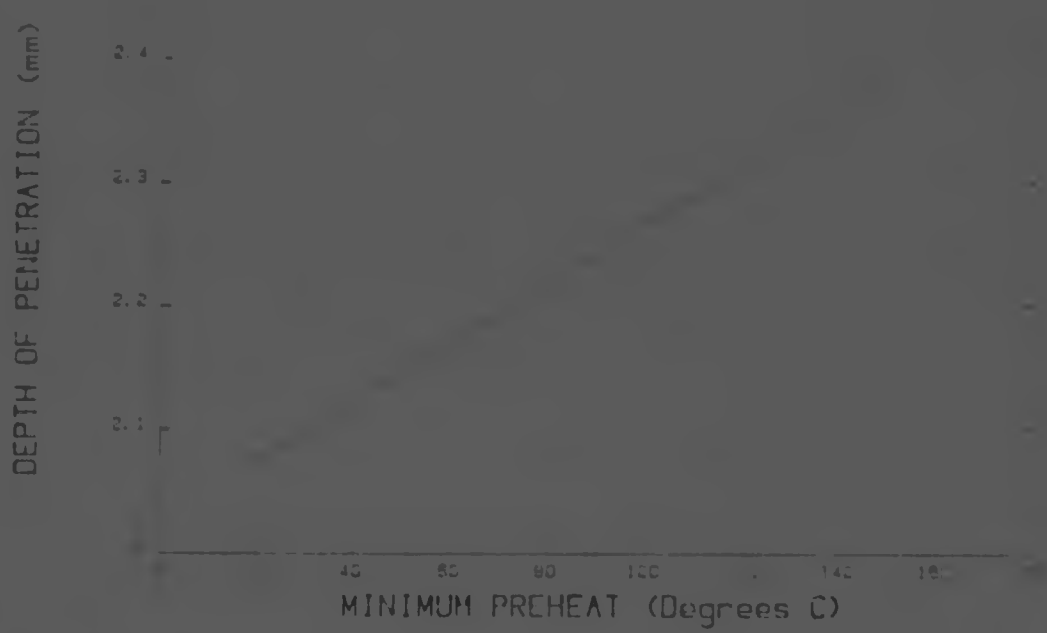



Figure 7.20 Graphical representation of depth of penetration vs minimum preheat.

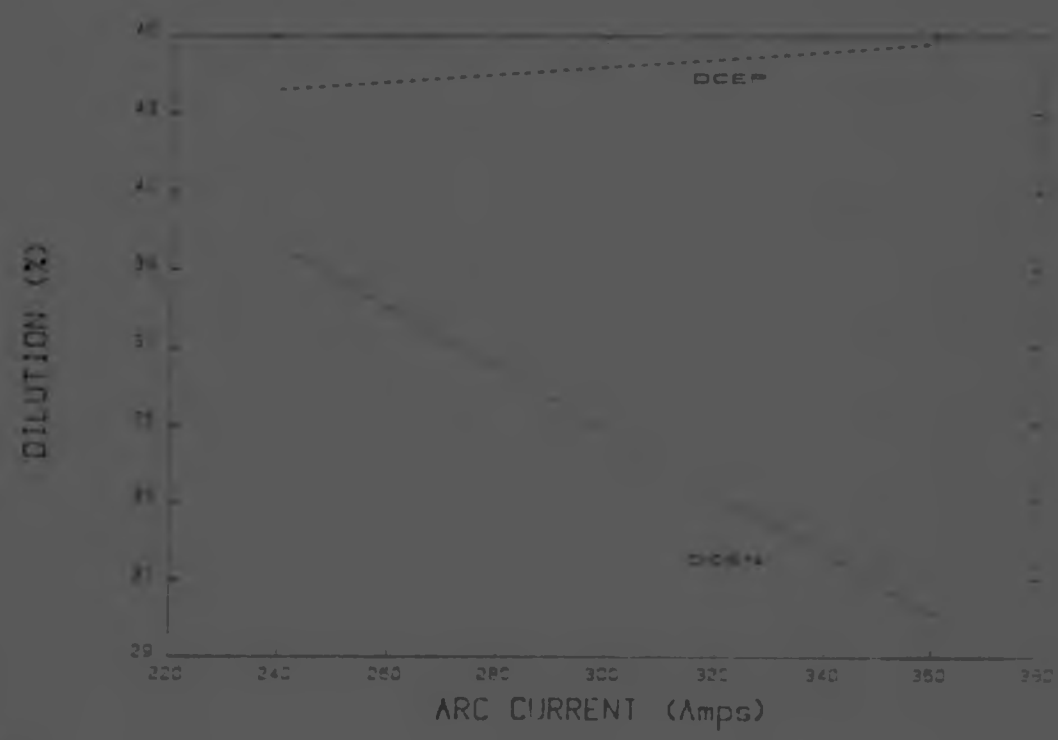



Figure 5.21 Graphical representation of dilution vs arc current for polarity.

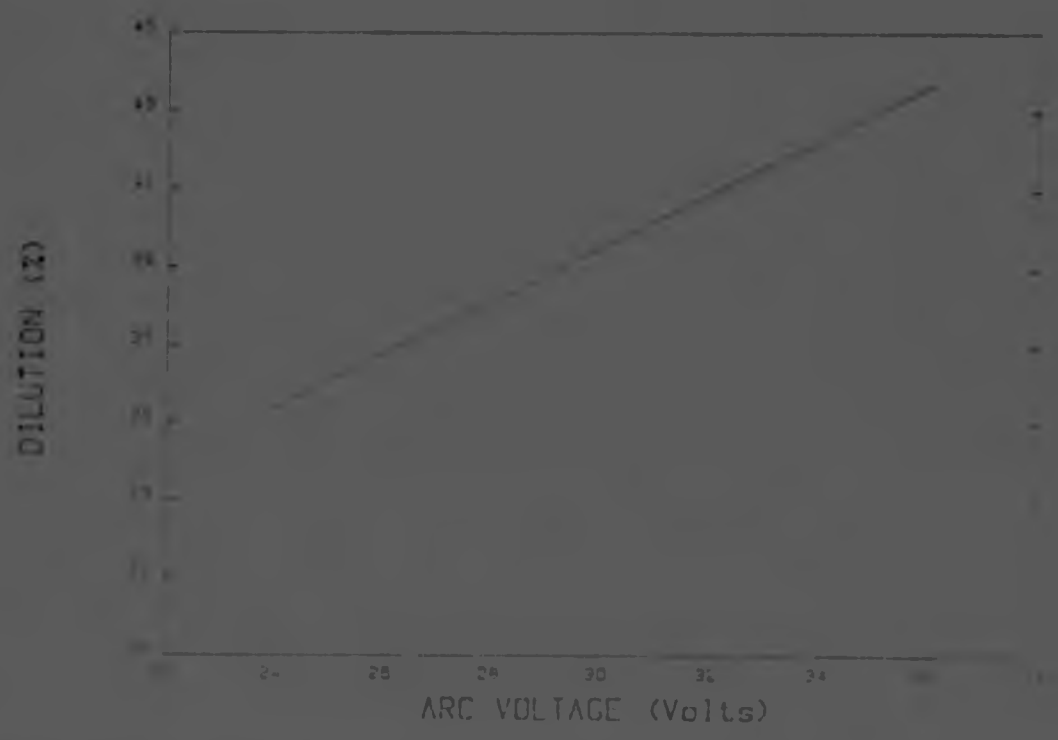



Figure 5.22 Graphical representation of deposit dilution vs arc current.

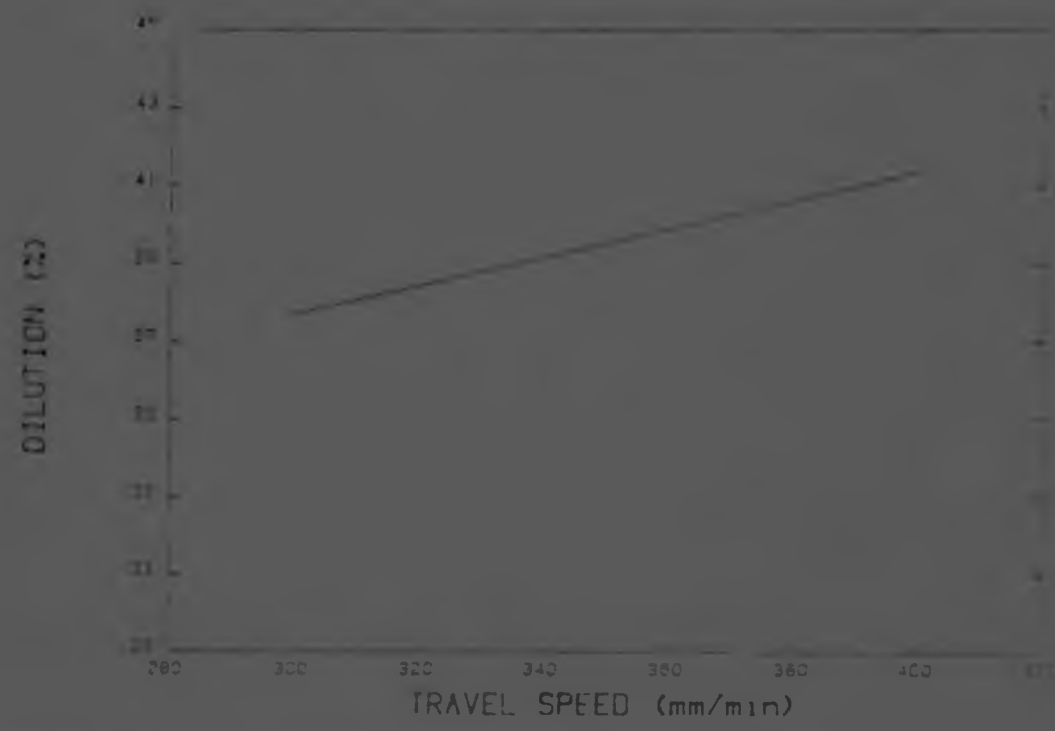



Figure 5.23 Graphical representation of deposit dilution vs travel speed.

