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MICRO HARDNESS SURVEY AND HEAT FLOW ANALYSIS OF GMAW PROCESS



A Project Report

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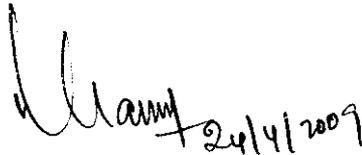
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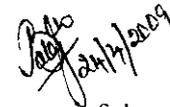
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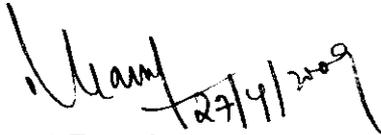


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ABSTRACT

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The arc welding processes have been extensively used for the fabrication of structures ranging from bridges and machinery to all kind of sea-borne vehicles to nuclear reactors and space rockets. This is because of its advantages like high joint efficiency, water and air tightness, limitless thickness and reduction in fabrication time and cost etc..

Among the various welding processes used in industries, GMAW is commonly employed because of its inherent advantages. In actual practice the hardness of the weld is not given that much importance and in most of the situation the weld strength provided is greater than the requirement. This leads to wastage of energy and materials. At the same time in some situations, the hardness of the weld is very low and this leads to failure of the weld joint. The estimation of hardness for any given combination of operating parameters is very important to know the load carrying capacity and to achieve welding efficiency.

Thus in order to determine the changes in the micro hardness values of the welded areas under different circumstances, design matrix is constructed using five process parameters, [Wire feed rate (F), Welding speed (S), Time gap between passes (t), Angle of electrode (θ) and Velocity of cooling air (V)] and the micro hardness values are measured at various points at very close distances in all the three zones namely base metal zone, heat affected zone and fusion zone.

Hence the problems of wastage of resources and weld failure can be effectively solved by predicting hardness of the weld relating with the various GMAW process variables.

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CHAPTER 1

INTRODUCTION

INTRODUCTION

1.1 Introduction

The welding processes have been extensively used for the fabrication of structures ranging from bridges and machinery to all kinds of sea-borne vehicles to nuclear reactors and space rockets. This is because of the following advantages they enjoy as compared to other metal joining techniques :

- High joint efficiency
- Water and air tight joint
- Weight saving
- No limit on thickness
- Complex structural shapes can be welded easily
- Reduction in fabrication time and cost

At the same time welding creates various problems on its own and some of them are as follows:

- (i) **Difficult to arrest fracture:** Once a crack starts to propagate in welded structures it is difficult to arrest.
- (ii) **Possibility of defects:** Welds are often plagued with various defects like porosity, hair line crack, slag inclusion, etc.
- (iii) **Sensitive to materials:** Materials like steels with higher strength, aluminium, etc are generally more sensitive to even small defects.
- (iv) **Residual stresses:** Uncontrolled localized heating and cooling during welding results in residual stresses which will affect the service life of the weldment.
- (v) **Distortion:** The non-uniform plastic deformations in all directions cause mismatching of components during assembly of the welded structures.

The main cause for all these problems is the welding thermal cycle that occurs in the weld metal and base metal regions in the weldment.

Due to the welding thermal cycle experienced during welding the strength of the weldment changes. The main aim of this research work is to investigate and analyse the strength of the weld, hardness in the weldment and heat flow in a multi-pass GMAW welded structural steel plate, and give recommendations for controlling and reducing their negative effects on the weld structure.

1.2 BASIC PRINCIPLE OF OPERATION OF MIG:

At the most basic level, MIG welders are similar in principle to ARC Welders in that they use an electric arc to melt and fuse metal surfaces and a sacrificial 'electrode' together. However whereas an ARC Welder uses a simple, short metal rod that has to be replaced frequently as it is consumed, MIG welders use a thin metal wire that is fed, by an electric motor, continuously into the melting weld pool. Because this wire is supplied in a very long coiled length, it lasts for many hours. The wire will be made of an alloy appropriate to the metal being welded and as we have already said, this could be steel, Aluminium or Stainless Steel.

But, just as in Arc Welding, something has to be done to keep Oxygen gas (from the atmosphere) reacting vigorously with the hot, molten weld pool and so spoiling the weld. Arc Welders use a special coating on the welding rod (called flux) that melts and covers the weld pool to act as barrier between it and the surrounding oxygen. Unfortunately, this coating cools to form a hard 'slag' that retains heat and can also become trapped in the weld, seriously weakening it.

MIG Welders tackle the Oxygen problem in an entirely different way, by effectively blowing it away from the Weld pool with another gas. But this time it's a gas carefully chosen for its inert properties and that means it will not react with the molten weld pool. Take a look at the simple diagram below and you'll see what we mean. As the electric arc melts the metal

surfaces and wire to form the molten weld pool, the special protective gas is blown out of a surrounding Nozzle and so shields the weld pool from that pesky Oxygen.

There's an important distinction to be made here. Conventional Oxy Acetylene (Ethane) gas welders actually burn the highly flammable Acetylene gas with Oxygen to generate intense heat. With MIG welders the heat is generated by the electrical power from the welder NOT from the inert gas (which does not burn and is NOT flammable).

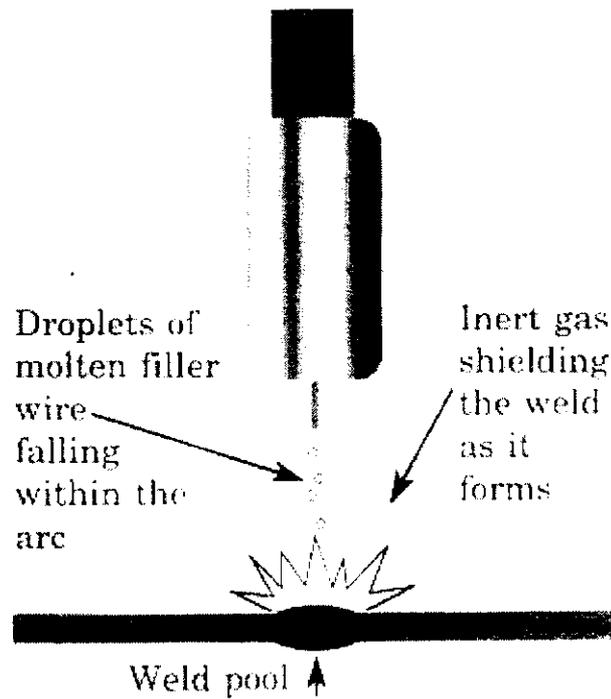


FIG. 1.1. FILLER WIRE AND INERT GAS FROM NOZZLE

1.3 THE GAS SHIELD AND MIG VS MAG

However, there are some snags with this gas shield method. One snag is that the shielding gas itself can easily be blown away and so successfully welding outdoors on breezy days, or even indoors in strong draughts, can be near impossible. This is where good old Arc Welders have a distinct advantage since they are largely unaffected by air turbulence, but as we will see later, MIG type Welders can be sneakily adapted to overcome air turbulence too. Another snag is that highly inert, non reactive gases are relatively rare and so are comparatively expensive to isolate and comparatively expensive to buy. By way of example, one such gas used is Argon and it is in fact a pure element so cannot be 'manufactured'. It does however occur naturally as a tiny percentage of the air we breathe and so it can be isolated industrially by cooling large quantities of air down until it reaches the one unique temperature where Argon alone condenses to form a liquid and so can be collected. By storing it in pressurised bottles the Argon can be prevented from expanding and forming a gas again at room temperatures. The pressure that builds up as the stored gas reaches room temperatures is harnessed and used to expel gas from the bottle and drive it through the Mig Welder and out onto the arc. However if uncontrolled the Argon would scream out of the pressure bottle like the exhaust from a rocket engine and so it first passes through a device called a Regulator that carefully controls the amount of escaping gas.

We now know then that an inert gas is required to successfully MIG weld, but in addition to Argon, several other gases are also used depending on the type of metal being welded. In fact, some of these gases are combined in various mixtures to give the best balance between performance and economy. These gases are supplied in either small disposable bottles (for occasional hobby use), or standard gas bottles (for prolonged and professional use). Whilst small disposable bottles are commonly available, standard gas bottles have to be hired from specialist companies and are much bulkier, heavier and difficult to handle, but are far, far more economical for the serious, regular user or those with a large project to undertake.

Specialist gas companies often produce their own recommended mixtures of gases, depending on application. However, here's a rough guide to help you select from the many available:

TABLE 1.1: TYPES OF GAS USED AND ITS APPLICATION

Gas Type	% in Mixture	Application
Carbon Dioxide (CO ₂)	100%	Mild steel where small quantities of spatter are acceptable and for Structural Steels
Carbon Dioxide (CO ₂) Argon (Ar)	95% 5%	Mild steel where visually pleasing, spatter-free welding is essential
Argon (Ar) Oxygen (O ₂)	95%-99% 5%-1%	Stainless steel

As can be seen from the table, it is essential that the correct gas mixture is selected depending on the metal to be joined. Try welding Aluminium or Stainless Steel with Carbon Dioxide, and the results will be as bad as if no gas was used at all. In fact, although the name MIG stands for Metal Inert Gas, only Argon is truly inert and therefore only welds made with pure Argon are true Metal Inert Gas, or MIG welds. In the case of Carbon Dioxide and mixtures containing Oxygen, the gas itself (more correctly the Oxygen within the gas) actually undergoes a limited reaction with the molten weld pool and so is said to be active, hence welds of this type are said to be Metal Active Gas, or MAG welds. As can be seen, the term MIG or MAG simply denotes how the gas used reacts with the weld pool.

A good example of this occurs in the use of pure Carbon Dioxide gas when welding mild steels. Carbon Dioxide is actually used because it is very easy and cheap to produce, but it is not totally inert and so reacts with the mild steel weld pool to produce spatter (molten droplets expelled from the weld pool). The poorer the purity of Carbon Dioxide used, the livelier is this reaction. This is one of the reasons why so-called 'pub gas' (bottles of Carbon Dioxide borrowed from local, friendly pub landlord) can produce inconsistent and untidy welds. To get round the reactive properties of Carbon Dioxide, professional gas mixtures for welding mild steel also include up to 5% Argon, which 'calms' the otherwise lively nature of the weld pool.

1.4 REGULATORS AND CONTROLLING THE GAS SHIELD

As mentioned earlier, the Regulator is an essential part of all MIG welders so always check that any MIG welder you buy comes complete with one. There are several varieties of regulator too, one type is Brass Regulator – it is Very cheap and basic, but does not give guide to gas usage or remaining bottle contents, the second type is Brass Regulator with Contents Gauge – it gives guide to remaining bottle content, and the last type is Brass Regulator with Contents Gauge and Flow Gauge – it Gives guide to remaining bottle content, and flow gauge permits accurate measurement of gas consumption during welding.

Note that all three types of Regulator above are available for both small, disposable gas bottles and standard gas bottles, but they are not interchangeable between these bottle types. Typically, smaller MIG welders are supplied with a brass Regulator and contents gauge (a simple pressure gauge) to fit small, disposable gas bottles, whereas larger MIG welders (for serious home or professional use) are supplied with a brass Regulator and contents gauge to fit standard bottle types.

If you are welding frequently and want to achieve the best balance between high quality welds and economic gas usage, then it is strongly recommended to invest in a Regulator with a built-in flow gauge in addition to a contents (pressure) gauge since only a true flow gauge (not a pressure gauge) will allow you to accurately measure, and therefore control, the amount of gas flowing out of the welding nozzle when actually welding. You can then use a little trial and error on test welds to achieve the minimum necessary gas flow whilst maintaining a high quality weld. A flow gauge will also give an early indication of blockages within the gas tube or welding nozzle.

MIG WIRES

Now that we understand how the gas is used and controlled we can turn our attention to the actual welding wire. As stated earlier, this wire is stored on coils and fed continuously to the actual weld pool by an electric motor. The wire can be mild steel, Aluminium or a stainless steel alloy to match the metal being welded and also comes in varying diameters depending on the size and thickness of weld required.

There are some critical factors that affect the success of MIG weld and these relate to both wire and machine so let's look at these in more detail.

Firstly, the wire itself must be absolutely spotless and corrosion free. In MIG welding cleanliness is most definitely next to godliness and so the slightest trace of corrosion, paint, oil etc on the wire will affect the weld quality. This also goes for the metal actually being welded so make sure you thoroughly clean surfaces that you are MIG welding and be doubly sure your MIG wire is in tip top condition.

Better quality mild steel MIG wire comes with a very fine copper plating to both aid conduction and prevent surface corrosion. Even so, never store any type of MIG (even Aluminium) in damp environments such as garages, sheds or unheated workshops. It goes without saying that the MIG welder itself shouldn't be stored in these conditions either but don't leave MIG wire in the machine if you are laying it up for long periods between use, just in case. Corroded MIG wire will not only give poor quality welds, but also wear and contaminate the torch head and liner.

The actual diameter of the MIG wire is critical too because it needs to be pushed along between rollers by that electric motor. The rollers will be grooved to exactly fit a specific diameter of wire (typically 1.0mm, 0.8mm or 0.6mm) and it is extremely important that the wire and rollers are machined to be a precision fit or problems with inconsistent wire feed can result.

When selecting a wire diameter, you should bear in mind the thickness of metal to be welded. As a rough rule of thumb, 0.6mm diameter wire should be selected for welding thinner sheet such as vehicle bodywork whereas 0.8mm wire should be used for thicker chassis sections

and fabrication work. Note that 1.0mm thick wire is usually only compatible with high power professional machines. Again whatever diameter you choose make doubly sure your machine has the correct size of grooved rollers.

Lastly, as well as being supplied in different diameters, Wires are supplied on different size drums depending on the amount required. Not all weights of drum fit all MIG welders, especially if you are buying the large 15 Kg sizes so you should double check before you part with your cash. Even if your welder can accommodate it we recommend that you don't buy a large 15 Kg drum of wire if you are not welding frequently because stored for long periods and forgotten you may find the dreaded corrosion sets in and ruins it. Here's a handy reference guide to the types and sizes of wire commonly available.

TABLE 1.2: TYPES AND SIZE OF WIRES

Wire Type	Diameter (mm)	Reel Size (kg)	Gas Required
Mild Steel	0.6	0.7	CO ₂ or CO ₂ & Argon mix
Mild Steel	0.6	15.0	CO ₂ or CO ₂ & Argon mix
Mild Steel	0.8	15.0	CO ₂ or CO ₂ & Argon mix
Mild Steel	1.0	15.0	CO ₂ or CO ₂ & Argon mix
Structural Steel	1.2	10.0	CO ₂ or CO ₂ & Argon mix
Mild Steel	1.2	15.0	CO ₂ or CO ₂ & Argon mix
Stainless Steel	0.8	0.7	Argon & Oxygen mix

Note wires above 0.8mm diameter are generally only used on high power industrial machines and are therefore too large for the majority of home welders.