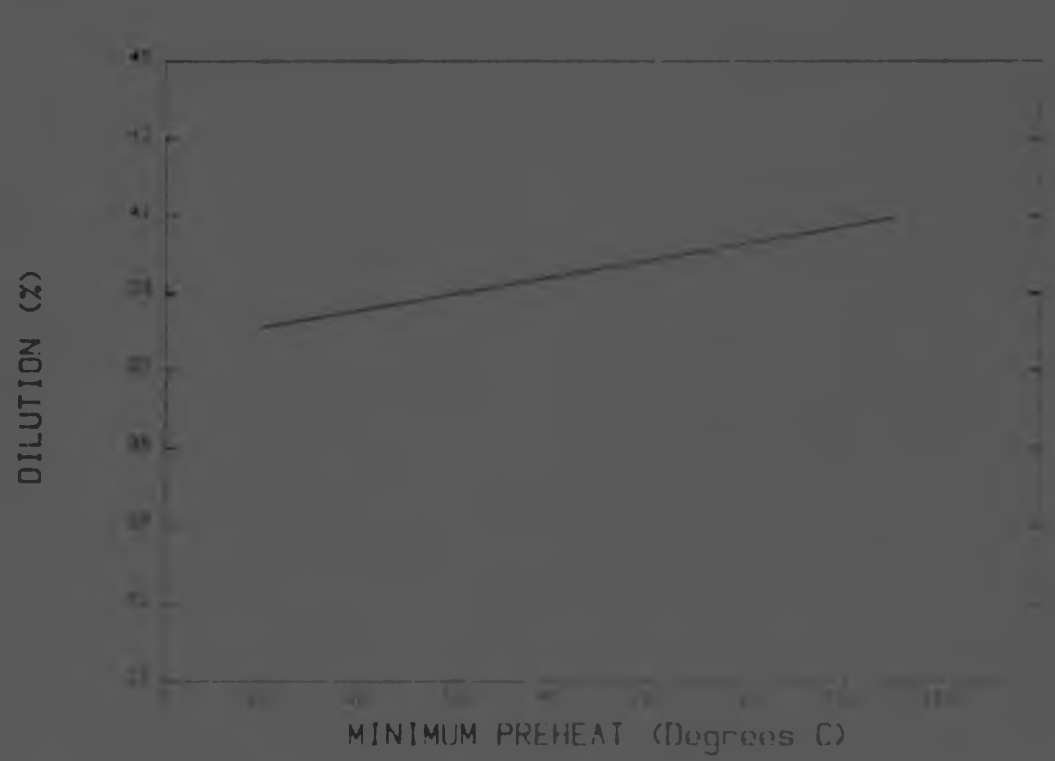



Figure 5.24 Graphical representation of deposit dilution vs minimum preheat.

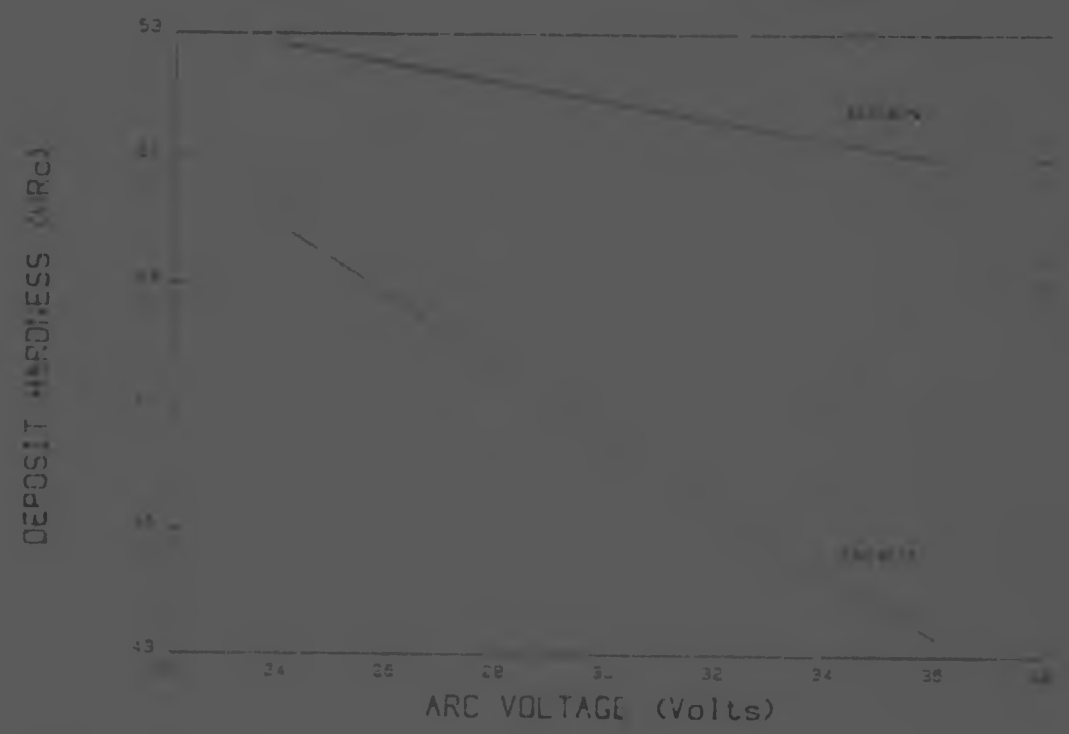



Figure [illegible] Graphical representation of deposit hardness vs arc voltage.

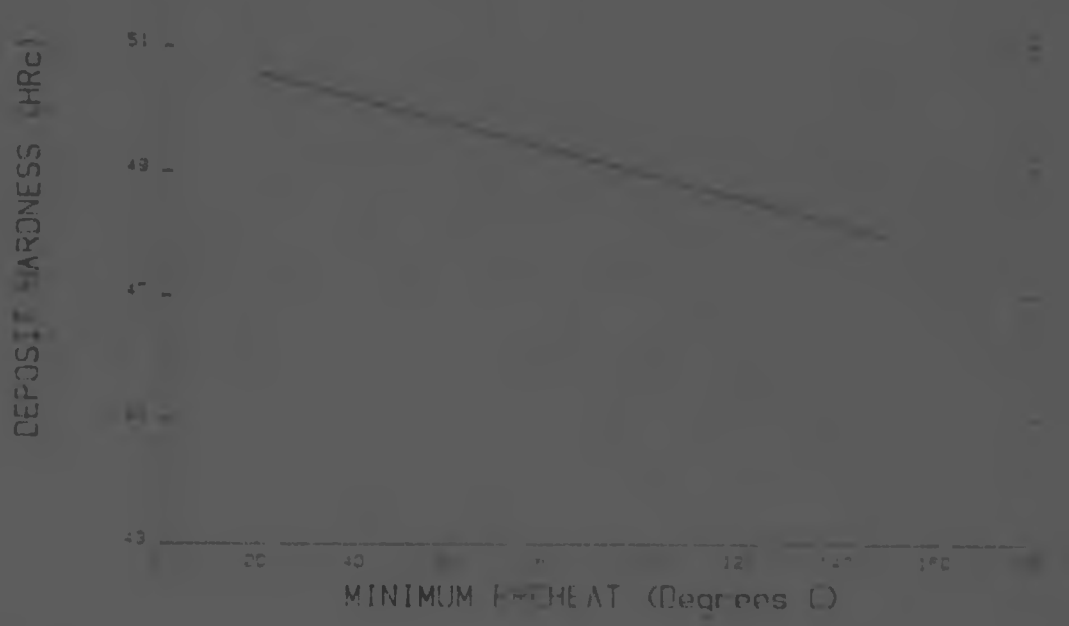



Figure [illegible].26 Graphical representation of deposit hardness vs minimum preheat.

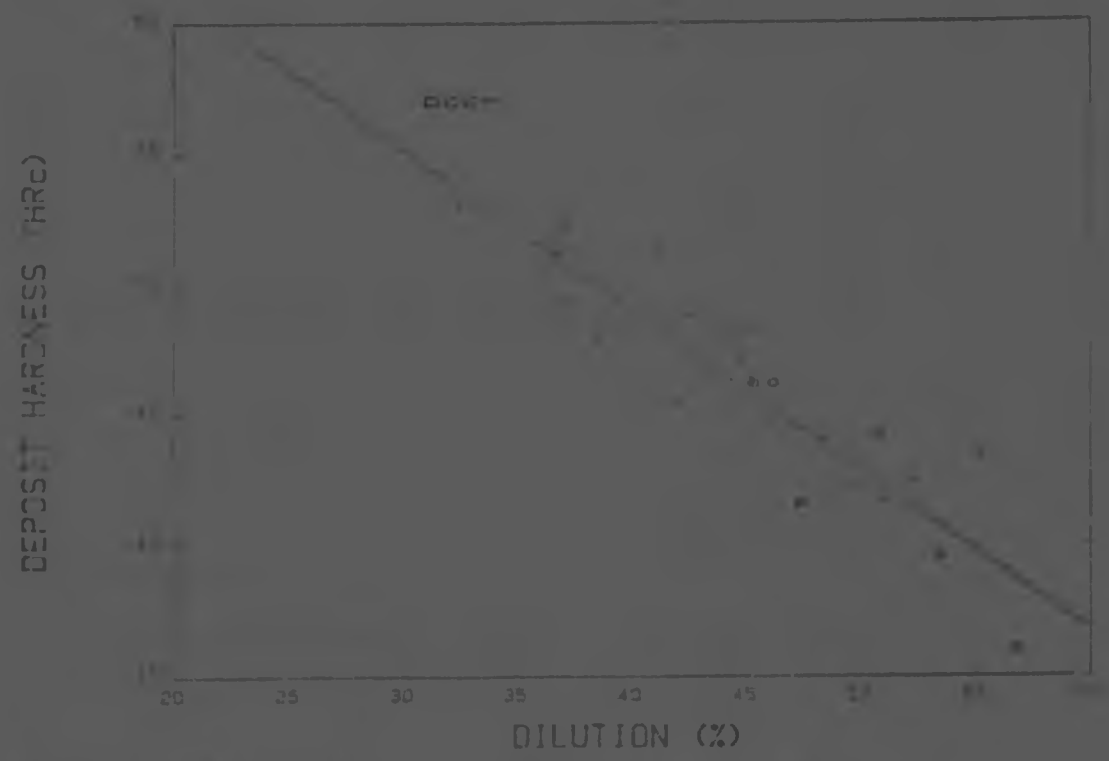



Figure 7.17 Graphical representation of deposit hardness against percentage dilution for electrode positive arc polarity.

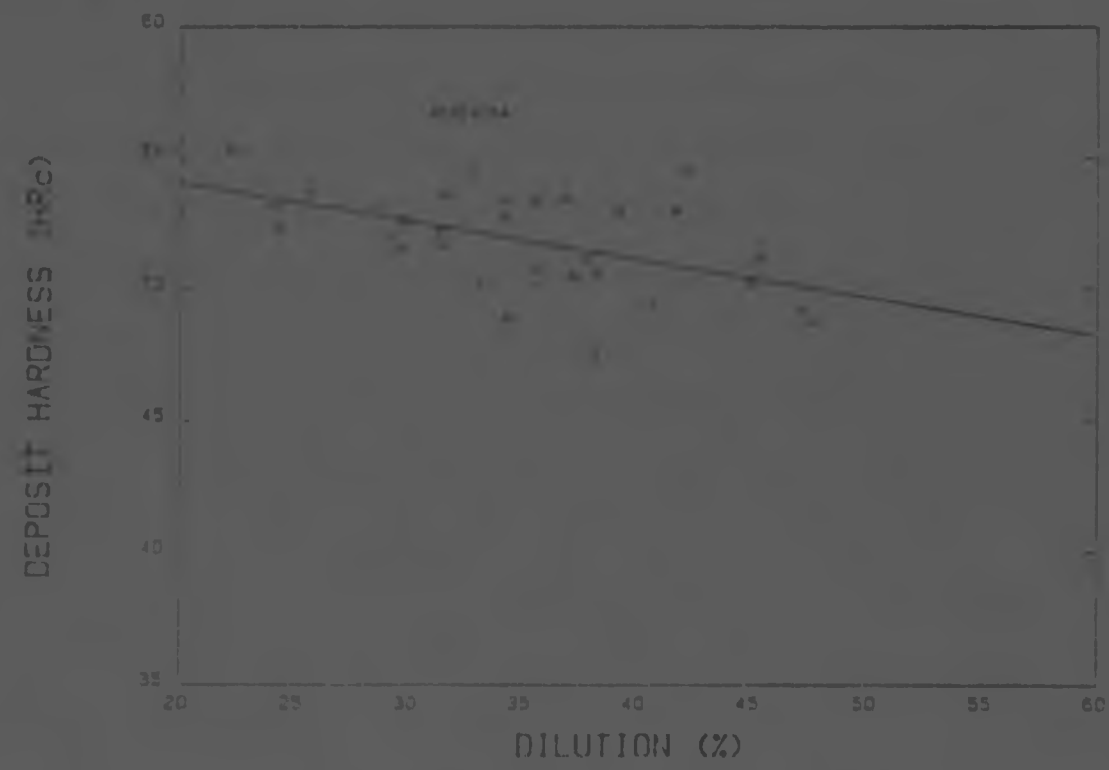



Figure 7.18 Graphical representation of deposit hardness against percentage dilution for electrode negative arc polarity.