1.5 MIG WELDER OUTPUT POWER

MIG welders are ideal for welding thin sheet metals but for maximum flexibility you should choose a machine that will also weld reasonably thick plate. Although not a perfect rule of thumb, it's generally true to say that the larger capacity machines also tend to be better designed and made.

To give a good balance between both heavier fabrication and thin panel welding, we recommend that you choose a machine with an output of at least 130 Amps. Just as with ARC welders, all this power generates heat in the welder's transformer so if you are going to be using it for prolonged periods make sure it comes with a cooling fan (often called "Turbo" models). Related to this is the so called Duty Cycle which in simple terms is the percentage of time the welder can actually be used in any given period without it automatically switching off to cool down. For instance, a duty cycle of 40% at 120 Amps means that you could weld for up to 40 minutes in any 100-minute period at a 120 Amp output setting. In practice you won't actually be welding continuously for 40 minutes but rather as you stop and start to complete different weld runs, the time the welder is 'resting' should average 60 percent of the time to prevent it switching off to cool. Copper wound transformers tend to produce less waste heat and so have better duty cycles than Aluminium equivalents so these are a bonus.

The welder must be fitted with a thermal overload device to switch it off automatically if it gets too hot. Check too that it has a strong steel case and for smaller machines is balanced when lifted by its carrying handle.

1.6 THE TRIGGER CONTROL AND TORCH

Take a look at a MIG welder and you will see that it has an earth clamp and cable rather like that found on a simple ARC welder. However, whereas an ARC welder has a simple holder and connecting cable for its welding electrodes, a MIG welder has a much more sophisticated trigger controlled 'torch' head and a flexible connecting tube down which shielding gas, welding wire and electrical current must flow.

The idea here is that the torch head is placed in close proximity (a few millimetres) to the metal being welded and the trigger is pressed. This pushes wire out of the Torch head's nozzle and switches on the power so 'igniting' the welding arc. At the same time shielding gas is released out of the torch head and over the arc and weld pool. Note that on poorer quality welders, whilst the wire feed and gas release is trigger controlled, the actual power for igniting the arc is always on. This is not particularly desirable since it can lead to the inadvertent striking of surface damaging Arcs if the torch head gets too close to the work piece.

The nozzle within the torch head forms the final electrical connection to the wire and so it is important that it is kept clean and in good condition. Just like wire feed rollers, nozzles are precision matched to the diameter of welding wire being used so check that the stamped diameter on the nozzle exactly matches that of the wire you are using.

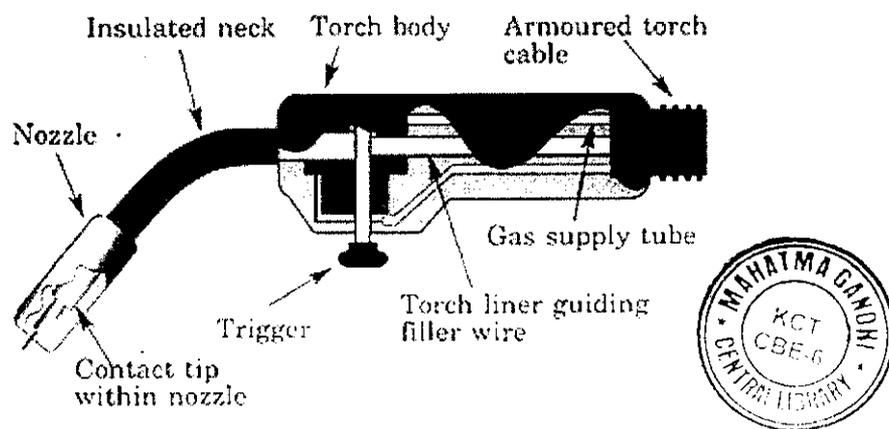


FIG. 1.2. TYPICAL MIG TORCH

1.7 CONSUMABLES

Unlike simple ARC welders, there are some parts of MIG Welders that should be considered consumables and these require regular inspection, maintenance and replacement if the machine is to produce consistently high quality welds. Luckily, these for the most part are associated with the torch head and the tubular liner that carries wire and gas to this head.

The torch head and the precision nozzle within it should always be handled with care. Dropping it to the ground or laying it down where it can be tripped over or trod on are recipes for disaster. Over time too, the head, nozzle tip and gas outlet can become clogged with weld spatter, especially in the hands of a novice welder. Regularly inspect these components and remove any build up of spatter, a special tool is cheaply available to assist this. It may also help to apply an anti spatter spray to the torch head before each use.

The actual tube that carries the MIG Wire from the reel to the torch head also deteriorates over time as the passage of wire wears it or leads to a build up of deposits. Corroded or kinked wire can also lead to problems and the end result of all these factors is that the wire feed becomes erratic and so impinges upon weld quality. If this starts to happen the only solution is to replace the liner and perhaps the torch head too. On most home MIG welders this means buying spares specific to the machine and part dismantling the machine to effect replacement. However, higher quality welders, and certainly professional models, allow the torch and liner to be rapidly replaced since they are fitted with a rapid release 'Euro torch' connector that allows standard torches and liners from any manufacturer to be used.

CHAPTER 2

LITERATURE SURVEY

LITERATURE SURVEY

2.1 INTRODUCTION

A brief and selective review of the relevant available information collected is presented in the following headings:

- (1) Experimental technique – Design of Experiments
- (2) Heat flow analysis

2.2 Experimental technique – design of experiments

It is essential to design the experiments on a sound basis rather than on the commonly employed trial and error method in conjunction with a small number of repeat experiments for confirmation of the results. However, for quality work and future predictions, trial and error methods are often little better than the guess work. Apart from the trial and error method of investigations, the commonly employed techniques by the researchers to analyse the effect of arc welding process parameters on weld responses are:

- (i) Theoretical approach
- (ii) Qualitative approach
- (iii) Qualitative cum dimensional analysis approach
- (iv) Specific qualitative approach
- (v) General quantitative approach.

Among the various techniques given above, theoretical approach is based on the predictions made on the basis of mathematical models developed by Rosenthal [1] and Christensen, et al [2], for determining temperature fields for welding plates of varying thickness. This approach has been used rarely to predict the angular distortion and residual stresses due to complexity caused by the interaction of different parameters involved.

Qualitative approach, perhaps the widely used approach, gives the investigator an intuitive grasp of the effects of welding process variables on the weld responses only over a narrow experiment range. Though it is not possible to predict angular distortion and residual stresses using this approach, it is useful for gaining knowledge of a welding process quickly and economically. Process parameter limits, easily established by this method, provide the basis for statistical design of experiment [3].

Qualitative cum dimensional analysis approach correlates the qualitative approach with dimensional analysis for predicting weld responses even beyond the limits of the ranges of the process parameters investigated [4]. This technique is quite useful but because the experiments are conducted on trial and error basis within narrow experimental ranges, neither optimization of parameters nor prediction of interactions between parameters is possible.

In specific quantitative approach the equations developed by different investigators for different studies are utilized to make predictions of weld responses [5].

This approach has a significant advance over the qualitative approaches, but the experimental designs produce predictive expressions of only limited applications.

The general quantitative approach has been popular for research in the field of medical, agriculture and chemical engineering for a long time. However, it has recently been used to design the experiments for welding research to predict the effect of welding input parameters on output parameters or response. Based on the results of the designed experiments, regression equations are developed using the method of least squares. F – Ratio and R – ratio test the adequacy of these equations. Using student t – test, the significance of each coefficient of different parameters are tested and final models are developed using only

those significant coefficients without sacrificing accuracy of the models. Final models can be tested again by drawing scatter diagrams, which relate the actual observed values and the predicted values, and conducting conformity tests for various combinational values of the process control parameters on residuals.

In general, this approach helps in minimizing the cost and time of testing and at the same time increases the probability of success. The use of commercially available software is reported in carrying out all the above analysis.

Therefore, it was decided to make use of statistical theory of experimental designs, which are well suited to engineering investigations. One such important design is central composite rotatable type favoured for the exploration of quadratic response surfaces [40].

Response surface methodology is a technique to determine and represent the cause and effect relationship between true mean responses and input control variables as a two or three-dimensional hyper surface.

The summary of the literature review about the experimental designs are listed below:

- Use of the statistical experimental techniques based on central composite rotatable design is well suited to welding related problems and investigations.
- The second order quadratic mathematical models can be used in predicting angular distortion and maximum longitudinal residual stress of multi-pass welds.
- Response surface methodology can be employed in empirical study of relationships between one or more measured responses and a number of independently controllable process variables.

As presented by several researchers, finite element method (FEM) has been successfully used to evaluate thermo mechanical response of the complex welding process. The microstructure of metal, which determines its mechanical properties such as tensile strength, hardness, etc., is a function of its chemical compositions, its initial structure, and the thermal process, which it undergoes during welding. Theoretically, if both the thermal histories and the response of the metal to the particular thermal history are known, the resulting changes in microstructure and mechanical properties can be predicted . In this research work the method of predicting temperature time histories with sufficient accuracy using FEA is detailed. Using this, metallurgical predictions will be easier.

The microstructure prediction of structural steel for a particular temperature history is presented in figure 2.4. For example in this cooling curve, the initial liquid phase is converted into liquid + delta (δ) phase. Further cooling induces reaction between liquid and δ phases to form γ -phase (austenite structure). As cooling progresses, as per the cooling curve, austenite is converted into α phase (martensite structure) after passing through γ -phase + α phase solution.

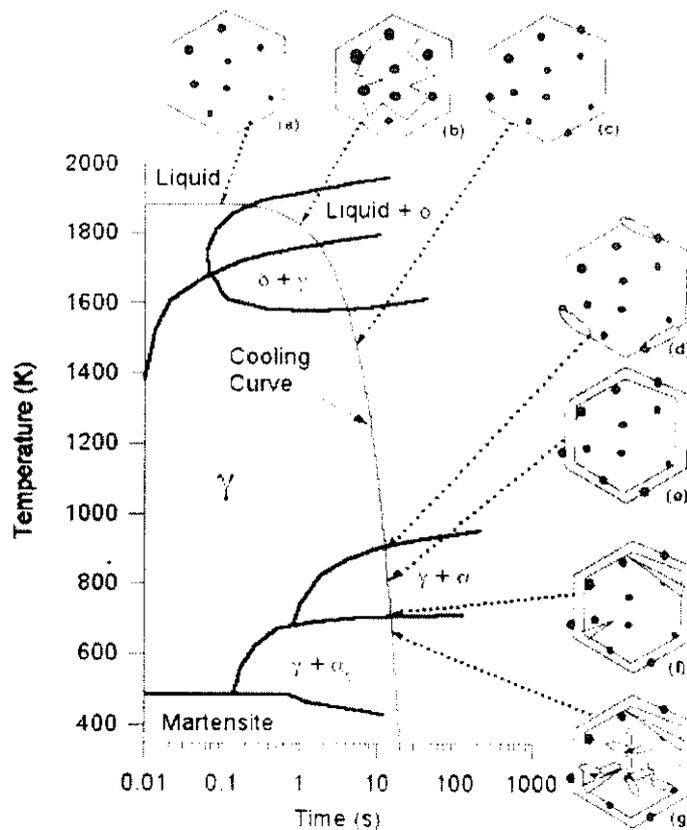


Fig.2.1 Microstructure variation for a particular cooling curve.

2.3 Heat flow analysis

The purpose of a thermal understanding of the welding operation is first of all to permit as comprehensive interpretation as possible of the metallurgical phenomena to take account of them in choosing welding processes and procedures. Apart from the metallurgical effects of heat flow in welding there are other phenomena involved including distortion, residual stresses and chemical modifications . . .

Temperature distribution in welding depends upon the type of the welding process used, type of heat source employed, energy input per unit time, configuration of the joint, type of joint, physical properties of the metal being welded and the nature of surrounding medium . . .

To interpret phenomena arising during welding operation at any given point in the welded structure, it is necessary to know the thermal cycle of welding, i.e. the temperature variation (θ) as a function of time (t)

Many investigators have studied experimentally the heat flow during arc welding.

Kihara et al. have studied the thermal history of the heat-affected zone and have found it difficult to make experimental data to match with the analytical results based on linear theory. They have measured thermal cycles of Heat Affected Zone (HAZ) of a bead laid on plate specimen using alumel – chromel thermocouple located at the bottom of the weld and at the toe of the weld bead.

They have proposed, on the data obtained in an extensive investigation, that the combined effect of plate thickness, pre-heating temperature and welding conditions on the cooling rate of the HAZ can be analyzed by a parameter, P, as follows.

$$P = \left[\frac{T - T_0}{\frac{I}{V}} \right]^{1.7} \left[1 + \frac{2}{\pi} \arctan \frac{t - t_0}{\alpha} \right]$$

T = Temperature at which cooling rate is considered, °C,

T₀ = Initial temperature or preheating temperature of the plate, °C.

I = Arc Current, Ampere,

V = Arc travel speed, inches per minute

t = plate thickness, inches

t₀, α = constants

It has been reported that continuous cooling transformation [CCT] diagrams are useful for studying the effects of welding heat input on metallurgical structures of the heat-affected

zone. Further they have investigated and presented the effects of certain parameters on cooling rate at heat-affected zone. Important effects are listed below:

- **Plate thickness and preheating temperature.** The cooling rates increases with the increase in plate thickness and preheat temperature.
- **Heat input.** The cooling rates were plotted against I / S and $V I / S$: I = Arc current, V = Welding voltage, S = welding speed. The values of cooling rate had a better correlation with I / S than $V I / S$. The result indicates that the amount of heat supplied to the plate Q is proportional to the arc current rather than the electric power. The cooling rate increases with the increase in the value of I / S .
- **Types of electrode coating.** Variations in the type of electrode coating introduce corresponding differences in the heat of the chemical reaction and in the melting point of the coating or slag and thus differences in the thermal cycles. According to the information presently available, differences in the cooling rate due to variations in the type of electrode coating are moderate, as long as welds are made under the same conditions.
- **Weld length and joint geometry.** The cooling rate increases with the weld length up to 64 mm. The cooling rate at the end of short weld is about twice the cooling rate at the centre of a long weld.

Relationships between cooling time and mechanical properties of specimens cooled at various rates from 1300°C have been presented . As the cooling rate increased, hardness decreased monotonously. However, the change of the impact value is rather complex.

Sekiguchi developed CCT diagram for structural steel showing critical points, critical cooling curves and critical cooling times. The investigators found that heat affected zone, which is cooled at a rate sufficiently slow to produce at least some transformation to eutectoid region, ordinarily do not crack spontaneously and exhibited a reasonable degree of ductility and toughness. However, too slow cooling is harmful to notch toughness. Considering above two factors, the cooling rate should be slow enough to avoid the formation of brittle martensite, but it should be rapid enough to not to lose good toughness. Fig.2.1 shows material microstructure response for a cooling curve.