# 6. CONCLUSIONS AND RECOMMENDATIONS

## 6.1 Introduction

In Chapters 1 and 2, the 'state-of-the-art' in modern arc welded hardfacing deposits was discussed. This highlighted the need for more objective research in the field of welding process variables. An experimental programme was set up as described in Chapter 3 to establish, in particular, the effects of arc current, voltage and polarity as well as travel speed, torch stand-off and substrate preheat on the wear resisting properties of a weld deposit. The experimental welds were deposited using a 2,8mm Cobalarc 100M flux-cored wire, under a wide range of welding conditions.

The results obtained in this programme are tabulated in Chapter 4, and the effects of the process variables determined with the aid of a computer analysis, are discussed in Chapter 5.

This final Chapter is a summary of the major conclusions reached during the project, together with recommendations to aid industrial manufacturers in correctly applying hardfacings of this type.

## ...NS AND RECOMMEND...TIONS

### ...ction

...ter 2, the 'state-of-the-art' in modern ...elded hardfacing deposits was discussed. This ...ghlighted the need for more objective research in the ...ld of welding process variables. An experimental ...rogramme was set up as described in Chapter 3 to ...stabl...n particular, the effects of arc current, ...oltage ...olarity as well as travel speed, torch ...and-o... ...ubstrate preheat on the wear resisting ...operties of a weld deposit. The experimental welds ... deposited using a 2,8mm Cobalarc 100M flux-cored ..., under a wide range of welding conditions.

...esults obtained in this programme are tabulated in ...hapter 4, and the effects of the process variables ...etermined with the aid of a computer analysis, are ...iscussed in Chapter 5.

... final Chapter is a summary of the major ...eached during the project, together with ...id industrial manufacturers in ...acings of this type.

The a... th...
factors which ...
deposits made w...
when depos...
travel speed an...
on the wel...
distance ...

...3 Arc Po...

There are a number ... electrode negative arc pol... electrode positive which is ... electrode suppliers. DCEN gives ... deposition efficienc..., especially ... currents, toge... with ... deposition rate.

A significant ... the weld metal ... from DCEP to DC..., ... with increases in v...

The use of DCEN also ... with a significantly lower ...

## 6.2 Welding Parameters

The arc current, arc voltage and arc polarity, are the factors which have the most marked effect on weld deposits made with the flux-cored arc welding process, when depositing a 2,8mm Cobalarc 100M electrode. The travel speed and preheat have only a secondary effect on the weld deposit, whilst the torch stand-off distance plays a very minor role.

## 6.3 Arc Polarity

There are a number of gains to be made by using electrode negative arc polarity, as opposed to electrode positive which is recommended by the electrode suppliers. DCEN gives rise to a much higher deposition efficiency, especially at higher arc currents, together with an increase in the effective deposition rate.

A significant drop in the level of porosity present in the weld metal occurs when the arc polarity is changed from DCEP to DCEN, and this effect is enhanced with increases in voltage.

The use of DCEN also gives rise to higher deposits, with a significantly lower dilution and a consequently

higher average hardness.

The only point against the use of DCEN, is the fact that this arc polarity generally gives rise to a somewhat narrower weld deposit. This would mean that more weld runs would be required to hardface a given surface, although the final deposit would be thicker and in some instances may obviate the need for a second layer of deposit. The narrowing effect of the DCEN process can to some extent be offset by increasing the voltage, although this must be done with extreme caution as it may be detrimental to other weld parameters.

It is therefore recommended that, in future, all flux-cored electrodes of this type be deposited with DC electrode negative (straight polarity), due to the many gains to be made as discussed in this report.

6.4 Arc Current

A higher arc current (approximately 360 Amps) must be used in hardfacing operations with electrodes of this type. Although this is in direct contrast with general hardfacing recommendations, it has been shown in this experimental programme that a higher arc current can be beneficial to the wear resistance of deposits of this nature, when DCEN is utilized.

An increase in arc current causes an increase in both the deposition efficiency and the deposition rate, and a decrease in the level of porosity present. There is also a substantial decrease in the dilution with increasing arc current if DCEN is used, and only a small increase in dilution with increasing arc current if DCEP is used.

Both the deposit height and the deposit width are increased (except for low voltage DCEN welding when width is decreased) by an increase in arc current. To obtain a flatter deposit it is preferable to increase the voltage rather than decrease the arc current.

## 6.5 Arc Voltage

This experimental programme has shown the importance of using a low arc voltage (approximately 24V) for the deposition of electrode wire of this type.

A decrease in the arc voltage results in a higher deposition efficiency, and an increase in the effective deposition rate. When DCEP is used, a lower voltage gives a much reduced average level of porosity, whilst a decrease in the voltage causes a small increase in porosity if DCEN is used.

The use of a lower arc voltage gives a deposit with

less dilution and a consequently higher hardness. A decrease in arc voltage also gives a narrower but higher deposit, and a deposit thickness of over 4mm is possible with a single pass weld.

## 6.6 Travel Speed

It is best to use a slower travel speed for depositing a hardfacing alloy of this type with the flux-cored arc welding process. This will give rise to an increase in the effective deposition rate, the width and the height of the deposit. This is also linked to a decrease in the deposit dilution.

It must however be remembered that the effect of travel speed on the process output is only of secondary importance when compared to those of current, voltage and polarity.

## 6.7 Preheat

The effects of preheat on the weld deposit in this experimental programme are also only of secondary importance.

The most significant effects on the weld deposit that result from an increase in the preheat, arean increase

in the deposition rate, the deposit width and the level of dilution. This in turn causes a reduction in the average hardness of the deposit.

It follows that a manufacturer should therefore not hesitate to use preheat where this is beneficial to the base material (eg. with high carbon equivalents), since an increase in preheat to 150 degrees C has only a relatively small effect on weld deposits of this type.

6.8 Torch Stand-off Distance

The only noted effect of increasing the torch stand-off distance from 24 to 36mm, was a small reduction in the deposition efficiency. It would therefore seem preferable to maintain a short electrode stickout or stand-off distance in practice.

6.9 Control of Welding Parameters

The level of variance in the actual values of arc current and arc voltage experienced in this programme indicate that very accurate control of the welding procedure is virtually impossible with the type of equipment used. In order to maintain a higher level of control over these factors, it would be necessary to obtain more sophisticated (and expensive) welding

machines with a closed-loop control system.

The equipment used in this project will however be satisfactory for most industrial applications, as long as due care is given to the setting of the welding parameters, and regular checking is carried out.

## 6.10 Microstructure

The effect of dilution on the microstructure of the weld metal has been clearly demonstrated, with an increase in dilution giving rise to a generally 'softer' weld metal with decreased abrasion resistance. This effect can in turn be linked to changes in the welding parameters.

## 6.11 Wear Tests

The variability introduced by the wear tests themselves masked the effects on wear resistance caused by the difference in the properties of the weld metal. This once again serves to emphasize the importance of field trials in determining the relative wear resistances of different materials.

## 6.12 Future Work

It is imperative that more studies of this nature are performed in future. This is required to produce more information on the effects of welding parameters outside the ranges considered in this experimental programme, as well the effects of the same welding parameters on deposits of different types since these will probably differ substantially from those experienced in this project.

An increase in knowledge of this type will, in future, enable manufacturers and suppliers of welding consumables to more accurately define the optimum welding conditions for each consumable type. It has been noted in this project that the range of welding parameters recommended by the suppliers of this particular electrode can give rise to an extremely wide variation in the properties and deposition characteristics of the hardfacing deposit. These in turn can lead to a less economically viable process in terms of material wastage (efficiency), increased labour and overhead costs, and a decrease in the wear life of the deposit.

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APPENDIX A

Full Specifications of Welding Equipment.

A1. Welding Machin

Type: Miller Deltaweld 650 CY50,
Constant Potential DC Arc.

NEMA Class 1 (100) Constant Voltage.

Primary

| | |
|---|---|
| Volts | 250/380/500 |
| Amperes | 180/71/54 |
| Three Phase | 50 Hz |
| KW | 37 |
| KVA | 46,6 |

Secondary

| | |
|---|---|
| Volts | 44 |
| Amperes | 650 |
| Duty Cycle | 100 % |
| Max OCV | 60 |
| Voltage Range | 14 - 46 |

A2. Wire Feeder and Gun

The wire feeder used in this experimental programme was a Millermatic S 52-A (115 VAC, 3 Amps, 50/60 Hz), with a Bernard 500 Amp gun with a lockable trigger and 10ft feed cable.

APPENDIX

Electronic Circuits used for the Measurement of Arc Current and Arc Voltage.

The instantaneous values of both arc current and arc voltage undergo rapid fluctuations which are impossible to measure with a standard voltmeter and tong tester. It was therefore necessary to obtain integrals of these values over a period of time and then divide this integral by the time period to obtain an accurate reading of the averages of the welding parameters.

The system finally adopted utilizes an OP-07 ultra-low offset voltage operational amplifier in the circuit shown in Figure B1. This system was found to give readings with a 1% accuracy, with an insignificant level of drift.

To measure arc current, the voltage drop across a shunt (50mV. 1000A) in the earth lead of the welding circuit, was passed through a potential divider and then into an integrating circuit as described above. The voltage drop across the arc was also put through a potential divider and then into an identical integrating circuit. The only difference in the above systems was the potential drops through the potential dividers.

The outputs from the two integrating circuits were then

fed into the two Y-channels of a Bryans chart recorder on which the X-axis could be set at a constant rate. The output from the chart recorder then gave straight line graphs with different gradients. The gradients were directly proportional to the arc current and arc voltage in each case.

Calibration of the systems showed that the following constants applied.