Davies and Garland developed an empirical relationship to predict the distribution of peak temperature in base metal of single pass welds in plate and is given below:

$$\frac{1}{t_p - t_0} = \frac{4.13 \rho c t y}{h_{net}} + \frac{1}{t_m - t_0}$$

Where	t_p	=	Peak temperature, °C at a distance of y, mm
	t_0	=	Initial uniform temperature of plate, °C
	t_m	=	Melting temperature, °C
	h_{net}	=	Heat input to the base metal, $V I \eta / S$, KJ/mm
	ρ	=	Density of base metal, g / mm ³
	c	=	Specific heat of solid metal, J / g °C
	t	=	Thickness of base plate, mm
	y	=	Perpendicular distance in mm from fusion line to point for which peak temperature is being calculated.

As a heat source, weld zones and nuggets are not as quantifiable as the originating sources used in welding. From the correlation between arc energy input and HAZ cooling rate developed by many researchers, the following general observations were made :

- The peak temperature decreases rapidly with increasing distance from weld centreline.

- The length of time required reaching peak temperature increases with increase in distance from the weld centreline.
- The rate of heating and cooling both decreases with increase in distance from weld centreline.

Easterling states that arc welding generates complex thermal cycles and the thorough understanding of the effects of the thermal cycles on the various aspects of the weld bead is essential to achieve satisfactory joints in metals. The resultant properties of the weldment depend not only on heating and cooling rates but also on the peak temperature and the time of retention at high temperature. Chemical composition, grain size, inclusion size and its distribution, microstructure and mechanical properties are all depend on the nature of the thermal cycle applied to the material.

Kohno and Jones stress that knowledge of the heat input and their effects on resultant properties of the weldments could be very valuable to engineers concerned for design and selection of welding parameters. Rosenthal and Easterling stress that heat input per unit length of weld has to be taken as the dominant factor in controlling cooling rate of the weld and hence the properties.

Based on the above observations, the scope of this research work is listed as follows:

- Experiments were carried out to measure the temperature – time history.
- Analysis on maximum temperature reached and cooling rate at a specific location was carried out to study the effects of process variables on these parameters.

CHAPTER 3

HISTORY OF GMAW PROCESS

3. HISTORY OF GMAW PROCESS:

At the most basic level, MIG welders are similar in principle to ARC Welders in that they use an electric arc to melt and fuse metal surfaces and a sacrificial 'electrode' together. However whereas an ARC Welder uses a simple, short metal rod that has to be replaced frequently as it is consumed, MIG welders use a thin metal wire that is fed, by an electric motor, continuously into the melting weld pool. Because this wire is supplied in a very long coiled length, it lasts for many hours. The wire will be made of an alloy appropriate to the metal being welded and as we have already said, this could be steel, Aluminium or Stainless Steel.

But, just as in Arc Welding, something has to be done to keep Oxygen gas (from the atmosphere) reacting vigorously with the hot, molten weld pool and so spoiling the weld. Arc Welders use a special coating on the welding rod (called flux) that melts and covers the weld pool to act as barrier between it and the surrounding oxygen. Unfortunately, this coating cools to form a hard 'slag' that retains heat and can also become trapped in the weld, seriously weakening it.

MIG Welders tackle the Oxygen problem in an entirely different way, by effectively blowing it away from the Weld pool with another gas. But this time it's a gas carefully chosen for its inert properties and that means it will not react with the molten weld pool. As the electric arc melts the metal surfaces and wire to form the molten weld pool, the special protective gas is blown out of a surrounding Nozzle and so shields the weld pool from that pesky Oxygen.

GMAW welding equipment basically consists of four units; the power supply, the wire feeding mechanism, the welding gun (also referred to as the torch) and the shielding gas supply.

3.1 POWER SUPPLY:

The basic concept of GMAW power supply was first developed in 1948. The characteristics of the GMAW machine are best described in terms of the four basic means by which metal is transferred from the electrode to the work piece namely, short circuiting transfer, globular transfer, spray transfer and pulsed – spray transfer

The short circuiting mode of GMAW was the first developed technique and is associated with low average currents and voltage levels. The electrode actually contacts the weld pool initiating a “short circuit” which causes a rapid rise in current flow, and the subsequent melting of the tip of the electrode. This short circuiting process occurs at a frequency in the range of 20 to over 200 cycles per second. No metal is transferred across the arc gap. This results in rather violent transfer of the molten metal, which results in high spatter.

As the voltage and amperage of the GMAW process are increased, the electrode starts to melt prior to contacting the work piece surface and metal is transferred across the arc. At a transition point, globular transfer occurs which is characterized by a droplet size with a diameter greater than that of the electrode. The larger droplet size which is affected by gravity is achieved only for small diameter wires that to in the flat position.

With increasing current and with the use of argon – rich shielding gas, a transition to spray transfer occurs. Spray transfer is characterized by very small drops, which are formed and detached at the rate of hundreds per second. They are accelerated across the arc gap by arc forces at speed sufficient to overcome the effect of gravity. This mode of operation is characterized by much deeper penetration and much lower spatter levels than either short circuit or globular modes. Spray transfer is capable of producing high – quality welds meeting any quality standards. It has one serious limitation; the large drop size, which rapidly forms from the high heat input, is acted upon by gravity, making this unsuitable for out of position welding.

The development of pulsed spray GMAW machine was undertaken in the 1960s to overcome some of the problems of spray transfer that occur above a certain transition current. Pulsed spray varies the current to peak above the transition level during which spray transfer occurs, and with background levels below this transition current. The background current provides some energy to melt the wire, but not sufficient enough to transfer metal. The peak current pulses complete the melting, adding enough energy to transfer molten droplets. The average current level is actually maintained below the transition current, thus limiting droplet size. Pulse spray technique provides the benefits of spray transfer (high penetration and low spatter) with lower heat input and permits welding in all positions.

During the late 1960s, transistorized power supply to GMAW process was developed. These controls had both Constant Current on Demand Wire (CCODW), and Constant Voltage Constant Wire (CVCW) modes of operation. The pulsing characteristics of both the modes produced a GMAW arc plasma column that was not available with conventional DC power supplies.

In the late 1970s, a new GMAW control system that provided the best features of the CCODW and CVCW modes was developed. This new mode used an inner constant current weld power supply servo control system with excellent current regulation dynamics.

In 1985 a GMAW control process, which provided direct real time adaptive control of the energy delivered in each peak current pulse, was developed. When the arc gap (nozzle-to-plate distance) encounters a reduced distance (because of a surface ripple or a side wall) the arc voltage would be reduced.

In mid 1990s fuzzy logic control, to automatically adjust arc voltage to optimize arc characteristics, resulting in excellent weld bead profiles that are free of spatter, was used in GMAW power source. This power supply alternates between constant voltage and constant current during the course of the welding process. Relationships between welding process parameter are factory pre-programmed for a specific wire type, diameter and shielding gas.

In late 1990s the application of stainless steel filler wires was successfully used in welding application and that was considered as a major accomplishment in this program.

3.2 Wire feed mechanism

The wire feed drive motor is used to drive the electrode wire automatically from the wire spool through the gun, up to the arc point. The speed of the wire feed can be varied by adjusting the controls on the wire feed control panel to set any required volume of metal melted per unit time.

3.3 Welding gun

The function of the welding gun is to carry the electrode wire, the welding current, and the shielding gas to the arc area. The gun has a trigger switch that controls the wire feed and arc as well as flow rate of the shielding gas. The welding operator directs the arc and controls the weld with the welding gun.

3.4 Shielding gas supply

External shielding gas is used to prevent the electrode and weldment from oxidizing. Some of the shielding gases commonly used with the GMAW process are pure argon, argon-helium, argon-oxygen, argon-carbon dioxide and carbon dioxide (CO₂). Because of its low cost, CO₂ is used primarily for the GMA welding of mild steel. CO₂ produces deep penetration pattern, good bead contour and there is no tendency towards under cutting.

The lay out GMAW welding equipment and cross section of the welding gun is shown in fig.3.1 and fig 1-2 respectively.

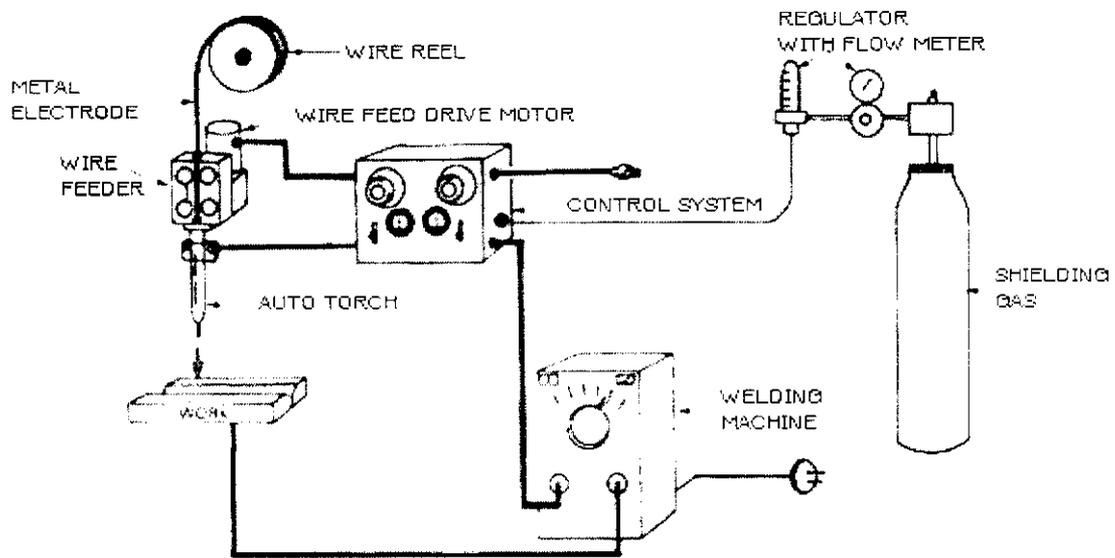


Fig 3.1. Lay out of GMAW process.

3.5 Structural steel plates

The popularly used structural steel designated as IS: 2062 (Grade A), manufactured by Steel Authority of India Limited (SAIL), of 16 mm thickness was used as base metal for the present investigations. The chemical composition and important mechanical properties of this mild steel are given below :

C% (Max)	Mn% (Max)	S% (Max)	P% (Max)	Si% (Max)	CE% (Max)
0.23	1.50	0.050	0.050	0.40	0.42

Minimum yield strength = 240 MPa

Minimum ultimate tensile strength = 410 MPa

Generally mild steels with 0.15 to 0.20% carbon contents have excellent weld ability. Mild steels at the upper end of the low carbon range i.e. 0.25 to 0.35% Carbon steels with manganese 1.40% have very good weld ability. If some

of the elements – particularly C, Si or S – are on the higher side of the permissible limits, surface pitting may occur.

Although carbon is the most significant alloying element affecting weldability, the effects of other elements can be estimated by converting them to their carbon equivalent (C. E.)

This C.E. value will determine the crack sensitivity, hardness and notch – bead bend angle of the weldment, which is the actual measure of weldability of steel. The carbon equivalent of the selected structural steel is 0.7 and its weldability is just good.

3.6 Design of experiments

Design of experiments (DOE) is a scientific approach of planning and conducting experiments to generate, analyse and interpretation of the data so that valid conclusions can be drawn efficiently and economically. It has proved to be very effective for improving the process yield, process performance and process variability. Direct and indirect effects of the process variables were analyzed and presented in the graphical form.

The following steps are the detailed procedures that were followed in this work to achieve the above aim.

Trial runs were conducted to find the limits of process parameters to facilitate the design of experiments for the development of mathematical models. Experiments were conducted as per the design matrix. The micro hardness and the heat flow were measured and graphs were drawn.

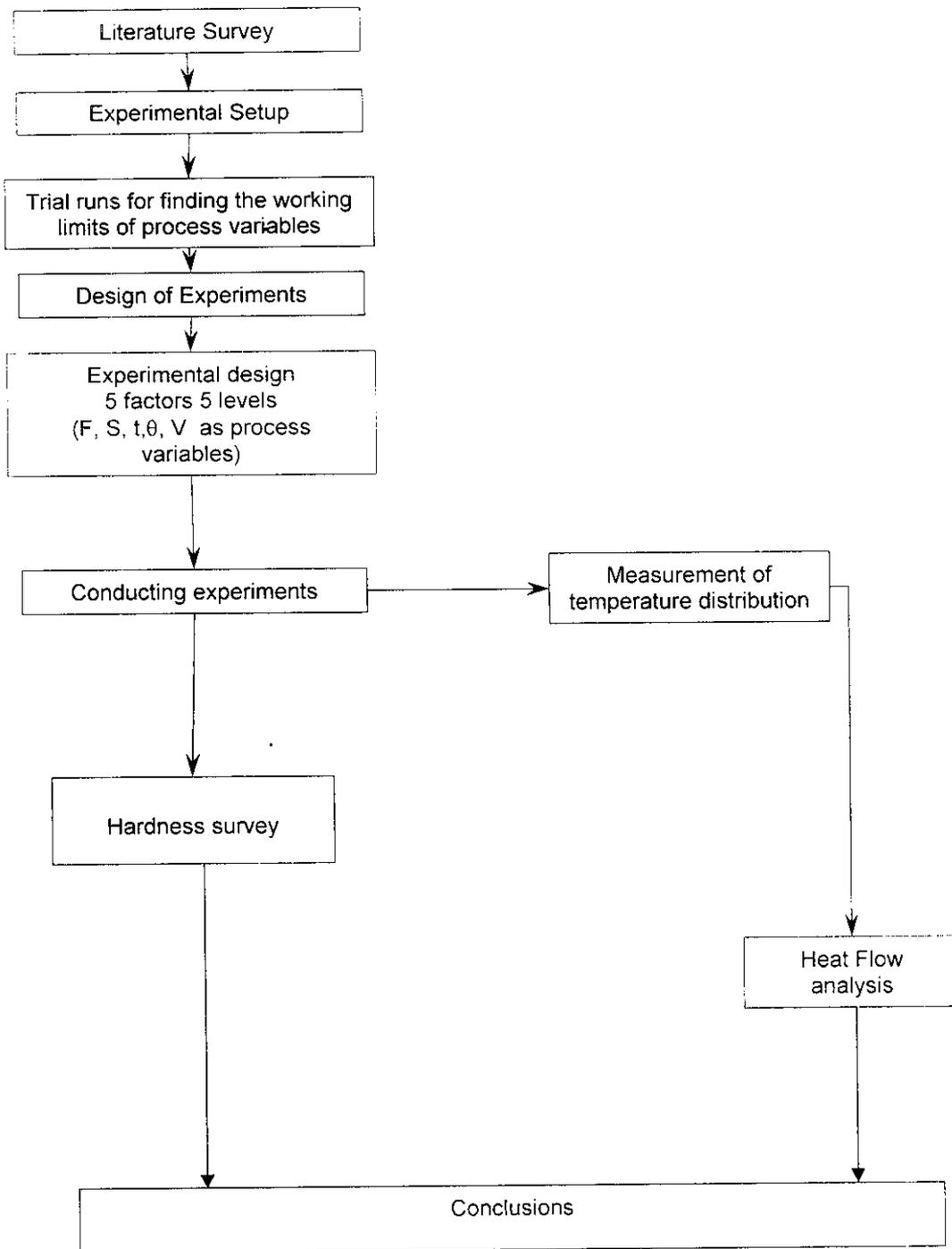


Fig 3.2. Sequence of project work

CHAPTER 4

EXPERIMENTAL DESIGNS

EXPERIMENTAL DESIGNS

4.1 Introduction

To study the effects of process control parameters on the angular distortion and maximum longitudinal residual stress, with the help of mathematical models, it is essential to generate the data by carrying out experiments corresponding to actual conditions of fabrication.

The experiment should provide the required information within minimum time and effort. Therefore, to conduct experiments, the experimental plan and program must be well prepared and designed. The design of experiments deals with the procedure of selecting the number of trials and conditions for running them, essential and sufficient for solving the problem that had been set with the required precision.

Among the various research techniques discussed in chapter II, the general quantitative approach, which is more logical than any other, was selected for designing the experiments. One of the important statistical techniques that had been recommended for the design of experiments in engineering investigations is the factorial technique. In the present work, a five level factorial technique was employed for the development of design matrix to conduct the necessary experiments.

In this Chapter, factorial techniques such as five level response surface designs, and all other relevant information pertaining to material used, experimental setup employed, etc. which directly or indirectly assist in design and conduct of the experiments are detailed.

4.2 Base material and consumables used

The chemical composition, mechanical properties and weldability of the structural steel, which is the base material for the research was discussed earlier in section 1.3. The cross sectional view of the specimen of size 300 X 150 X 25 mm with edge preparation is shown in fig 4.1.

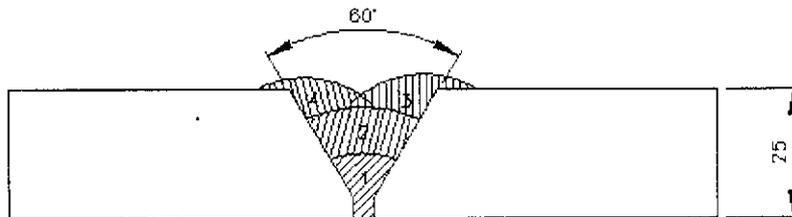


Fig.4.1 Cross section of a specimen showing edge preparation.

AWS ER 70 S – 6 (equivalent to DIN 8559) copper coated steel wire of 1.2 mm diameter in the form of coil was used as electrode for welding. The chemical composition of the steel wire is given below.

Carbon (C) – 0.07%

Manganese (Mn) – 1.45%

Silicon (Si) – 0.05%

External shielding gas carbon – dioxide (CO_2) is used to prevent the electrode and weldment from oxidizing. The specific recommendations for using CO_2 as shielding gas are discussed earlier in section 3.4. The flow rate and properties of CO_2 are given below.

Flow rate	= 200 cm^3/sec
Thermal conductivity	= 15.20 $\times 10^{-3}$ w/m-K
Specific heat	= 0.83 $\text{kJ/kg}^{-0}\text{K}$
Kinematic viscosity	= 7.36 $\times 10^{-6}$ m^2/sec
Density	= 1.9022 kg/m^3

4.3 Experimental setup

A semi-automatic thyrister controlled Metal Inert Gas welding machine, manufactured by NASH MACHINES & ELECTRONICS PVT LTD. was used for conducting all the experiments. It has provisions for fine control of wire feed rate and meters are also provided in the control panel to display arc voltage and welding current. A transformer cum rectifier of constant potential (flat characteristic) type power source specially designed for automatic MIG welding process was used. It could supply current from 50 Amp to 400 Amp and a supply voltage of 415 VAC, 50/60 HZ.

The movement of welding specimen against the fixed welding torch was carried out with the help of servo – motor driven linear manipulator. This linear manipulator has the capability of moving the base plate at pre-set welding speed in X and Y direction. The base plate is provided with T – slot to fix the welding specimen.

The lay out of the Gas metal arc welding machine and cross sectional view of welding gun is given in fig 3.1 and 1.2 respectively. Photographs of the experimental setup employed in this research work are shown in fig below.

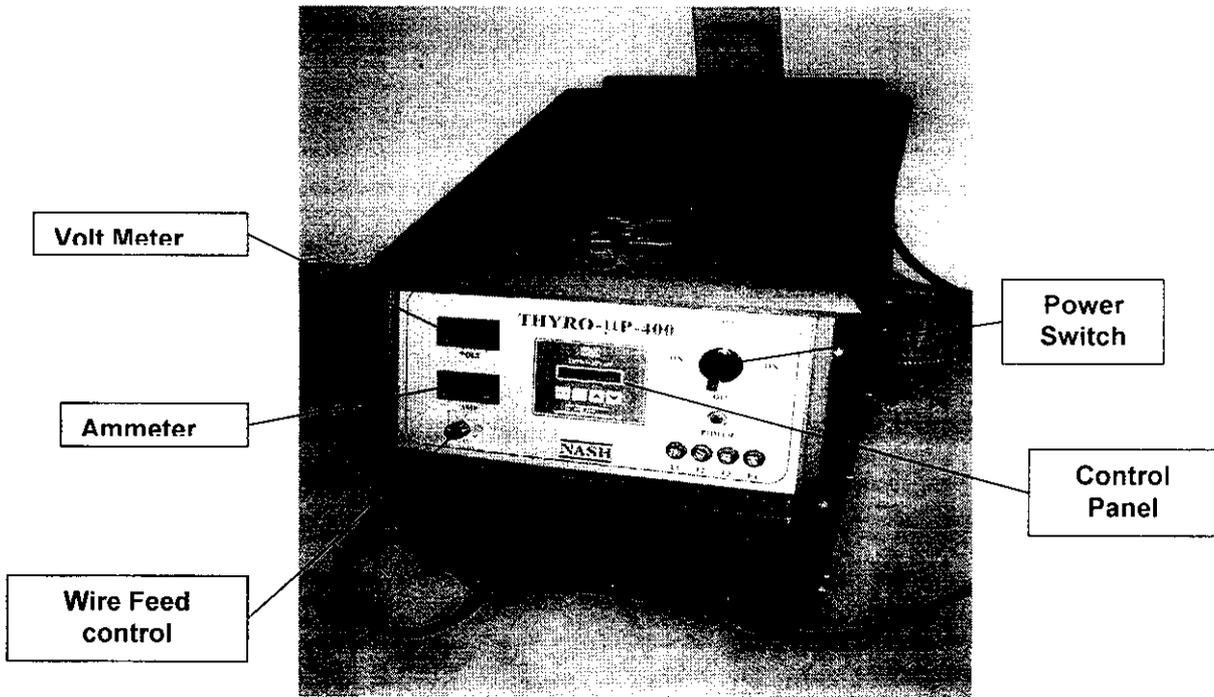


Fig. 4.2 Welding power source.

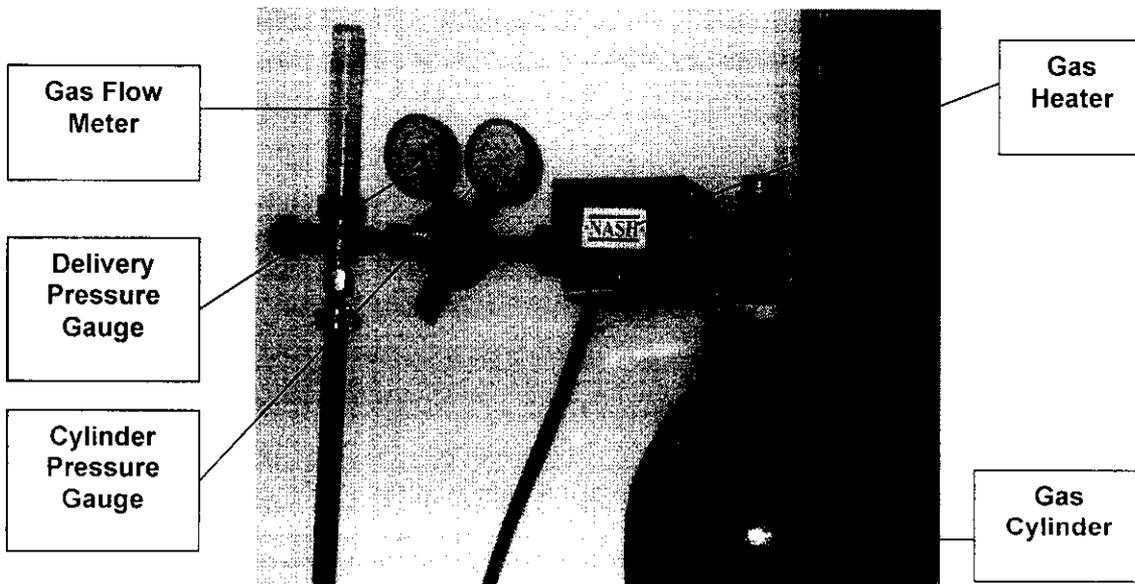


Fig. 4.3 Gas supply unit.

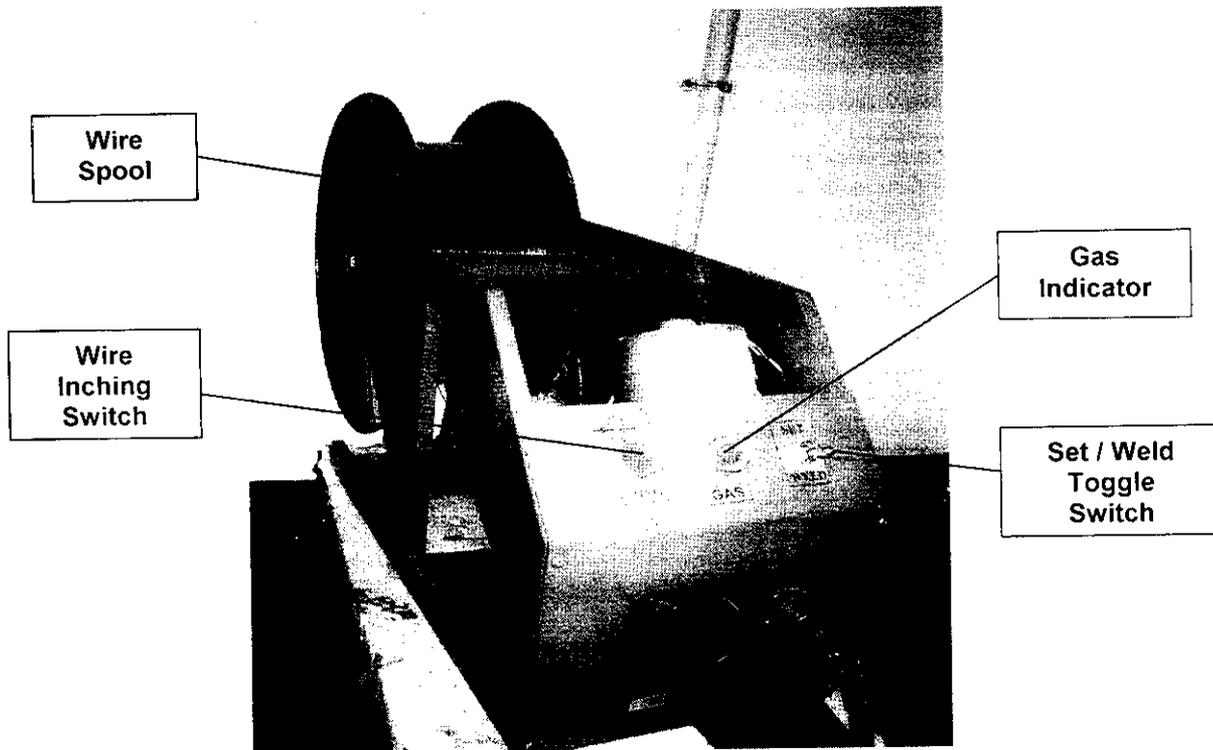


Fig. 4.4 Wire feeding mechanism.

4.4 Terminology used in design of experiments

The terms used in Design of experiments include factor, levels, treatment, response, direct effect and interaction effect. Brief descriptions of these terms are given below:

- **Factor** is an independent variable or attribute, which influences or is suspected of influencing the responses being investigated. A factor may be independently controllable and measurable variable (e.g. welding speed in mm/sec, wire feed rate in m/min) or it may be an attribute whose presence or identity may be determined.

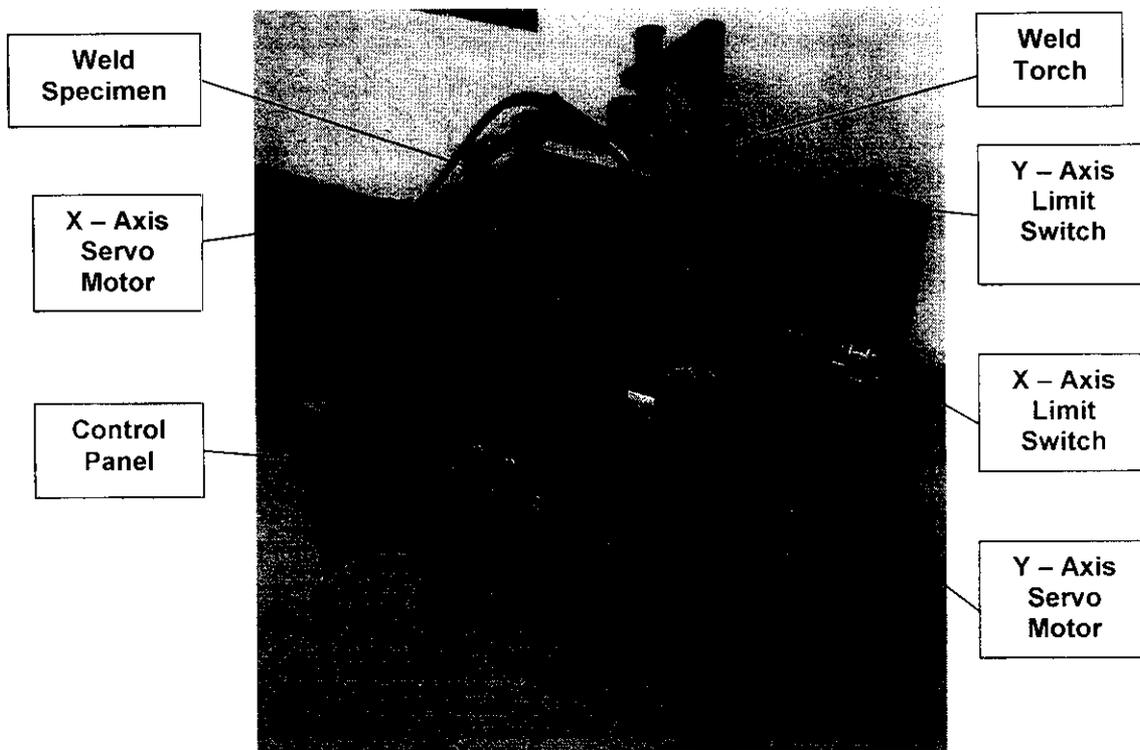


Fig 4.5. Linear manipulator.