For amperage measurement,

$$I(av) = 6971,7\ Vo/T$$

Where: I(av) = Average current over time T

Vo/T = Slope of graph on chart recorder

and for voltage measurement,

$$V(av) = 467,49\ Vo/T$$

Where: V(av) = Average voltage over time T

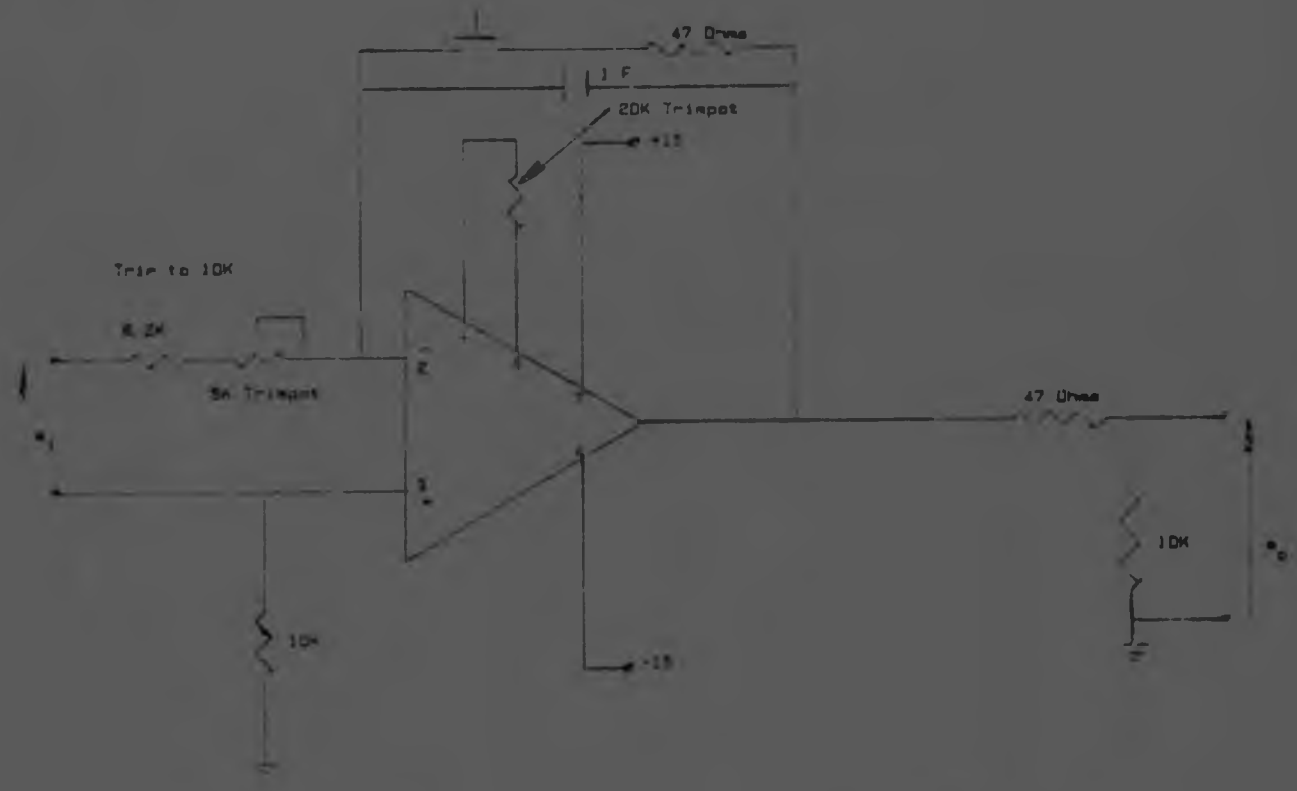



Figure B1 Diagram of the electronic integrating circuit used in the measurement of ion current and ion voltage.

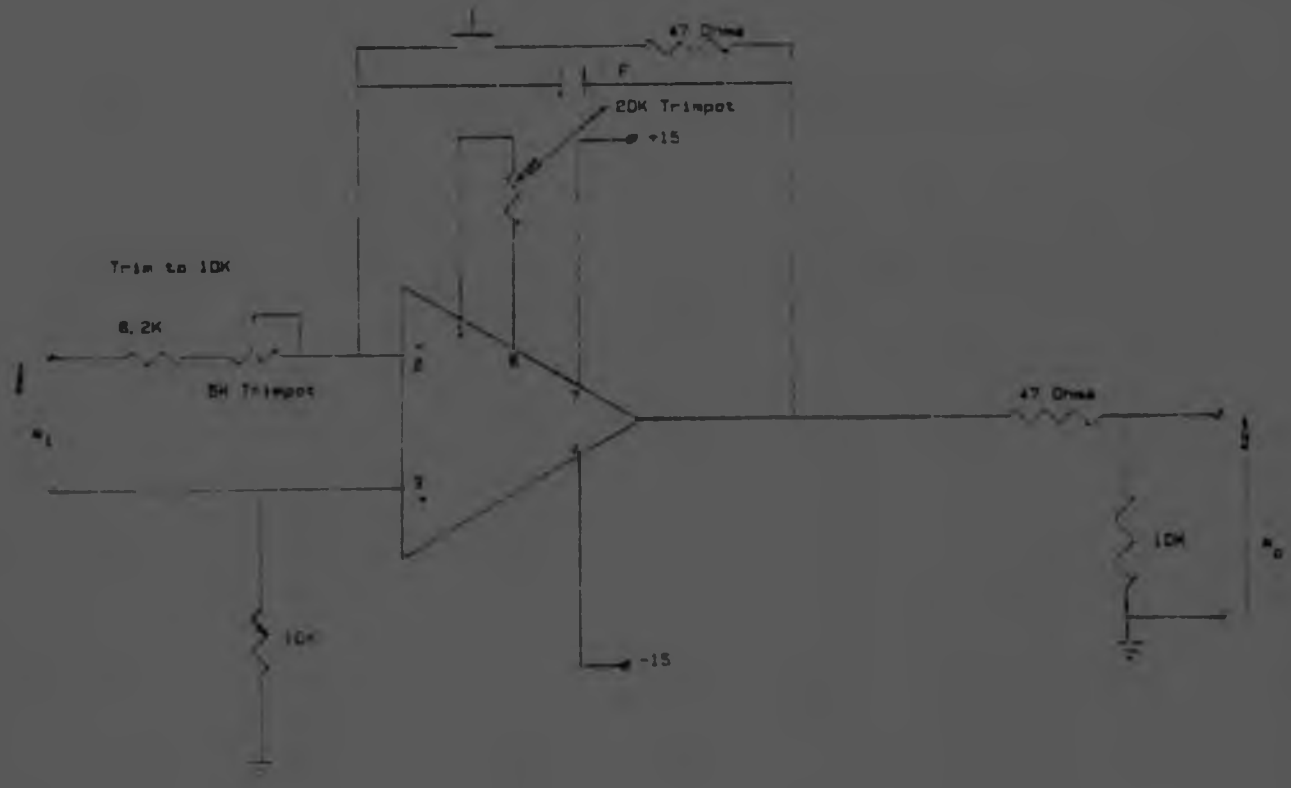



Figure B1 Diagram of the electronic integrating circuit used in the measurement of arc current and arc voltage.

APPENDIX C

Table of Treatment Combinations and Factor Settings for the 64 Test Welds

| SPECIMEN NUMBER | TREATMENT COMBINATION | FACTOR SETTINGS | | | | |
|---|---|---|---|---|---|---|
| | | ARC CURRENT (Amps) | ARC VOLTAGE (Volts) | TRAVEL SPEED (mm/min) | STAND OFF (mm) | MINIMUM PREHEAT (Deg.C) |
| 1 | 1 | 240 | 24 | 300 | 24 | 20 |
| 2 | a | 360 | 24 | 300 | 24 | 20 |
| 3 | b | 240 | 36 | 300 | 24 | 20 |
| 4 | ab | 360 | 36 | 300 | 24 | 20 |
| 5 | c | 240 | 24 | 400 | 24 | 20 |
| 6 | ac | 360 | 24 | 400 | 24 | 20 |
| 7 | bc | 240 | 36 | 400 | 24 | 20 |
| 8 | abc | 360 | 36 | 400 | 24 | 20 |
| 9 | d | 240 | 24 | 300 | 36 | 20 |
| 10 | ad | 360 | 24 | 300 | 36 | 20 |
| 11 | bd | 240 | 36 | 300 | 36 | 20 |
| 12 | abd | 360 | 36 | 300 | 36 | 20 |
| 13 | cd | 240 | 24 | 400 | 36 | 20 |
| 14 | acd | 360 | 24 | 400 | 36 | 20 |
| 15 | bcd | 240 | 36 | 400 | 36 | 20 |
| 16 | abcd | 360 | 36 | 400 | 36 | 20 |
| 17 | e | 240 | 24 | 300 | 24 | 150 |
| 18 | ae | 360 | 24 | 300 | 24 | 150 |
| 19 | be | 240 | 36 | 300 | 24 | 150 |
| 20 | abe | 360 | 36 | 300 | 24 | 150 |
| 21 | ce | 240 | 24 | 400 | 24 | 150 |
| 22 | ace | 360 | 24 | 400 | 24 | 150 |
| 23 | bce | 240 | 36 | 400 | 24 | 150 |
| 24 | abce | 360 | 36 | 400 | 24 | 150 |
| 25 | de | 240 | 24 | 300 | 36 | 150 |
| 26 | ade | 360 | 24 | 300 | 36 | 150 |
| 27 | bde | 240 | 36 | 300 | 36 | 150 |
| 28 | abde | 360 | 36 | 300 | 36 | 150 |
| 29 | cde | 240 | 24 | 400 | 36 | 150 |
| 30 | acde | 360 | 24 | 400 | 36 | 150 |
| 31 | bcde | 240 | 36 | 400 | 36 | 150 |
| 32 | abcde | 360 | 36 | 400 | 36 | 150 |

APPENDIX C Ctd.

| SPECIMEN NUMBER | TREATMENT COMBINATION | FACTOR SETTINGS | | | | |
|---|---|---|---|---|---|---|
| | | ARC CURRENT (Amps) | ARC VOLTAGE (Volts) | TRAVEL SPEED (mm/min) | STAND OFF (mm) | MINIMUM PREHEAT (Deg.C) |
| 33 | f | 240 | 24 | 300 | 24 | 20 |
| 34 | af | 360 | 24 | 300 | 24 | 20 |
| 35 | bf | 240 | 36 | 300 | 24 | 20 |
| 36 | abf | 360 | 36 | 300 | 24 | 20 |
| 37 | cf | 240 | 24 | 400 | 24 | 20 |
| 38 | acf | 360 | 24 | 400 | 24 | 20 |
| 39 | bcf | 240 | 36 | 400 | 24 | 20 |
| 40 | abcf | 360 | 36 | 400 | 24 | 20 |
| 41 | df | 240 | 24 | 300 | 36 | 20 |
| 42 | adf | 360 | 24 | 300 | 36 | 20 |
| 43 | bdf | 240 | 36 | 300 | 36 | 20 |
| 44 | abdf | 360 | 36 | 300 | 36 | 20 |
| 45 | cdf | 240 | 24 | 400 | 36 | 20 |
| 46 | acdf | 360 | 24 | 400 | 36 | 20 |
| 47 | bcdf | 240 | 36 | 400 | 36 | 20 |
| 48 | abcdf | 360 | 36 | 400 | 36 | 20 |
| 49 | ef | 240 | 24 | 300 | 24 | 150 |
| 50 | aef | 360 | 24 | 300 | 24 | 150 |
| 51 | bef | 240 | 36 | 300 | 24 | 150 |
| 52 | abef | 360 | 36 | 300 | 24 | 150 |
| 53 | cef | 240 | 24 | 400 | 24 | 150 |
| 54 | acef | 360 | 24 | 400 | 24 | 150 |
| 55 | bcef | 240 | 36 | 00 | 24 | 150 |
| 56 | abcef | 360 | 36 | 400 | 24 | 150 |
| 57 | def | 240 | 24 | 300 | 36 | 150 |
| 58 | adef | 360 | 24 | 300 | 36 | 150 |
| 59 | bdef | 240 | 36 | 300 | 36 | 150 |
| 60 | abdef | 360 | 36 | 300 | 36 | 150 |
| 61 | cdef | 240 | 24 | 400 | 36 | 150 |
| 62 | acdef | 360 | 24 | 400 | 36 | 150 |
| 63 | bcdef | 240 | 36 | 400 | 36 | 150 |
| 64 | abcdef | 360 | 36 | 400 | 36 | 150 |