- **Levels** are the values or qualitative features of a factor being examined in an experiment. If the factor is an attribute, each of its state is a level. For example, electrode polarity (one factor) has two levels either positive or negative. If the factor is variable, the range is decided into two or more intervals, each of which is then a level. For example, if the nozzle angle ranges from 70 degrees to 110 degrees and five ranges are used, then 70 to 80 should be one level, 80 to 90 a second level, and so on.
- **Treatment** is one set of levels of all factors employed in a given experimental run.
- **Response** is the numerical result of an observation or output parameter with a given treatment (e.g. angular distortion, maximum residual stress, etc.).

- **Effect** of a factor is the change in response due to changes in levels of that factor.
- **Direct effect** is the effect of a factor on response when the level of that factor is changed.
- **Interaction effect** is the combined effect when the levels of two or more factors are changed at a time.

TABLE 4.1 DESIGN OF EXPERIMENTS- DESIGN MATRIX:

Expt No	Wire Feed Rate (F)	Welding Speed (S)	Time Gap Between Passes (t)	Angle of Electrode (θ)	Velocity of Air (v)	Peak Hardness in HAZ
1	-1	-1	-1	-1	1	214
2	1	-1	-1	-1	-1	205
3	-1	1	-1	-1	-1	221.7
4	1	1	-1	-1	1	206.7
5	-1	-1	1	-1	-1	198.8
6	1	-1	1	-1	1	205.3
7	-1	1	1	-1	1	209.9
8	1	1	1	-1	-1	209.3
9	-1	-1	-1	1	-1	209
10	1	-1	-1	1	1	200.7
11	-1	1	-1	1	1	208.3
12	1	1	-1	1	-1	221
13	-1	-1	1	1	1	213.5
14	1	-1	1	1	-1	212
15	-1	1	1	1	-1	205.7
16	1	1	1	1	1	211.1
17	-2	0	0	0	0	200.7
18	2	0	0	0	0	211.98
19	0	-2	0	0	0	206.3
20	0	2	0	0	0	202
21	0	0	-2	0	0	212.1
22	0	0	2	0	0	211.5
23	0	0	0	-2	0	212.3
24	0	0	0	2	0	224.3
25	0	0	0	0	-2	204.9
26	0	0	0	0	2	208.7
27	0	0	0	0	0	213.3
28	0	0	0	0	0	218.7
29	0	0	0	0	0	221.3
30	0	0	0	0	0	219.4
31	0	0	0	0	0	217.1
32	0	0	0	0	0	214

TABLE 4.2: FACTOR LEVELS OF PARAMETERS:

Parameters	Notations	Units	Factor Levels				
			-2	-1	0	1	2
Wire Feed Rate	F	m/min	6	6.5	7	7.5	8
Welding Speed	S	cm/min	15	16	17	18	19
Time Gap between passes	t	min	5	10	15	20	25
Angle of Electrode	θ	degree	70	80	90	100	110
Velocity of Cooling Air	V	m/sec	0	8	16	24	32

CHAPTER 5

MICRO-HARDNESS SURVEY

MICRO-HARDNESS SURVEY

5.1 Introduction

Hardness testing has been proposed as a practical indicator for HAZ cooling rate because given steel when continuously cooled at various cooling rates from above its critical range will transform to particular microstructures each having intrinsic levels of hardness. That is, both microstructure and its hardness are firmly determined by the rate of cooling that prevails as the austenitized steel undergoes transformation. In general, faster cooling rates produce harder microstructure. This hardness-cooling rate relationship is reliable in its repeatability, and is dependent on the given hardenability of steel, which is a characteristic of carbon and low-alloy steels that is governed primarily by their composition and the austenite grain size. A number of tests have been developed for quantifying the hardenability of steel

Standard metallurgical procedures were used to prepare the samples for micro hardness studies. The samples were etched with 2% nital to facilitate micro hardness survey along the different zones of the weldment such as weld metal, fusion zone, HAZ and unaffected metal. For each specimen, measurements were taken on both sides and the mean value was calculated. These mean values were used to plot a two dimensional graphs to show the relationship between the hardness and the distance along the centreline of the weld bead profile.

To study the effect of process variables Wire feed rate (F), Welding speed (S), Time gap between passes (t), Angle of electrode (θ) and Velocity of cooling air (V) on peak hardness, ten specimens (Experiments. 17 to 26) were selected from the experimental designs. The combination of process variables is tabulated in Table. 5.1.

Table 5.1
Combinations of process variable for experiments

Sl. No	Exp t No	Wire Feed Rate (F-m/min)	Welding Speed (S-cm/min)	Time Gap Between Passes (t-min)	Angle of Electrode (θ -degrees)	Velocity of Air (V-m/sec)
1.	17	6	17	15	90	16
2.	18	8	17	15	90	16
3.	19	7	15	15	90	16
4.	20	7	19	15	90	16
5.	21	7	17	5	90	16
6.	22	7	17	25	90	16
7.	23	7	17	15	70	16
8.	24	7	17	15	110	16
9.	25	7	17	15	90	0
10.	26	7	17	15	90	32

5.2 Analysis of Micro Hardness Survey:

The micro hardness survey carried out in various zones of carbon steel weldments is presented in fig5.1 to 5.27. The hardness was measured at very close distances (in the order of 0.02 mm in the fusion zone and HAZ) across the bead profile along its centre line. A hardness curve for the weldment may be divided into four regions such as weld metal(WM), fusion boundary or fusion zone(FUZ), heat affected zone(HAZ), and unaffected base metal(BM) and the same has been done in all the cases presented in these figures.

It is evident from the figures that the micro hardness values of HAZ are higher than the unaffected base metal and the other zones of weldment in all the cases. Also, it was found that hardness value is maximum in coarse grain region or grain growth region of the super critical zone of HAZ in all the cases analyzed. This might be due to the formation of non aligned ferrite along with M-A-C (Martensite-Austenite-Carbides).

5.3 Direct Effect of Wire Feed Rate

It is known that the dimensions of all the different regions of HAZ namely FUZ, GGZ, GRZ increases with the increase in the value of F. These effects are due to the fact that as F increases the heat input value also increases more or less proportionately. But increase in the heat input level results in the increase of peak temperature. The value of peak temperature has a positive effect on the width of the different zones of the HAZ.

It is observed that PMH increases with the increase in F. The primary reason for these effects is increase in heat input level as F is increased. Higher the heat input, faster the cooling rate and harder the micro structure. Hence PMH increases as F is increased.

It can be seen from fig 5.17 and 5.18. that for feed rate of 6 m/min. PMH value is 200.7 VHN and for the feed rate of 8 m/min, PMH value is 211.98 VHN. Thus it is clear that as feed rate increases the hardness value decreases.

5.4 Effect of Welding Speed

Welding speed is the main factor controlling the heat input and hence the dimensions of HAZ. PMH decrease with increase in S. These effects are due to the reason that heat input is almost inversely proportional to the welding speed. As S increases heat input decreases. Since the heat input decreases the peak temperature decreases the cooling rate will be slower and hence the PMH decreases with the increase in welding speed S.

It can be seen from the fig. 5.19 where welding speed is 15 cm/min, the PMH value is 206.3 VHN whereas from fig. 5.20 where the welding speed is 19 cm/min, the PMH value is 202 VHN. Thus it is quite clear that the PMH decreases with the increase in welding speed.

5.5 Effect of Time Gap between Passes

The time gap between passes is having negative effect on PMH. When the time gap between the passes is less the temperature of the base metal is higher. Hence the peak temperature is also high. This effect leads to faster cooling rate and hence greater the value of PMH.

It can be seen from the fig. 5.21 where time gap between passes is 5 min, the PMH value is 212.1 VHN whereas from fig. 5.22 where time gap between passes is 25 min, the PMH value is 211.5 VHN. Thus it is quite clear that the PMH decreases with the increase in time gap between passes.

5.6 Effects of Angle of Electrode to Work Piece

In case of backward welding ($\theta < 90$), the arc is focused in the direction opposite to its direction of movement which keeps the weld pool ahead of it in hot condition. But in forward ($\theta > 90$), the arc is kept in the same direction of welding, and hence it melts only the surface of the base plate ahead of the torch. Because of these reason θ has significant effect on PMH.

Also it is known that the dimensions of the different zones of HAZ decrease as θ increases from 70 to 110 degrees. The reason of these effects is increasing θ from 70 to 110 degrees results in shifting torch from backward to forward. As backward welding keeps the molten pool in worm conditions cooling takes place slightly at lower rate compared to forward welding. As cooling rate is more in the forward welding the PMH increases as the torch shifted from backward to forward welding condition.

It can be seen from the fig. 5.23 where $\theta = 70$ degrees, the PMH value is 212.3 VHN whereas from fig. 5.24 where $\theta = 110$ degrees, the PMH value is 224.3 VHN. Thus it is quite clear that the PMH increases as the torch shifted from backward to forward welding condition.

5.7 Effect of Velocity of Cooling Air

The value of PMH increases with the increase in velocity of cooling air. This is because of the fact that as the velocity of cooling air increases, the cooling rate of the molten metal in the weld pool also increases. And we know that greater the cooling rate, greater the value of PMH. However the effect is decreased due to decrease in peak temperature as velocity of cooling air increases.

It can be seen from the fig. 5.25 where the velocity of cooling air is 0 m/sec, the PMH value is 204.9VHN whereas in the fig.5.26, where the cooling velocity of air is 32 m/sec, the PMH value is 208.7 VHN. Hence it is quite evident from the above comparison that the greater the value of cooling velocity, greater the value of PMH.

ABBREVIATIONS:

WM	-	Weld metal
FUZ	-	Fusion zone
HAZ	-	Heat affected zone
BM	-	Base metal
S	-	Welding speed
V	-	Velocity of cooling air
F	-	Wire feed rate
T	-	Time gap between passes

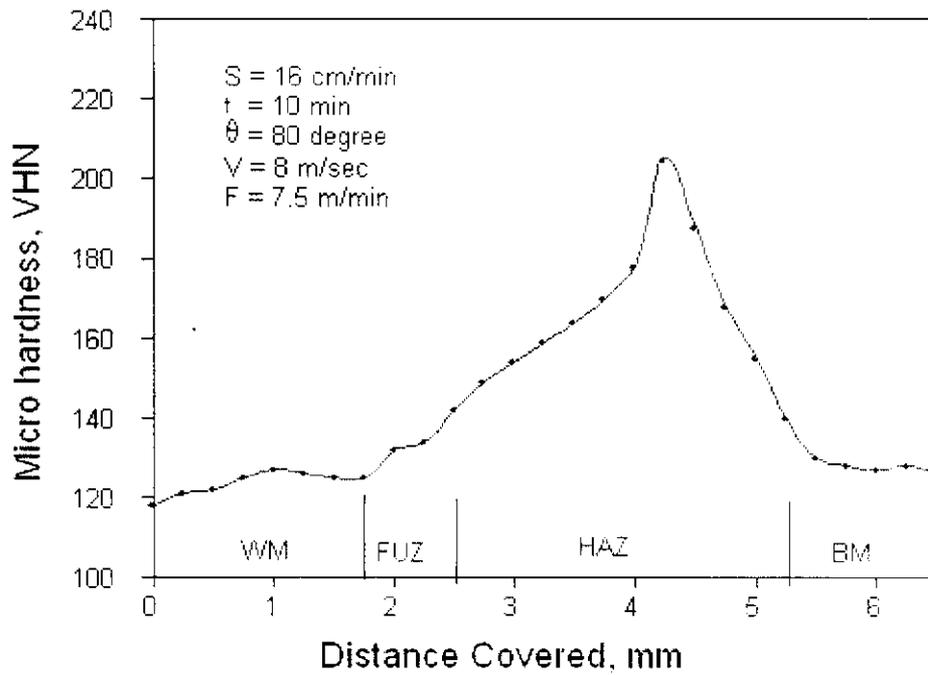


Fig. 5.1 Micro-Hardness Survey (Specimen No. 1)

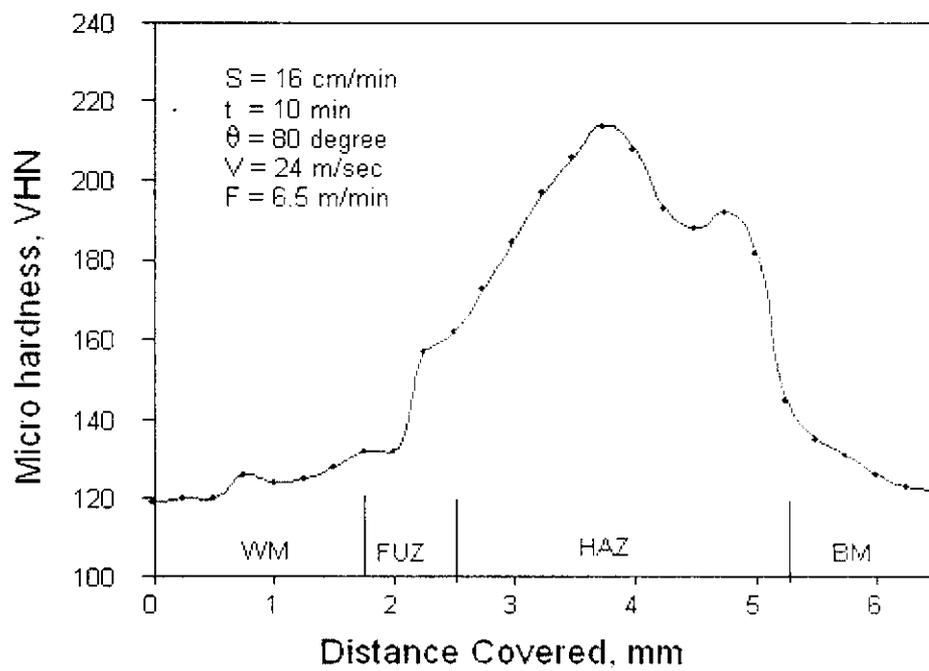


Fig. 5.2 Micro-Hardness Survey (Specimen No. 2)