APPENDIX D

Table of Measurements taken from the Photographs of the 320 Polished Weld Sections

| SURFACE/ SPECIMEN NUMBER | WIDTH (mm) | MEASUREMENTS FROM PHOTOGRAPHS WIDTH (mm) | HEIGHT (mm) | DEPTH (mm) | AREAS (square mm) AREA A | TOTAL |
|---|---|---|---|---|---|---|
| A1 | 10.69 | 53.54 | 14.61 | 8.94 | 536.4 | 846.2 |
| B1 | 9.14 | 44.52 | 15.01 | 9.85 | 488.3 | 781.0 |
| C1 | 9.61 | 47.27 | 11.67 | 8.66 | 398.6 | 699.0 |
| D1 | 9.51 | 46.07 | 16.48 | 9.24 | 526.2 | 835.7 |
| E1 | 9.51 | 42.03 | 17.78 | 7.50 | 485.1 | 701.7 |
| A2 | 14.71 | 63.64 | 12.85 | 9.98 | 837.9 | 1288.4 |
| B2 | 14.56 | 68.92 | 17.21 | 10.71 | 823.2 | 1321.0 |
| C2 | 14.11 | 60.53 | 14.19 | 9.35 | 648.4 | 1065.3 |
| D2 | 15.00 | 70.87 | 14.46 | 11.74 | 751.5 | 1309.5 |
| E2 | 14.83 | 65.75 | 14.31 | 13.51 | 690.5 | 1129.5 |
| A3 | 13.67 | 60.12 | 14.93 | 9.80 | 610.5 | 1006.2 |
| B3 | 12.98 | 56.49 | 10.82 | 8.50 | 408.3 | 744.4 |
| C3 | 12.80 | 57.04 | 10.51 | 9.94 | 410.5 | 779.0 |
| D3 | 13.96 | 60.37 | 12.14 | 8.78 | 466.0 | 829.5 |
| E3 | 12.60 | 54.84 | 10.17 | 9.98 | 408.3 | 767.4 |
| A4 | 18.21 | 80.85 | 15.60 | 12.69 | 807.0 | 1414.6 |
| B4 | 16.78 | 69.31 | 13.60 | 13.01 | 649.7 | 1267.4 |
| C4 | 17.82 | 77.68 | 11.71 | 9.94 | 663.2 | 1229.5 |
| D4 | 18.16 | 75.07 | 12.91 | 9.75 | 741.0 | 1237.9 |
| E4 | 16.60 | 73.37 | 13.17 | 11.35 | 627.4 | 1179.8 |
| A5 | 9.83 | 50.20 | 14.39 | 7.88 | 501.1 | 774.7 |
| B5 | 9.24 | 42.37 | 12.48 | 8.78 | 376.1 | 604.2 |
| C5 | 8.75 | 44.28 | 18.17 | 10.50 | 545.2 | 848.4 |
| D5 | 9.51 | 43.32 | 8.35 | 7.33 | 265.2 | 490.5 |
| E5 | 9.17 | 40.64 | 12.44 | 7.68 | 335.3 | 560.0 |
| A6 | 14.98 | 61.52 | 14.80 | 11.21 | 684.9 | 1134.6 |
| B6 | 13.88 | 61.57 | 16.33 | 12.28 | 741.0 | 1246.3 |
| C6 | 13.64 | 56.97 | 12.10 | 10.25 | 467.3 | 919.0 |
| D6 | 15.19 | 67.12 | 12.74 | 9.01 | 647.0 | 1071.5 |
| E6 | 14.03 | 63.02 | 14.48 | 9.35 | 694.7 | 1117.9 |
| A7 | 11.00 | 55.84 | 13.58 | 9.89 | 438.2 | 759.5 |
| B7 | 10.21 | 49.98 | 8.25 | 7.31 | 166.0 | 410.6 |
| C7 | 10.69 | 54.53 | 10.46 | 8.82 | 317.0 | 625.5 |
| D7 | 11.32 | 56.00 | 12.93 | 7.40 | 514.0 | 797.9 |
| E7 | 10.30 | 55.50 | 11.71 | 10.41 | 436.2 | 846.7 |
| A8 | 13.11 | 62.78 | 9.71 | 9.71 | 440.3 | 875.7 |
| B8 | 12.98 | 63.82 | 12.05 | 8.38 | 455.2 | 853.9 |
| C8 | 12.61 | 60.45 | 8.71 | 8.08 | 357.5 | 697.9 |
| D8 | 12.66 | 62.65 | 9.10 | 11.41 | 368.1 | 852.5 |
| E8 | 13.32 | 70.81 | 8.44 | 10.78 | 441.5 | 951.0 |

APPENDIX D Cod.

| SURFACE/ SPECIMEN NUMBER | WIDTH (mm) | MEASUREMENTS FROM PHTOTGRAPHS | | | | |
|---|---|---|---|---|---|---|
| | | WIDTH (mm) | HEIGHT (mm) | DEPTH (mm) | AREAS (Square mm) AREA A | TOTAL |
| A9 | 9.60 | 43.96 | 15.82 | 10.89 | 502.1 | 823.4 |
| B9 | 8.69 | 40.73 | 16.28 | 9.61 | 464.2 | 762.2 |
| C9 | 9.28 | 43.25 | 15.17 | 9.33 | 400.0 | 654.7 |
| D9 | 9.44 | 43.76 | 15.19 | 14.73 | 457.8 | 707.4 |
| E9 | 8.83 | 38.02 | 14.83 | 9.88 | 391.6 | 576.7 |
| A10 | 14.86 | 60.72 | 17.17 | 8.94 | 816.7 | 1147.4 |
| B10 | 14.08 | 61.14 | 18.28 | 11.91 | 859.0 | 1334.6 |
| C10 | 15.06 | 60.99 | 14.92 | 7.41 | 688.4 | 979.7 |
| D10 | 13.66 | 59.84 | 14.60 | 14.06 | 659.0 | 1069.5 |
| E10 | 14.03 | 59.71 | 15.31 | 7.25 | 684.2 | 983.2 |
| A11 | 11.24 | 54.95 | 13.76 | 8.24 | 465.2 | 746.7 |
| B11 | 10.11 | 45.67 | 13.08 | 9.32 | 376.7 | 667.4 |
| C11 | 11.00 | 53.6 | 13.01 | 12.96 | 461.1 | 728.4 |
| D11 | 10.00 | 44.29 | 8.69 | 8.50 | 268.3 | 501.1 |
| E11 | 10.64 | 46.87 | 14.21 | 13.56 | 463.2 | 713.0 |
| A12 | 16.07 | 69.84 | 11.30 | 11.66 | 543.2 | 1086.3 |
| B12 | 15.00 | 66.65 | [illegible] | 12.01 | 699.0 | 1219.0 |
| C12 | 15.78 | 69.28 | 13.66 | 10.21 | 684.2 | 1122.6 |
| D12 | 14.61 | 64.15 | 13.32 | 12.10 | 507.3 | 1008.4 |
| E12 | 14.00 | 61.45 | 10.33 | 11.73 | 429.5 | 903.2 |
| A13 | 8.33 | 39.93 | 13.03 | 8.66 | 379.0 | 608.4 |
| B13 | 9.35 | 42.21 | 13.96 | 7.31 | 412.6 | 633.7 |
| C13 | 8.21 | 39.50 | 14.13 | 7.48 | 414.7 | 614.7 |
| D13 | 9.14 | 41.59 | 13.69 | 8.16 | 383.2 | 619.0 |
| E13 | 8.16 | 36.37 | 10.58 | 7.40 | 258.2 | 435.7 |
| A14 | 12.30 | 55.97 | 13.38 | 10.23 | 564.2 | 974.9 |
| B14 | 13.00 | 53.89 | 13.38 | 13.30 | 570.5 | 873.7 |
| C14 | 12.00 | 55.52 | 14.67 | 13.16 | 614.7 | 926.4 |
| D14 | 11.00 | 45.57 | 13.16 | 12.32 | 442.2 | 680.0 |
| E14 | 12.98 | 58.02 | 11.03 | 8.61 | 541.0 | 899.0 |
| A15 | 11.01 | 57.75 | 9.10 | 8.33 | 343.2 | 642.2 |
| B15 | 11.58 | 62.27 | 8.58 | 13.93 | 370.6 | 892.7 |
| C15 | 11.17 | 57.50 | 10.74 | 13.11 | 290.6 | 766.4 |
| D15 | 10.11 | 54.47 | 7.44 | 12.80 | 311.6 | 762.2 |
| E15 | 8.82 | 43.28 | 9.28 | 9.00 | 275.7 | 522.7 |
| A16 | 13.00 | 63.79 | 11.55 | 9.83 | 44[illegible] | 974.7 |
| B16 | 13.67 | 67.00 | 9.78 | 12.50 | 440.0 | 974.7 |
| C16 | 14.58 | 69.31 | 11.03 | 12.66 | 604.2 | 1170.7 |
| D16 | 12.89 | 63.71 | 13.83 | 12.50 | 412.6 | 890.5 |
| E16 | 12.96 | 63.75 | 11.75 | 9.91 | 553.7 | 985.2 |

APPENDIX D Ctd.

| SURFACE/ SPECIMEN NUMBER | WIDTH (mm) | MEASUREMENTS FROM PHTOTGRAPHS | | | | |
|---|---|---|---|---|---|---|
| | | WIDTH (mm) | HEIGHT (mm) | DEPTH (mm) | AREAS (Square mm) AREA A | TOTAL |
| A9 | 9.60 | 43.96 | 15.82 | 10.89 | 502.1 | 823.4 |
| B9 | 8.69 | 40.73 | 16.28 | 9.61 | 464.2 | 762.2 |
| C9 | 9.28 | 43.25 | 15.17 | 9.33 | 400.0 | 654.7 |
| D9 | 9.44 | 43.76 | 15.19 | 14.73 | 457.8 | 707.4 |
| E9 | 8.83 | 38.02 | 14.83 | 9.88 | 391.6 | 576.7 |
| A10 | 14.86 | 60.72 | 17.17 | 8.94 | 816.7 | 1147.4 |
| B10 | 14.08 | 61.14 | 18.28 | 11.91 | 859.0 | 1334.6 |
| C10 | 15.06 | 60.99 | 14.92 | 7.41 | 688.4 | 979.7 |
| D10 | 13.66 | 59.84 | 14.60 | 14.06 | 659.0 | 1069.5 |
| E10 | 14.03 | 59.71 | 15.31 | 7.25 | 684.2 | 983.2 |
| A11 | 11.24 | 54.95 | 13.76 | 8.24 | 465.2 | 746.7 |
| B11 | 10.11 | 45.67 | 13.08 | 9.32 | 376.7 | 667.4 |
| C11 | 11.00 | 53.6 | 13.01 | 12.96 | 461.1 | 728.4 |
| D11 | 10.00 | 44.29 | 8.49 | 8.50 | 268.3 | 501.1 |
| E11 | 10.64 | 46.87 | 14.21 | 13.56 | 463.2 | 713.0 |
| A12 | 16.07 | 69.84 | 11.30 | 11.66 | 543.2 | 1086.3 |
| B12 | 15.00 | 66.65 | 14.10 | 12.01 | 699.0 | 1219.0 |
| C12 | 15.78 | 69.28 | 13.66 | 10.21 | 684.2 | 1122.8 |
| D12 | 14.61 | 64.15 | 13.32 | 12.10 | 507.3 | 1008.4 |
| E12 | 14.00 | 61.45 | 10.33 | 11.73 | 429.5 | 903.2 |
| A13 | 8.33 | 39.93 | 13.03 | 8.66 | 379.0 | 608.4 |
| B13 | 9.35 | 42.21 | 13.96 | 7.31 | 412.6 | 633.7 |
| C13 | 8.21 | 39.50 | 14.13 | 7.48 | 414.7 | 614.7 |
| D13 | 9.14 | 41.59 | 13.69 | 8.16 | 383.2 | 619.0 |
| E13 | 8.16 | 36.37 | 10.58 | 7.40 | 258.2 | 435.7 |
| A14 | 12.30 | 55.97 | 13.38 | 10.23 | 564.2 | 974.9 |
| B14 | 13.00 | 53.89 | 13.38 | 13.30 | 570.5 | 873.7 |
| C14 | 12.00 | 55.52 | 14.67 | 13.16 | 614.7 | 926.4 |
| D14 | 11.00 | 45.57 | 13.16 | 12.32 | 442.2 | 680.0 |
| E14 | 12.98 | 58.02 | 11.03 | 8.61 | 541.0 | 899.0 |
| A15 | 11.01 | 57.75 | 9.10 | 8.33 | 343.2 | 642.2 |
| B15 | 11.58 | 62.27 | 8.58 | 13.93 | 370.6 | 892.7 |
| C15 | 11.17 | 57.50 | 10.74 | 13.11 | 290.6 | 766.4 |
| D15 | 10.24 | 54.47 | 7.44 | 12.80 | 311.6 | 762.3 |
| E15 | 8.82 | 43.28 | 9.28 | 9.00 | 275.7 | 522.3 |
| A16 | 13.39 | 63.79 | 11.55 | 9.83 | 443.3 | 974.7 |
| B16 | 13.67 | 67.00 | 9.78 | 12.50 | 440.0 | 974.7 |
| C16 | 14.58 | 69.31 | 11.03 | 12.66 | 604.2 | 1170. |
| D16 | 12.89 | 63.71 | 13.83 | 12.58 | 412.6 | 890.5 |
| E16 | 12.96 | 63.75 | 11.75 | 9.91 | 553.7 | 985.2 |

APPENDIX D Ctd.

| SURFACE/ SPECIMEN NUMBER | WIDTH (mm) | MEASUREMENTS FROM PHTOTGRAPHS WIDTH (mm) | HEIGHT (mm) | DEPTH (mm) | AREAS (Square mm) AREA A | TOTAL |
|---|---|---|---|---|---|---|
| A17 | 7.59 | 35.65 | 17.21 | 11.75 | 450.5 | 722.0 |
| B17 | 8.19 | 37.32 | 19.39 | 10.28 | 499.0 | 764.2 |
| C17 | 8.89 | 41.15 | 16.16 | 11.74 | 467.3 | 770.5 |
| D17 | 8.41 | 38.97 | 16.35 | 12.66 | 456.7 | 751.5 |
| E17 | 8.25 | 35.84 | 16.67 | 9.32 | 347.3 | 569.7 |
| A18 | 16.88 | 73.18 | 15.86 | 12.08 | 827.2 | 1402.0 |
| B18 | 16.06 | 70.18 | 17.67 | 9.60 | 877.9 | 1372.5 |
| C18 | 15.53 | 67.05 | 13.67 | 10.50 | 659.0 | 1151.5 |
| D18 | 15.61 | 68.45 | 15.16 | 10.41 | 800.0 | 1301.0 |
| E18 | 14.98 | 64.42 | 14.58 | 9.69 | 854.7 | 1170.5 |
| A19 | 12.51 | 54.57 | 13.00 | 12.46 | 463.2 | 880.0 |
| B19 | 13.30 | 56.37 | 11.78 | 13.06 | 442.1 | 911.5 |
| C19 | 14.23 | 61.40 | 9.91 | 11.08 | 433.7 | 808.4 |
| D19 | 12.98 | 55.29 | 11.71 | 11.53 | 461.1 | 844.2 |
| E19 | 13.08 | 56.17 | 12.07 | 11.51 | 467.3 | 867.4 |
| A20 | 15.78 | 69.17 | 11.25 | 12.67 | 522.0 | 1111.5 |
| B20 | 17.20 | 74.34 | 10.25 | 12.41 | 524.2 | 1153.6 |
| C20 | 17.16 | 74.00 | 10.96 | 12.26 | 555.7 | 1151.5 |
| D20 | 16.85 | 73.59 | 9.42 | 11.66 | 480.0 | 1073.6 |
| E20 | 17.06 | 73.75 | 9.60 | 10.39 | 511.6 | 1082.0 |
| A21 | 8.53 | 42.37 | 13.21 | 12.10 | 370.5 | 720.0 |
| B21 | 9.18 | 47.34 | 11.33 | 10.58 | 387.3 | 715.7 |
| C21 | 8.89 | 43.53 | 12.76 | 10.71 | 387.3 | 686.2 |
| D21 | 8.38 | 43.07 | 13.36 | 9.88 | 341.1 | 595.7 |
| E21 | 9.21 | 44.12 | 14.98 | 13.93 | 505.2 | 751.5 |
| A22 | 15.50 | 74.24 | 15.98 | 12.51 | 970.5 | 1640.0 |
| B22 | 13.98 | 66.90 | 13.66 | 12.30 | 684.2 | 1301.0 |
| C22 | 14.60 | 70.03 | 13.71 | 13.28 | 692.5 | 1370.5 |
| D22 | 14.82 | 71.30 | 16.17 | 10.69 | 840.0 | 1425.3 |
| E22 | 14.78 | 71.29 | 13.51 | 12.96 | 711.5 | 1362.0 |
| A23 | 13.43 | 64.80 | 8.99 | 11.10 | 385.2 | 867.4 |
| B23 | 12.51 | 61.37 | 11.08 | 10.98 | 488.3 | 936.0 |
| C23 | 12.08 | 58.52 | 12.66 | 10.58 | 486.2 | 907.4 |
| D23 | 13.13 | 64.06 | 11.41 | 12.25 | 509.5 | 989.5 |
| E23 | 13.28 | 65.24 | 10.64 | 12.86 | 488.3 | 1025.3 |
| A24 | 15.60 | 74.74 | 9.74 | 15.93 | 450.5 | 1174.6 |
| B24 | 15.00 | 72.12 | 9.94 | 13.63 | 490.5 | 1170.5 |
| C24 | 16.38 | 78.47 | 10.89 | 12.71 | 517.9 | 1225.3 |
| D24 | 15.13 | 73.18 | 10.00 | 14.74 | 473.7 | 1103.1 |
| E24 | 14.58 | 71.14 | 12.46 | 12.73 | 585.2 | 1151.5 |

APPENDIX D Ctd.

| SURFACE/ SPECIMEN NUMBER | WIDTH (mm) | MEASUREMENTS FROM PHTOTGRAPHS WIDTH (mm) | HEIGHT (mm) | DEPTH (mm) | AREAS (Square mm) AREA A | TOTAL |
|---|---|---|---|---|---|---|
| A17 | 7.59 | 35.65 | 17.21 | 11.75 | 450.5 | 722.0 |
| B17 | 8.19 | 37.32 | 19 39 | 10.28 | 499.0 | 764.2 |
| C17 | 8.89 | 41.15 | 16.16 | 11.74 | 467.3 | 770.5 |
| D17 | 8.41 | 38.97 | 16.35 | 12.66 | 456.7 | 751.5 |
| E17 | 8.25 | 35.84 | 16.67 | 9.32 | 347.3 | 569.7 |
| A18 | 16.88 | 73.18 | 15.86 | 12.08 | 827.2 | 1402.0 |
| B18 | 16.06 | 70.18 | 17.67 | 9.60 | 877.9 | 1372.5 |
| C18 | 15.53 | 67.05 | 13.67 | 10.50 | 659.0 | 1151.5 |
| D18 | 15.61 | 68.45 | 15.16 | 10.41 | 800.0 | 1301.0 |
| E18 | 14.98 | 64.42 | 14.58 | 9.69 | 854.7 | 1170.5 |
| A19 | 12.51 | 54.57 | 13.00 | 12.46 | 463.2 | 880.0 |
| B19 | 13.30 | 56.37 | 11.78 | 13.06 | 442.1 | 911.5 |
| C19 | 14.23 | 61.40 | 9.91 | 11.08 | 433.7 | 808.4 |
| D19 | 12.98 | 55.29 | 11.71 | 11.53 | 461.1 | 844.2 |
| E19 | 13.08 | 56.17 | 12.07 | 11.51 | 467.3 | 867.4 |
| A20 | 15.78 | 69.17 | 11.25 | 12.67 | 522.0 | 1111.5 |
| B20 | 17.20 | 74.34 | 10.15 | 12.41 | 524.2 | 1153.6 |
| C20 | 17.16 | 74.00 | 10.96 | 12.26 | 555.7 | 1151.5 |
| D20 | 16.85 | 73.59 | 9.42 | 11.66 | 480.0 | 1073.6 |
| E20 | 17.06 | 73.75 | 9.60 | 10.39 | 511.6 | 1082.0 |
| A21 | 8.53 | 42.37 | 13.21 | 12.10 | 370.5 | 720.0 |
| B21 | 9.38 | 47.34 | 11.33 | 10.58 | 387.3 | 715.7 |
| C21 | 8.89 | 43.53 | 12.76 | 10.71 | 387.3 | 686.2 |
| D21 | 8.38 | 43.07 | 13.36 | 9.88 | 341.1 | 595.7 |
| E21 | 9.21 | 44.12 | 14.98 | 13.93 | 505.2 | 751.5 |
| A22 | 15.50 | 74.24 | 15.98 | 12.51 | 970.5 | 1640.0 |
| B22 | 13.98 | 66.90 | 13.66 | 12.30 | 684.2 | 1301.0 |
| C22 | 14.60 | 70.03 | 13.71 | 13.28 | 692.5 | 1370.5 |
| D22 | 14.82 | 71.30 | 16.17 | 10.69 | 840.0 | 1425.3 |
| E22 | 14.78 | 71.29 | 13.51 | 12.96 | 711.5 | 1362.0 |
| A23 | 13.43 | 64.80 | 8.99 | 11.10 | 385.2 | 867.4 |
| B23 | 12.51 | 61.37 | 11.08 | 10.98 | 488.3 | 936.0 |
| C23 | 12.08 | 58.52 | 12.66 | 10.58 | 486.2 | 907.4 |
| D23 | 13.13 | 64.06 | 11.41 | 12.25 | 509.5 | 989.5 |
| E23 | 13.28 | 65.24 | 10.64 | 12.86 | 488.3 | 1025.3 |
| A24 | 15.60 | 74.74 | 9.74 | 15.93 | 450.5 | 1174.6 |
| B24 | 15.00 | 72.12 | 9.94 | 13.63 | 490.5 | 1170.5 |
| C24 | 16.38 | 78.47 | 10.89 | 12.71 | 517.9 | 1225.3 |
| D24 | 15.13 | 73.18 | 10.00 | 13.21 | 473.7 | 1103.1 |
| E24 | 14.58 | 71.14 | 12.46 | 12.73 | 585.2 | 1151.5 |