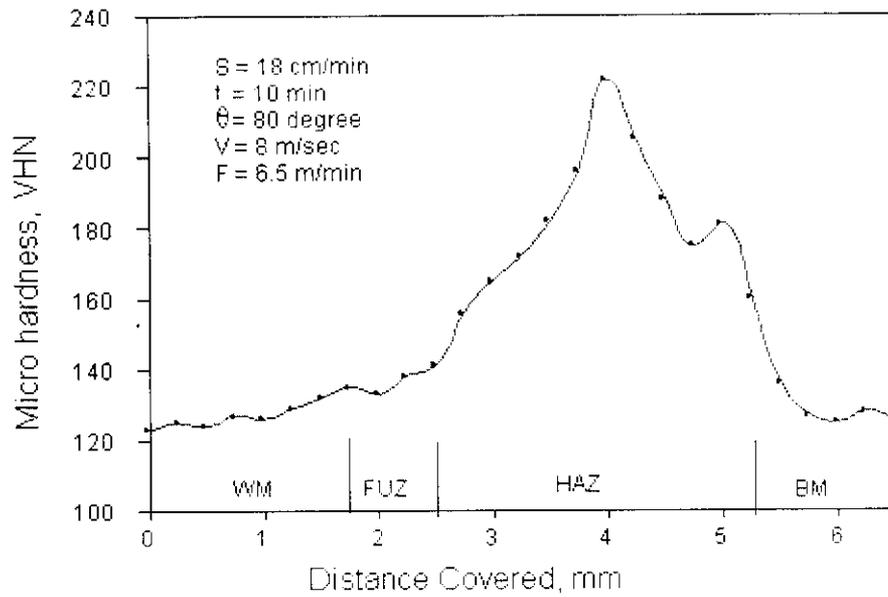


Fig. 5.3 Micro-Hardness Survey (Specimen No. 3)

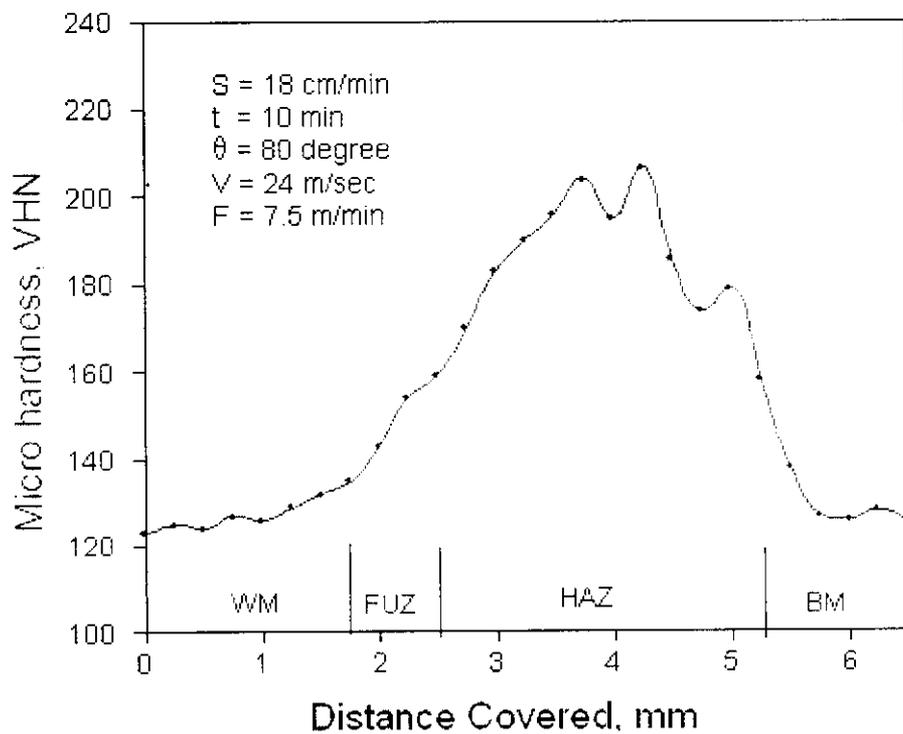


Fig. 5.4 Micro-Hardness Survey (Specimen No. 4)

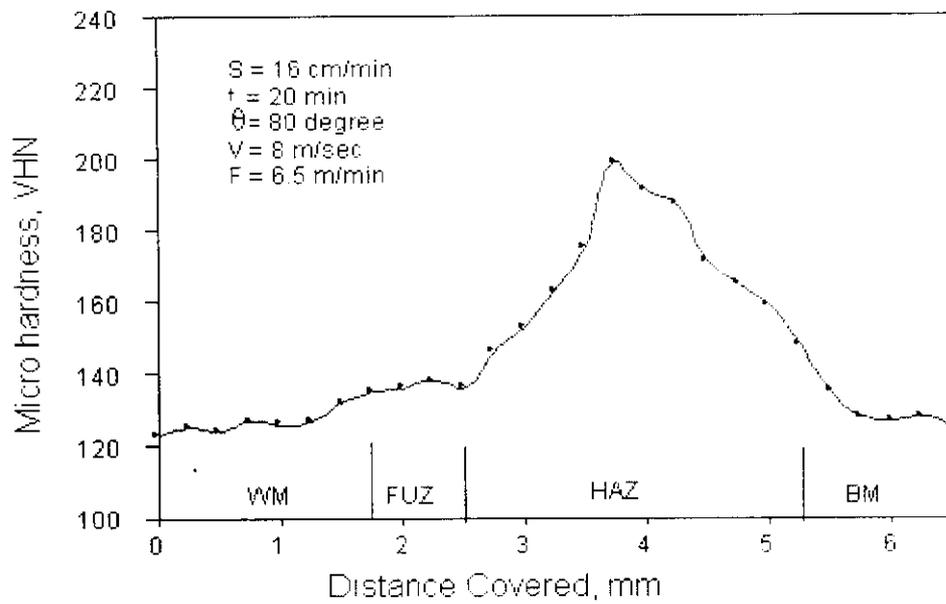


Fig. 5.5 Micro-Hardness Survey (Specimen No. 5)

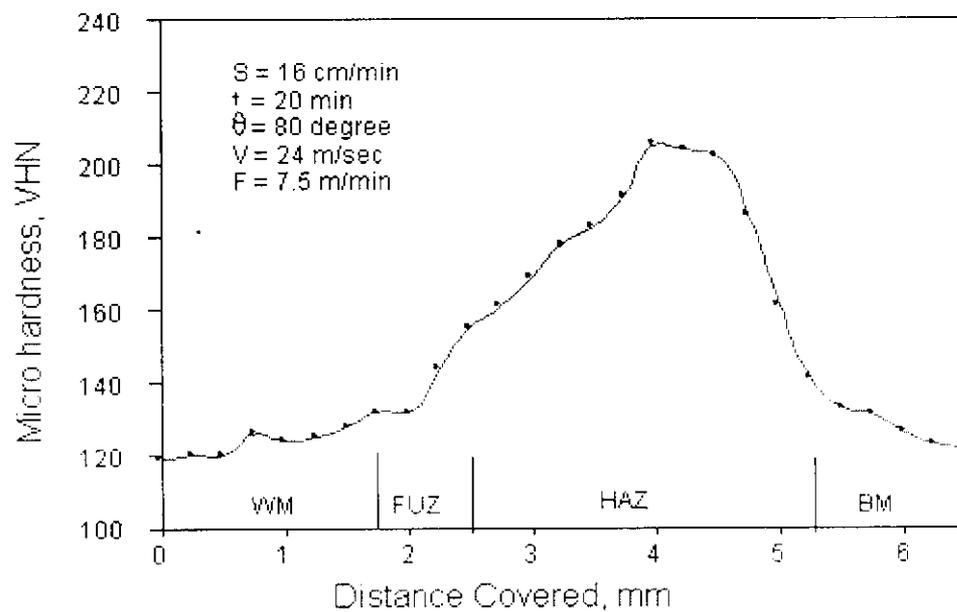


Fig. 5.6 Micro-Hardness Survey (Specimen No. 6)

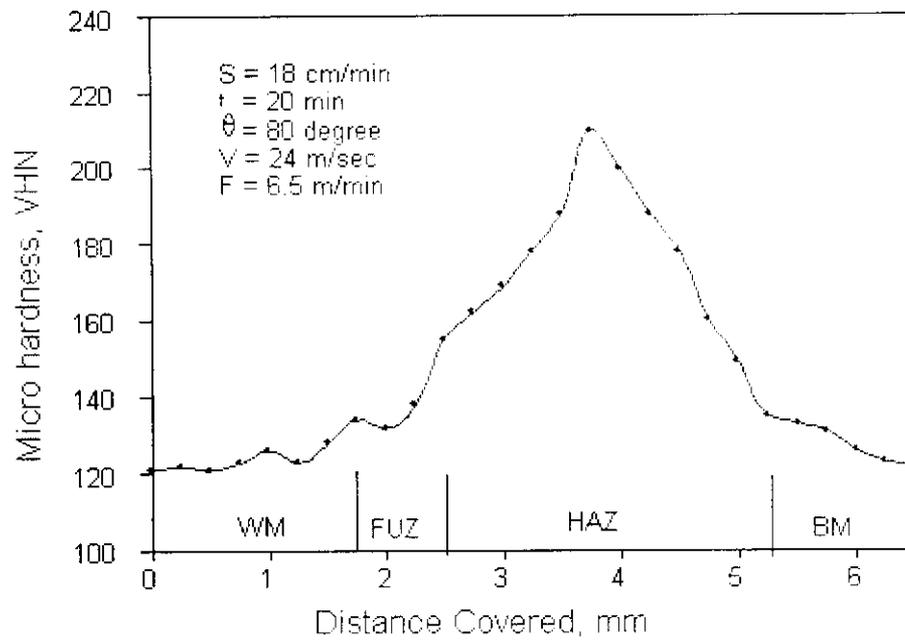


Fig. 5.7 Micro-Hardness Survey (Specimen No. 7)

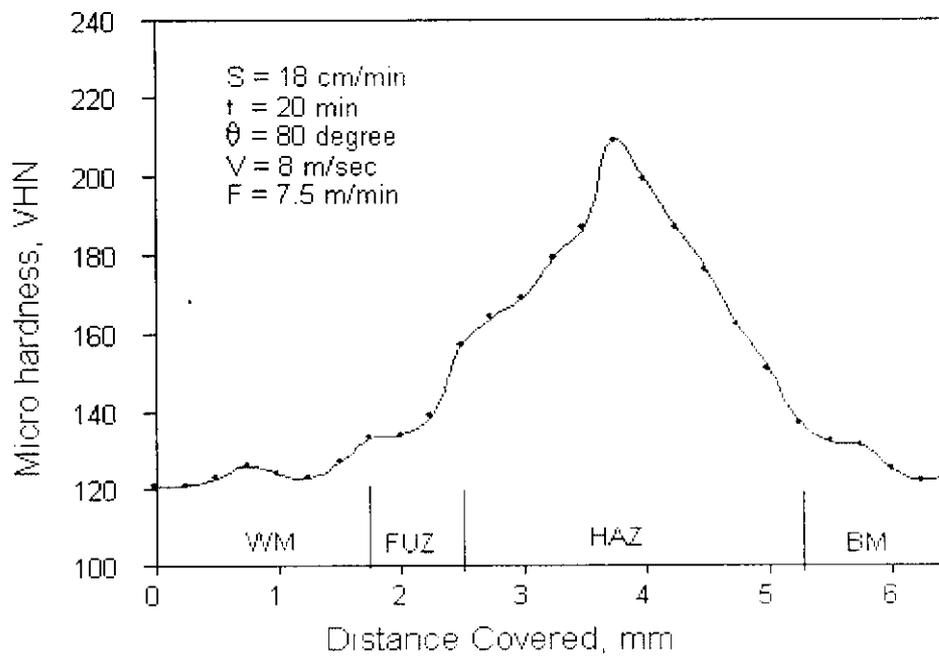


Fig. 5.8 Micro-Hardness Survey (Specimen No. 8)

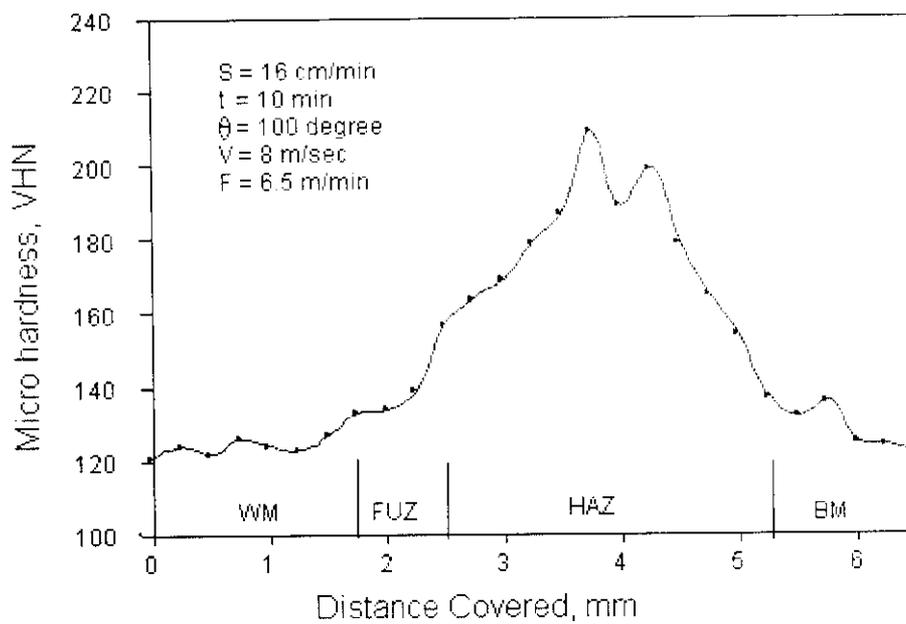


Fig. 5.9 Micro-Hardness Survey (Specimen No. 9)

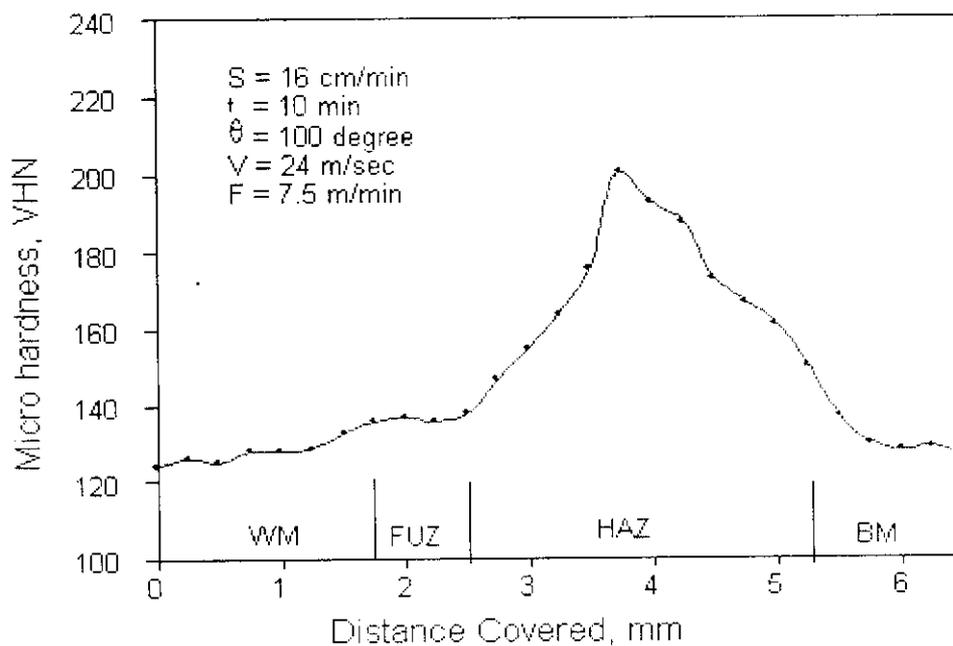


Fig. 5.10 Micro-Hardness Survey (Specimen No. 10)

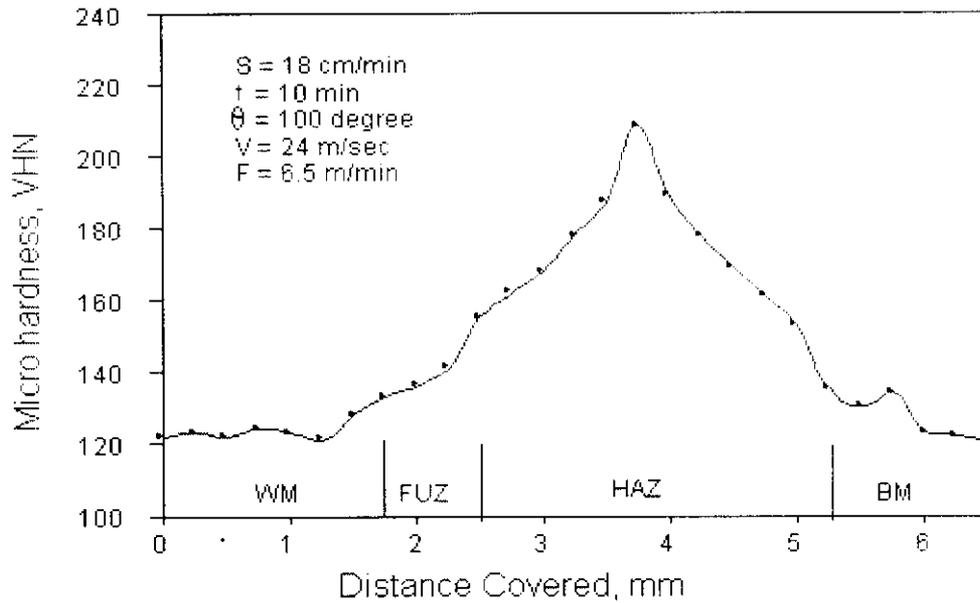


Fig. 5.11 Micro-Hardness Survey (Specimen No. 11)

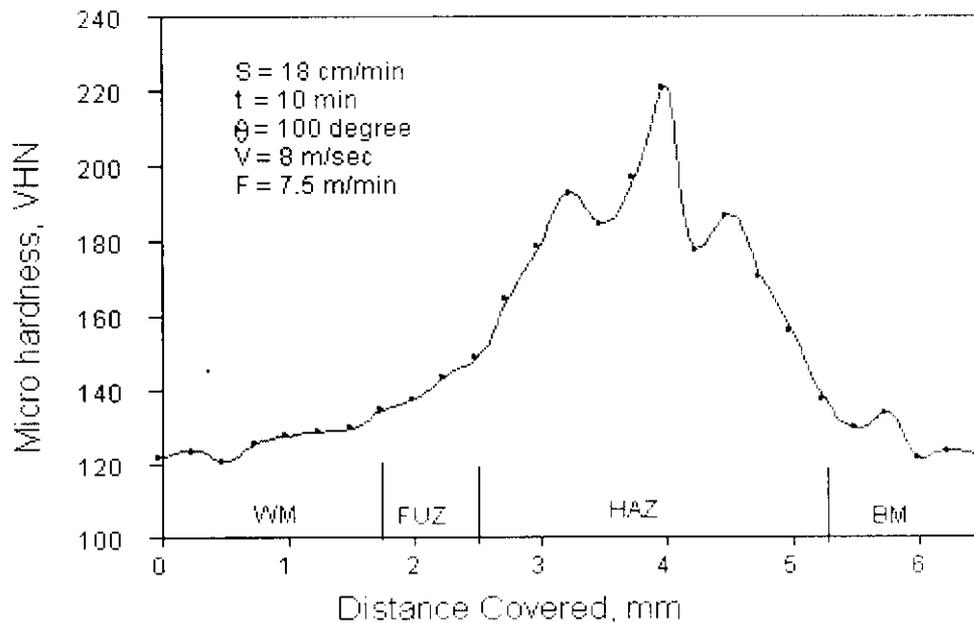


Fig. 5.12 Micro-Hardness Survey (Specimen No. 12)

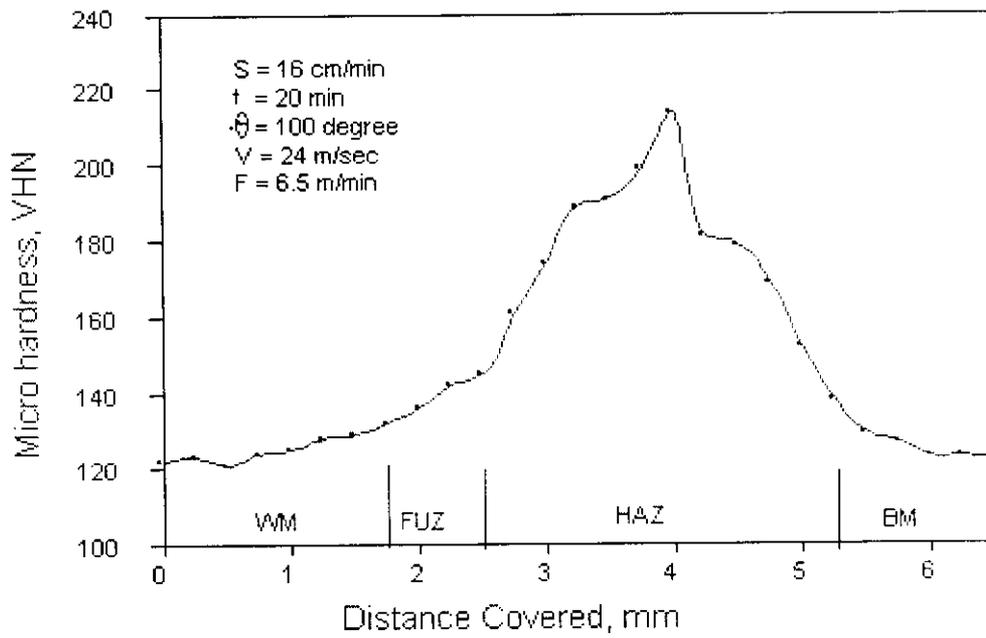


Fig. 5.13 Micro-Hardness Survey (Specimen No. 13)

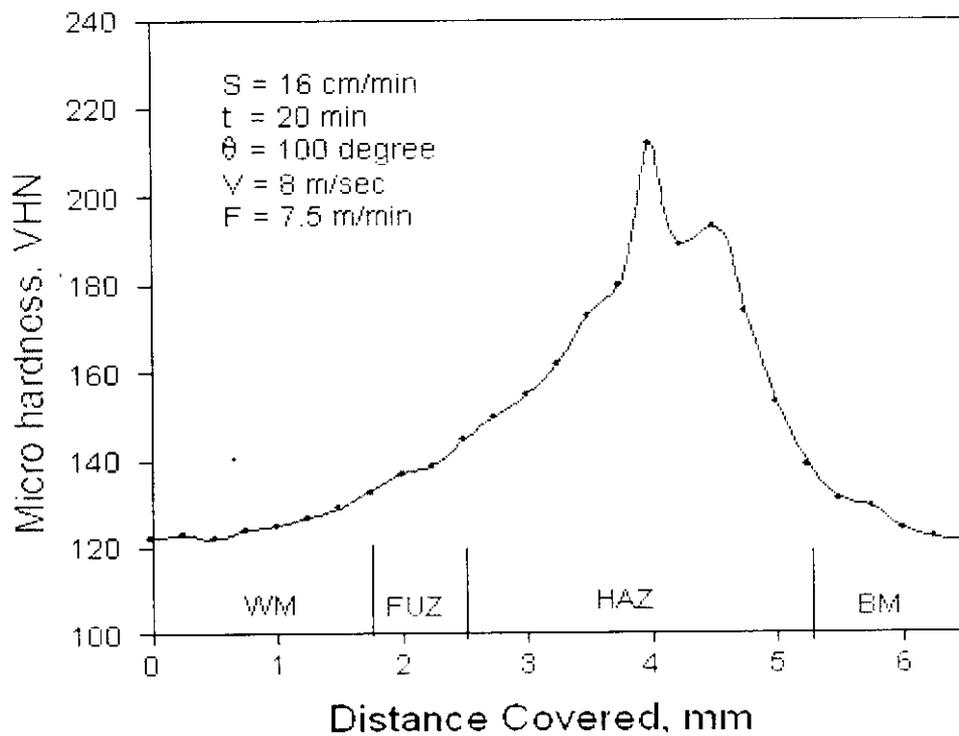


Fig. 5.14 Micro-Hardness Survey (Specimen No. 14)

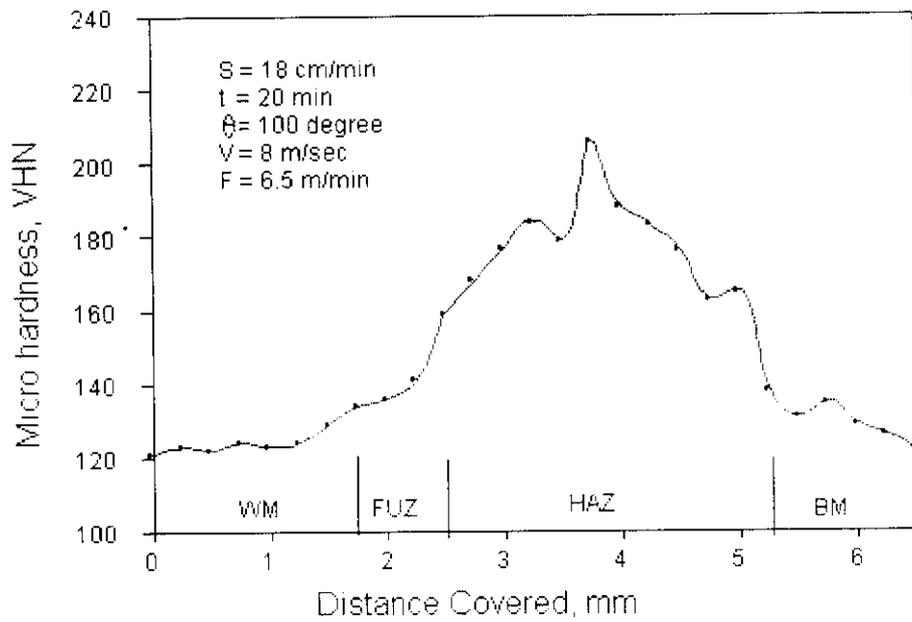


Fig. 5.15 Micro-Hardness Survey (Specimen No. 15)

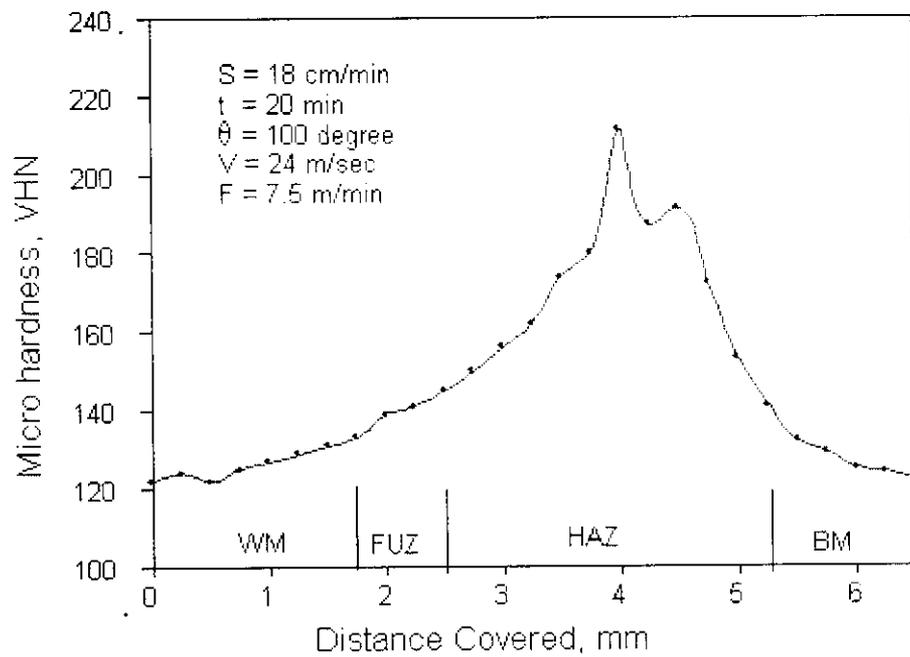


Fig. 5.16 Micro-Hardness Survey (Specimen No. 16)

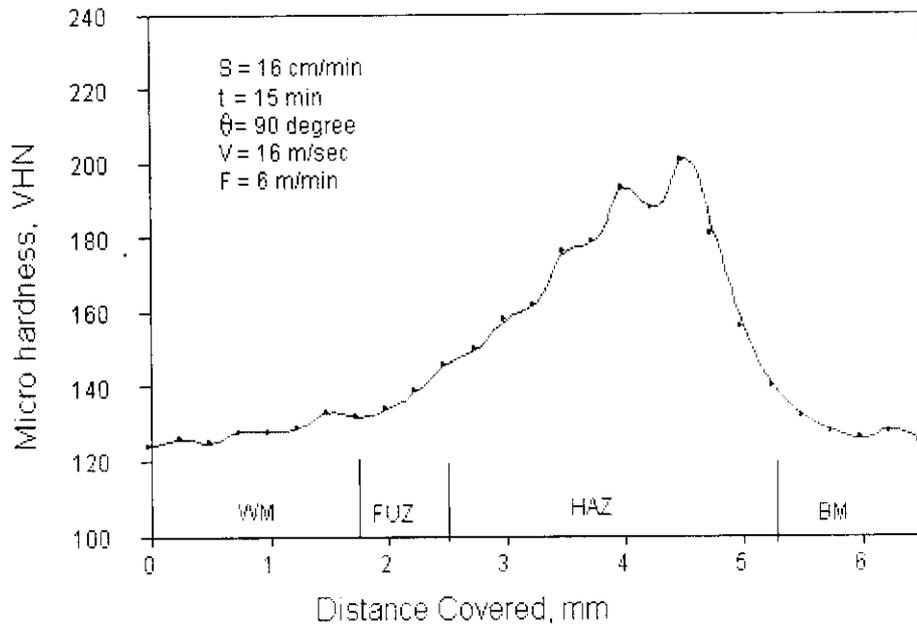


Fig. 5.17 Micro-Hardness Survey (Specimen No. 17)