APPENDIX D Ctd.

| SURFACE/ SPECIMEN NUMBER | WIDTH (mm) | MEASUREMENTS FROM PHTOTGRAPHS | | | | |
|---|---|---|---|---|---|---|
| | | WIDTH (mm) | HEIGHT (mm) | DEPTH (mm) | AREAS (Square mm) AREA A | TOTAL |
| A25 | 10.33 | 50.47 | 14.83 | 10.83 | 528.4 | 886.2 |
| B25 | 9.28 | 45.20 | 13.60 | 10.94 | 454.7 | 740.2 |
| C25 | 9.67 | 46.67 | 14.73 | 12.66 | 454.7 | 797.9 |
| D25 | 10.58 | 51.92 | 14.78 | 11.98 | 505.2 | 920.0 |
| E25 | 9.53 | 47.1 | 11.08 | 11.17 | 366.2 | 677.9 |
| A26 | 16.00 | 67.40 | 15.38 | 10.08 | 812.5 | 1288.4 |
| B26 | 15.73 | 67.19 | 15.55 | 11.05 | 797.9 | 1288.4 |
| C26 | 16.46 | 69.37 | 17.91 | 10.03 | 951.5 | 1391.5 |
| D26 | 14.32 | 61.20 | 14.38 | 9.98 | 581.0 | 1008.4 |
| E26 | 15.53 | 75.84 | 16.96 | 11.71 | 1014.7 | 1637.9 |
| A27 | 14.11 | 70.34 | 16.01 | 15.92 | 705.2 | 1406.3 |
| B27 | 13.00 | 64.96 | 12.58 | 14.03 | 572.5 | 1160.0 |
| C27 | 14.21 | 70.19 | 13.23 | 13.71 | 673.7 | 1305.3 |
| D27 | 13.17 | 64.59 | 12.66 | 13.17 | 534.7 | 1061.0 |
| E27 | 12.75 | 54.22 | 12.00 | 9.55 | 448.3 | 795.7 |
| A28 | 17.56 | 77.12 | 14.66 | 11.21 | 772.5 | 1335.0 |
| B28 | 18.92 | 80.00 | 12.35 | 13.25 | 698.9 | 1410.0 |
| C28 | 17.82 | 77.00 | 12.86 | 12.64 | 673.7 | 1309.0 |
| D28 | 18.14 | 75.64 | 13.21 | 12.93 | 697.7 | 1314.0 |
| E28 | 18.48 | 78.34 | 12.93 | 12.39 | 722.0 | 1358.0 |
| A29 | 10.17 | 49.78 | 12.66 | 9.80 | 393.7 | 724.2 |
| B29 | 10.64 | 40.42 | 15.86 | 11.24 | 526.2 | 907.4 |
| C29 | 10.41 | 51.84 | 12.98 | 10.96 | 454.7 | 837.9 |
| D29 | 9.30 | 44.17 | 11.00 | 11.55 | 364.2 | 682.0 |
| E29 | 9.53 | 45.76 | 11.05 | 11.05 | 332.6 | 661.0 |
| A30 | 11.66 | 54.21 | 12.39 | 10.01 | 480.0 | 840.0 |
| B30 | 13.08 | 61.52 | 14.08 | 11.19 | 621.0 | 1103.1 |
| C30 | 12.74 | 59.02 | 12.10 | 9.53 | 501.1 | 911.5 |
| D30 | 11.94 | 56.44 | 13.44 | 8.21 | 536.7 | 867.4 |
| E30 | 11.78 | 55.87 | 10.83 | 11.32 | 404.2 | 827.4 |
| A31 | 10.14 | 57.50 | 9.01 | 10.33 | 347.3 | 730.5 |
| B31 | 9.01 | 51.03 | 11.55 | 9.46 | 391.6 | 701.0 |
| C31 | 9.88 | 55.82 | 10.66 | 11.61 | 357.8 | 772.5 |
| D31 | 10.32 | 57.94 | 10.67 | 8.94 | 431.6 | 797.9 |
| E31 | 8.82 | 43.54 | 12.80 | 9.30 | 376.7 | 648.4 |
| A32 | 16.14 | 77.90 | 11.05 | 15.26 | 595.7 | 1292.5 |
| B32 | 18.38 | 84.74 | 12.88 | 12.88 | 766.2 | 1475.8 |
| C32 | 15.93 | 77.90 | 11.25 | 11.01 | 541.0 | 1197.9 |
| D32 | 15.03 | 68.55 | 12.28 | 15.13 | 568.4 | 1212.5 |
| E32 | 15.17 | 74.57 | 11.10 | 13.36 | 576.7 | 1231.5 |

APPENDIX D Cont.

| SURFACE/ SPECIMEN NUMBER | WIDTH (mm) | MEASUREMENTS FROM PHTOTGRAPHS | | | | |
|---|---|---|---|---|---|---|
| | | WIDTH (mm) | HEIGHT (mm) | DEPTH (mm) | AREAS (Square mm) AREA A | TOTAL |
| A33 | 11.28 | 50.38 | 13.13 | 13.41 | 671.5 | 995.7 |
| B33 | 11.61 | 50.00 | 12.50 | 9.14 | 650.5 | 974.7 |
| C33 | 10.44 | 46.73 | 16.71 | 8.00 | 543.2 | 814.7 |
| D33 | 9.67 | 41.97 | 16.67 | 6.00 | 494.7 | 690.5 |
| E33 | 10.41 | 43.67 | 15.73 | 6.80 | 515.7 | 738.9 |
| A34 | 9.58 | 39.65 | 19.21 | 10.78 | 614.7 | 882.0 |
| B34 | 10.50 | 42.12 | 20.50 | 10.69 | 682.0 | 976.7 |
| C34 | 9.94 | 41.17 | 21.70 | 11.50 | 698.9 | 993.7 |
| D34 | 10.41 | 42.50 | 20.28 | 11.14 | 667.4 | 934.7 |
| E34 | 10.28 | 42.53 | 21.76 | 9.66 | 753.7 | 1004.2 |
| A35 | 12.35 | 59.84 | 14.92 | 10.08 | 587.4 | 981.0 |
| B35 | 14.32 | 67.92 | 15.61 | 12.75 | 757.9 | 1324.1 |
| C35 | 11.88 | 57.75 | 11.41 | 10.30 | 461.1 | 856.7 |
| D35 | 12.51 | 59.82 | 14.50 | 11.69 | 568.4 | 1016.7 |
| E35 | 10.51 | 50.15 | 14.01 | 8.30 | 475.7 | 722.0 |
| A36 | 13.19 | 56.35 | 15.38 | 7.94 | 667.4 | 1002.0 |
| B36 | 12.74 | 53.42 | 15.43 | 7.16 | 637.9 | 928.4 |
| C36 | 13.78 | 57.99 | 13.61 | 6.45 | 661.0 | 913.7 |
| D36 | 13.63 | 56.95 | 15.94 | 8.73 | 610.5 | 945.1 |
| E36 | 14.37 | 61.67 | 16.11 | 7.51 | 741.0 | 1042.0 |
| A37 | 9.67 | 42.90 | 14.93 | 7.16 | 484.2 | 688.4 |
| B37 | 10.41 | 50.65 | 14.78 | 6.30 | 583.2 | 835.7 |
| C37 | 9.08 | 39.76 | 14.36 | 5.91 | 379.0 | 564.2 |
| D37 | 9.78 | 46.70 | 12.74 | 7.41 | 353.7 | 619.0 |
| E37 | 9.78 | 44.84 | 13.33 | 5.72 | 440.0 | 640.0 |
| A38 | 9.01 | 42.35 | 24.82 | 9.75 | 894.7 | 1273.5 |
| B38 | 7.61 | 36.28 | 23.70 | 10.92 | 707.4 | 983.2 |
| C38 | 8.60 | 40.51 | 20.89 | 9.46 | 682.0 | 926.2 |
| D38 | 8.64 | 41.17 | 22.38 | 9.50 | 743.2 | 989.5 |
| E38 | 8.80 | 40.37 | 21.00 | 8.75 | 701.0 | 920.0 |
| A39 | 10.19 | 49.52 | 9.94 | 11.05 | 341.1 | 629.5 |
| B39 | 9.03 | 44.35 | 11.69 | 6.91 | 343.2 | 511.6 |
| C39 | 10.46 | 49.90 | 10.00 | 8.60 | 317.8 | 581.0 |
| D39 | 10.82 | 52.52 | 8.00 | 8.51 | 296.7 | 606.2 |
| E39 | 10.41 | 49.96 | 8.25 | 8.63 | 265.2 | 526.2 |
| A40 | 11.38 | 54.55 | 12.66 | 8.89 | 496.7 | 821.0 |
| B40 | 11.08 | 51.09 | 14.67 | 10.23 | 522.0 | 848.4 |
| C40 | 11.46 | 55.05 | 15.76 | 9.76 | 570.5 | 989.5 |
| D40 | 11.32 | 52.12 | 13.63 | 9.26 | 465.2 | 732.5 |
| E40 | 11.08 | 53.65 | 6.68 | 8.78 | 610.7 | 909.5 |

APPENDIX D Ctd.

| SURFACE/ SPECIMEN NUMBER | WIDTH (mm) | MEASUREMENTS FROM PHOTOGRAPHS | | | | |
|---|---|---|---|---|---|---|
| | | WIDTH (mm) | HEIGHT (mm) | DEPTH (mm) | AREAS (Square mm AREA A | TOTAL |
| A41 | 10.55 | 48.40 | 14.69 | 7.24 | 505.2 | 800.0 |
| B41 | 10.19 | 47.73 | 16.53 | 6.99 | 589.5 | 837.9 |
| C41 | 11.64 | 52.65 | 13.35 | 7.33 | 520.0 | 800.0 |
| D41 | 10.58 | 48.93 | 16.89 | 10.44 | 600.0 | 960.0 |
| E41 | 11.88 | 49.85 | 14.06 | 6.74 | 524.2 | 768.4 |
| A42 | 10.61 | 43.82 | 20.00 | 9.82 | 627.4 | 884.2 |
| B42 | 10.17 | 45.87 | 23.53 | 10.51 | 873.7 | 1183.1 |
| C42 | 10.00 | 40.50 | 20.96 | 9.03 | 677.9 | 892.5 |
| D42 | 9.28 | 41.65 | 22.01 | 10.64 | 774.7 | 1031.5 |
| E42 | 9.16 | 37 87 | 20.08 | 9.00 | 640.0 | 858.9 |
| A43 | 12.61 | 54.45 | 15.71 | 8.60 | 574.7 | 865.2 |
| B43 | 13.11 | 56.77 | 14.96 | 11.25 | 627.4 | 1014.7 |
| C43 | 12.11 | 52.65 | 12.66 | 11.38 | 469.5 | 802.0 |
| D43 | 12.58 | 54.42 | 17.21 | 11.86 | 587.4 | 1014.7 |
| E43 | 12.24 | 52.94 | 12.58 | 10.74 | 509.5 | 863.3 |
| A44 | 13.86 | 59.82 | 14.63 | 5.83 | 642.0 | 852.5 |
| B44 | 12.98 | 55.28 | 14.38 | 7.7 | 644.2 | 915.7 |
| C44 | 13.48 | 58.62 | 16.38 | 7.26 | 732.5 | 1025.3 |
| D44 | 12.16 | 52.37 | 15.23 | 7.98 | 547.4 | 867.4 |
| E44 | 13.16 | 56.67 | 15.61 | 8.25 | 666.9 | 949.5 |
| A45 | 10.39 | 47.29 | 14.21 | 6.2 | 520.0 | 739.0 |
| B45 | 9.60 | 46.47 | 12.86 | 6.37 | 423.2 | 663.2 |
| C45 | 10.38 | 47.28 | 12.50 | 7.28 | 383.2 | 661.0 |
| D45 | 9.88 | 48.27 | 13.36 | 7.75 | 480.0 | 747.4 |
| E45 | 9.67 | 47.32 | 12.71 | 6.40 | 444.2 | 686.2 |
| A46 | 8.55 | 37.02 | 19.26 | 4.69 | 549.5 | 680.0 |
| B46 | 9.01 | 38.90 | 14.28 | 6.69 | 579.0 | 726.2 |
| C46 | 9.17 | 39.23 | 20.18 | 7.75 | 576.7 | 770.5 |
| D46 | 9.51 | 40.26 | 17.76 | 6.66 | 570.5 | 736.7 |
| E46 | 9.28 | 45.15 | 20.25 | 8.16 | 734.7 | 974.7 |
| A47 | 10.48 | 49.37 | 17.50 | 6.61 | 623.2 | 831.5 |
| B47 | 11.69 | 55.42 | 8.91 | 10.85 | 311.6 | 709.5 |
| C47 | 11.78 | 54.6 | 10.25 | 10.30 | 397.8 | 764.2 |
| D47 | 11.25 | 53.04 | 8.66 | 11.32 | 324.2 | 711.5 |
| E47 | 11.78 | 55.84 | 14.76 | 10.75 | 656.7 | 995.7 |
| A48 | 11.28 | 52.40 | 11.78 | 4.99 | 488.3 | 698.9 |
| B48 | 9.91 | 44.21 | 10.88 | 7.00 | 313.7 | 513.7 |
| C48 | 12.10 | 55.84 | 13.67 | 13.33 | 557.9 | 837.9 |
| D48 | 12.14 | 55.00 | 13.46 | 7.16 | 494.7 | 768.4 |
| E48 | 10.91 | 52.78 | 15.39 | 9.24 | 576.7 | 877.9 |

APPENDIX D Ctd.

| SURFACE/ SPECIMEN NUMBER | WIDTH (mm) | MEASUREMENTS FROM PHTOTGRAPHS | | | | |
|---|---|---|---|---|---|---|
| | | WIDTH (mm) | HEIGHT (mm) | DEPTH (mm) | AREAS (Square mm) AREA A | TOTAL |
| A49 | 11.78 | 50.48 | 16.06 | 11.69 | 612.5 | 1019.0 |
| B49 | 13.66 | 55.70 | 16.18 | 13.21 | 726.2 | 1185.3 |
| C49 | 12.30 | 53.35 | 15.86 | 11.03 | 654.7 | 1067.4 |
| D49 | 13.06 | 53.87 | 17.88 | 13.82 | 694.7 | 1054.8 |
| E49 | 12.66 | 48.87 | 14.91 | 13.33 | 545.2 | 831.5 |
| A50 | 10.38 | 40.35 | 19.14 | 11.24 | 608.4 | 873.7 |
| B50 | 10.28 | 39.93 | 19.76 | 10.55 | 625.2 | 871.5 |
| C50 | 9.61 | 36.73 | 19.32 | 10.96 | 541.0 | 785.5 |
| D50 | 10.08 | 38.62 | 18.66 | 10.91 | 606.2 | 852.5 |
| E50 | 10.05 | 39.17 | 19.35 | 10.39 | 614.7 | 854.7 |
| A51 | 15.32 | 60.79 | 13.81 | 11.85 | 581.0 | 1044.1 |
| B51 | 14.71 | 57.12 | 13.71 | 12 39 | 562.0 | 1010.5 |
| C51 | 13.69 | 53.57 | 12.14 | 9.10 | 511.6 | 814.7 |
| D51 | 17.57 | 67.24 | 16.35 | 11.75 | 774.7 | 1250.5 |
| E51 | 15.38 | 60.04 | 15.08 | 12.55 | 661.0 | 1111.5 |
| A52 | 14.10 | 55.52 | 14.68 | 12.66 | 642.0 | 934.7 |
| B52 | 14.91 | 57.15 | 16.82 | 7.44 | 739.0 | 972.5 |
| C52 | 13.83 | 54.04 | 13.83 | 13.32 | 551.5 | 882.0 |
| D52 | 14.19 | 54.92 | 13.00 | 9.64 | 484.2 | 842.0 |
| E52 | 14.51 | 56.62 | 14.86 | 12.91 | 633.7 | 936.7 |
| A53 | 9.85 | 45.14 | 12.01 | 7.06 | 357.8 | 612.5 |
| B53 | 10.64 | 55.02 | 13.75 | 10.66 | 562.0 | 1406.3 |
| C53 | 10.61 | 49.00 | 12.30 | 7.90 | 435.7 | 703.2 |
| D53 | 10.30 | 53.6 | 12.19 | 6.94 | 488.3 | 770.5 |
| E53 | 9.25 | 42.70 | 12.98 | 7.41 | 360.0 | 606.2 |
| A54 | 8.74 | 37.35 | 18.53 | 10.13 | 589.5 | 812.5 |
| B54 | 9.78 | 41.37 | 18.53 | 8.66 | 560.0 | 774.7 |
| C54 | 9.14 | 38.67 | 13.31 | 10.00 | 557.9 | 833.7 |
| D54 | 9.51 | 40.35 | 17.67 | 9.10 | 595.7 | 840.0 |
| E54 | 9.51 | 43.59 | 19.93 | 9.85 | 633.7 | 915.7 |
| A55 | 11.96 | 56.34 | 11.55 | 12.21 | 427.3 | 888.4 |
| B55 | 11.58 | 61.78 | 9.28 | 11.86 | 406.2 | 928.4 |
| C55 | 11.98 | 55.79 | 13.78 | 10.53 | 568.4 | 934.7 |
| D55 | 12.17 | 63.74 | 11.58 | 10.53 | 494.2 | 960.0 |
| E55 | 12.88 | 66.87 | 12.24 | 10.36 | 610.5 | 1080.0 |
| A56 | 13.66 | 71.38 | 19.48 | 10.55 | 913.7 | 1046.1 |
| B56 | 13.61 | 65.43 | 17.73 | 8.69 | 854.7 | 1258.9 |
| C56 | 13.83 | 73.28 | 17.14 | 11.28 | 859.0 | 1463.1 |
| D56 | 12.75 | 61.77 | 13.58 | 8.53 | 589.5 | 985.2 |
| E56 | 12.48 | 63.70 | 16.75 | 10.60 | 665.2 | 1174.6 |

APPENDIX D Ctd.

| SURFACE/ SPECIMEN NUMBER | WIDTH (mm) | MEASUREMENTS FROM PHTOTGRAPHS | | | | |
|---|---|---|---|---|---|---|
| | | WIDTH (mm) | HEIGHT (mm) | DEPTH (mm) | AREAS (Square mm) AREA A | TOTAL |
| A57 | 9.98 | 48.03 | 17.53 | 9.33 | 616.7 | 936.7 |
| B57 | 11.03 | 47.21 | 16.26 | 9.33 | 564.2 | 873.7 |
| C57 | 10.69 | 52.12 | 15.51 | 7.83 | 616.7 | 943.2 |
| D57 | 11.13 | 47.93 | 11.39 | 8.85 | 395.7 | 698.9 |
| E57 | 10.00 | 43.25 | 14.14 | 5.90 | 437.8 | 635.7 |
| A58 | 9.78 | 41.81 | 21.10 | 11.66 | 707.4 | 964.2 |
| B58 | 10.11 | 42.90 | 22.39 | 10.49 | 791.5 | 1079.0 |
| C58 | 8.66 | 37.00 | 19.21 | 9.91 | 547.4 | 787.4 |
| D58 | 10.11 | 43.40 | 22.51 | 9.35 | 804.2 | 1044.1 |
| E58 | 10.41 | 44.46 | 23.32 | 7.51 | 863.2 | 1040.0 |
| A59 | 12.38 | 53.87 | 13.30 | 10.73 | 505.2 | 863.2 |
| B59 | 12.58 | 55.04 | 10.03 | 12.26 | 395.7 | 816.7 |
| C59 | 12.80 | 56.78 | 9.16 | 10.41 | 336.8 | 745.2 |
| D59 | 13.41 | 58.79 | 10.57 | 11.42 | 408.3 | 777.4 |
| E59 | 13.06 | 56.29 | 11.00 | 11.25 | 847.4 | 858.9 |
| A60 | 13.48 | 57.55 | 15.38 | 8.73 | 650.5 | 955.7 |
| B60 | 12.60 | 54.29 | 17.04 | 8.33 | 692.5 | 1010.5 |
| C60 | 12.16 | 52.75 | 16.39 | 9.83 | 591.5 | 928.4 |
| D60 | 14.17 | 60.62 | 15.41 | 8.05 | 726.2 | 1094.6 |
| E60 | 14.11 | 59.87 | 15.66 | 5.51 | 711.5 | 932.5 |
| A61 | 10.19 | 49.65 | 11.28 | 9.51 | 391.6 | 751.5 |
| B61 | 11.16 | 54.79 | 15.93 | 5.66 | 682.0 | 907.4 |
| C61 | 10.98 | 54.25 | 13.01 | 7.91 | 511.6 | 808.4 |
| D61 | 10.55 | 51.97 | 12.36 | 8.53 | 446.2 | 753.7 |
| E61 | 11.83 | 57.87 | 16.33 | 8.67 | 640.0 | 1014.7 |
| A62 | 7.78 | 33.84 | 21.78 | 10.71 | 627.4 | 869.5 |
| B62 | 7.95 | 33.57 | 20.08 | 10.05 | 566.2 | 774.7 |
| C62 | 8.08 | 34.67 | 19.17 | 6.76 | 530.5 | 684.3 |
| D62 | 8.60 | 36.42 | 20.00 | 7.31 | 581.0 | 741.0 |
| E62 | 8.08 | 38.85 | 21.73 | 7.65 | 673.7 | 863.9 |
| A63 | 11.83 | 54.97 | 9.58 | 10.46 | 385.2 | 789.1 |
| B63 | 12.33 | 55.65 | 9.13 | 10.96 | 315.7 | 692.5 |
| C63 | 11.75 | 54.25 | 10.85 | 9.05 | 387.3 | 732.5 |
| D63 | 14.03 | 63.57 | 11.14 | 8.21 | 509.5 | 835.7 |
| E63 | 11.78 | 55.85 | 10.71 | 9.11 | 368.3 | 711.5 |
| A64 | 11.32 | 56.42 | 15.17 | 11.94 | 669.5 | 1077.9 |
| B64 | 12.16 | 54.64 | 12.98 | 9.61 | 461.1 | 829.5 |
| C64 | 11.91 | 50.95 | 14.73 | 9.00 | 553.7 | 892.5 |
| D64 | 12.11 | 56.49 | 14.51 | 10.46 | 574.7 | 966.2 |
| E64 | 11.46 | 53.04 | 15.66 | 8.85 | 618.9 | 901.0 |

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