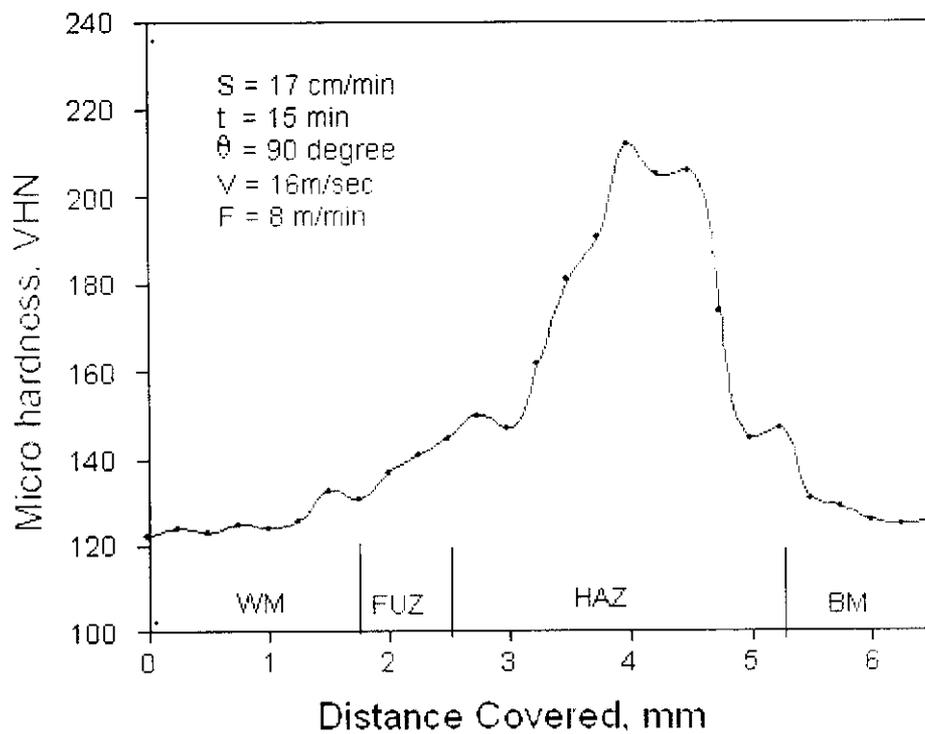


Fig. 5.18 Micro-Hardness Survey (Specimen No. 18)

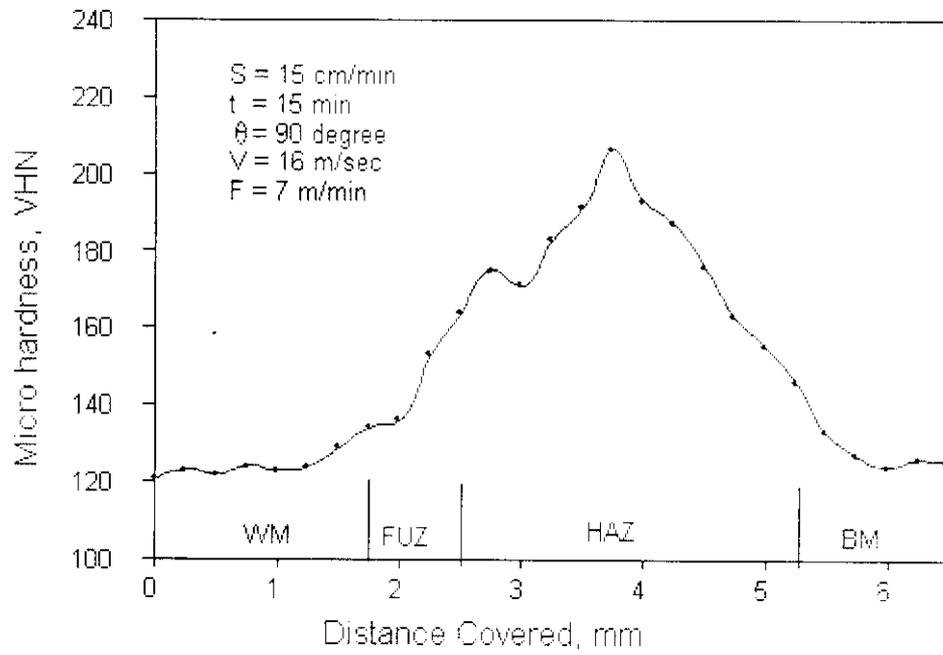


Fig. 5.19 Micro-Hardness Survey (Specimen No. 19)

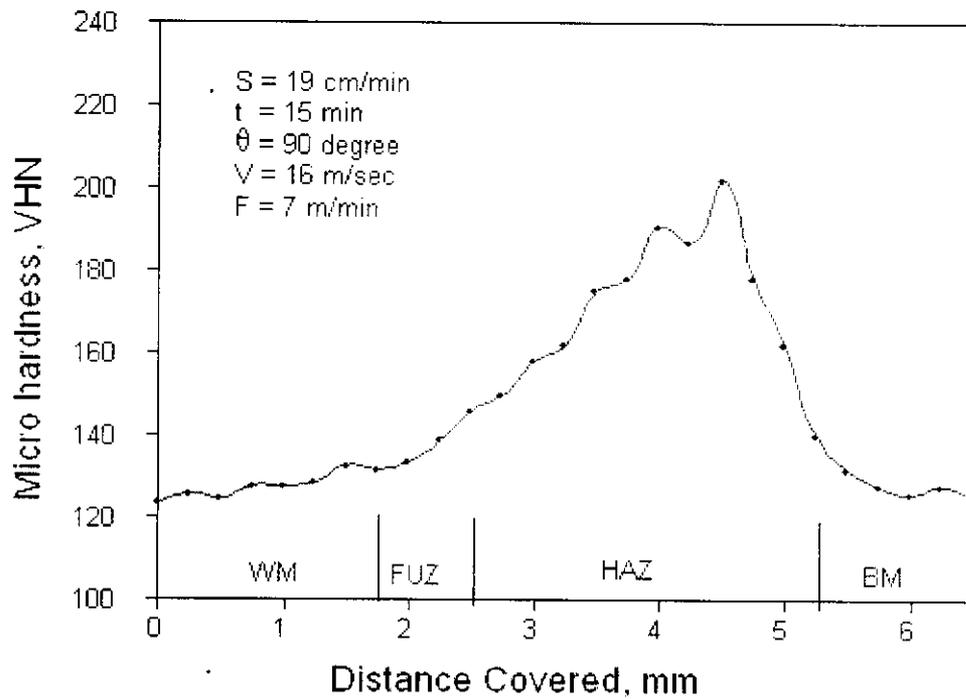


Fig. 5.20 Micro-Hardness Survey (Specimen No. 20)

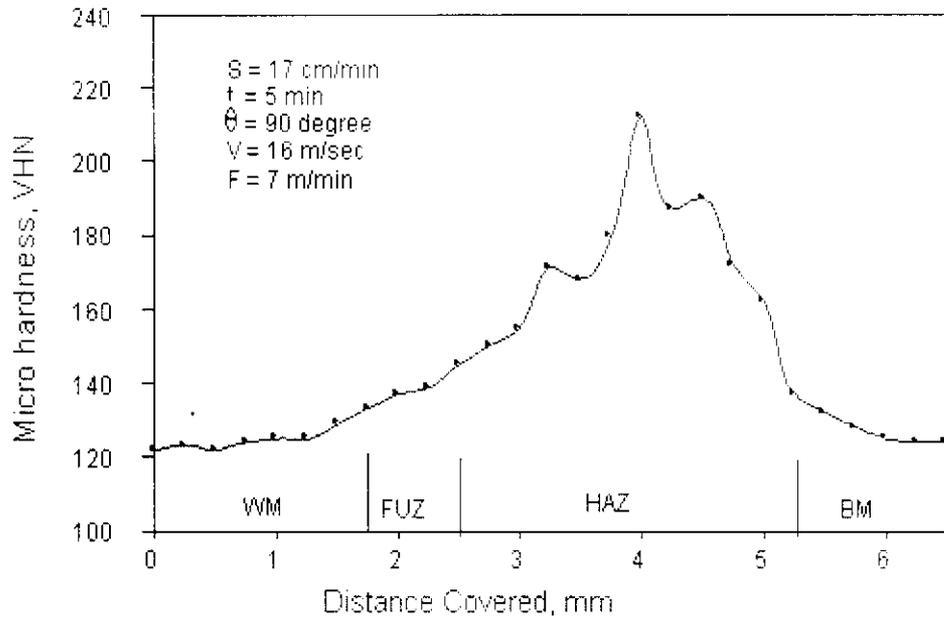


Fig. 5.21 Micro-Hardness Survey (Specimen No. 21)

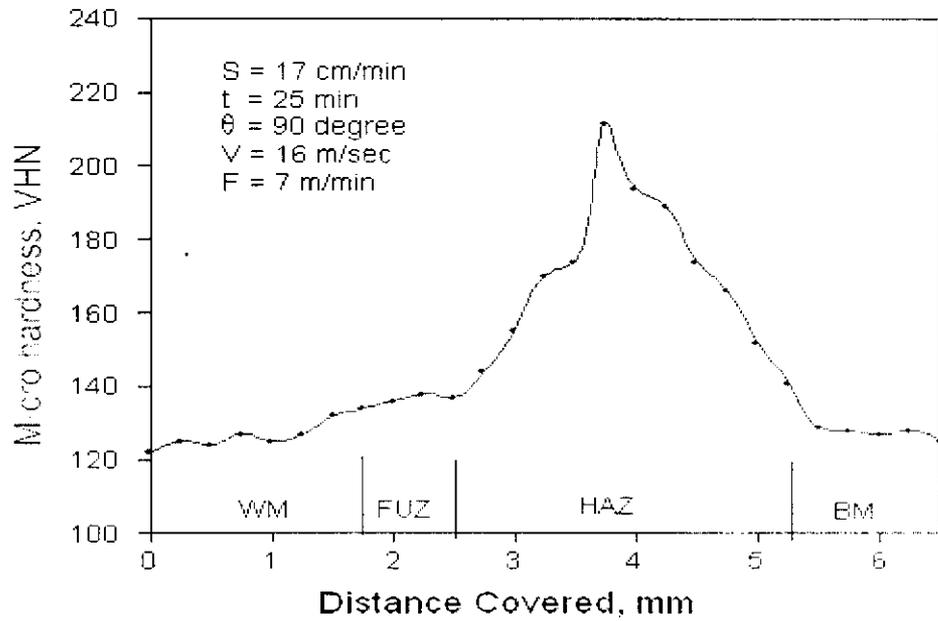


Fig. 5.22 Micro-Hardness Survey (Specimen No. 22)

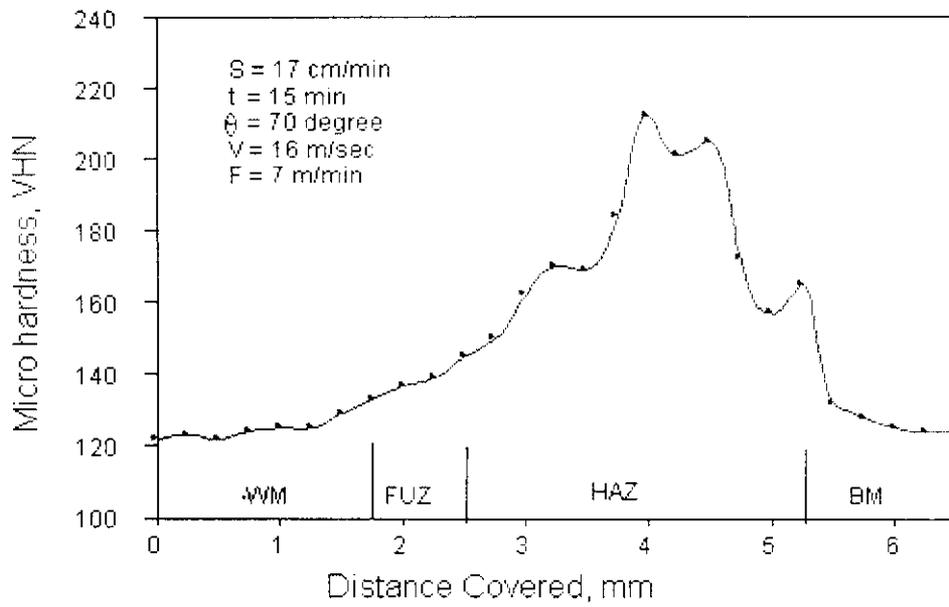


Fig. 5.23 Micro-Hardness Survey (Specimen No. 23)

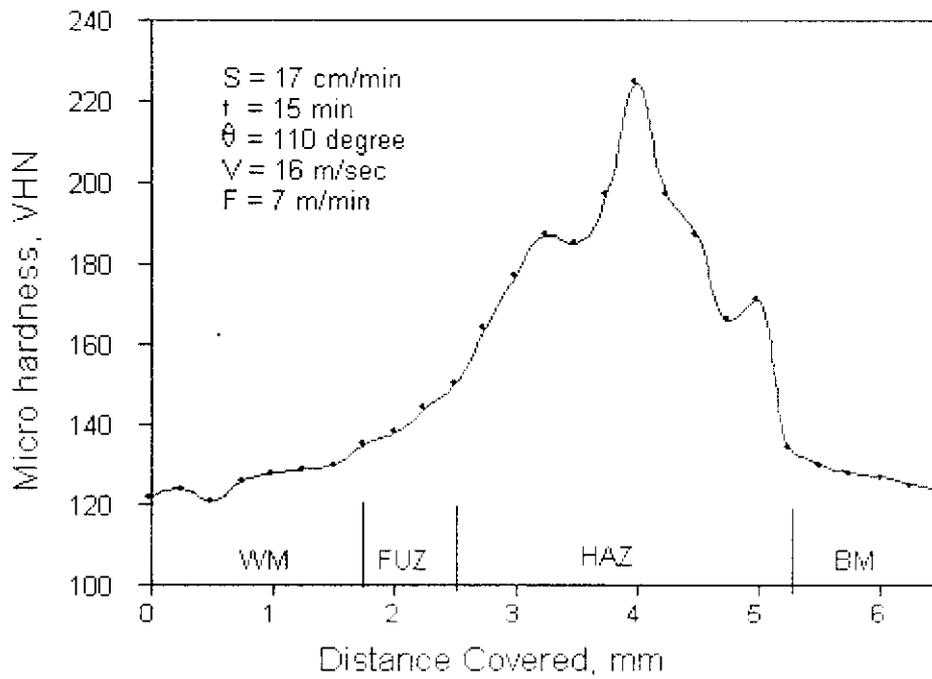


Fig. 5.24 Micro-Hardness Survey (Specimen No. 24)

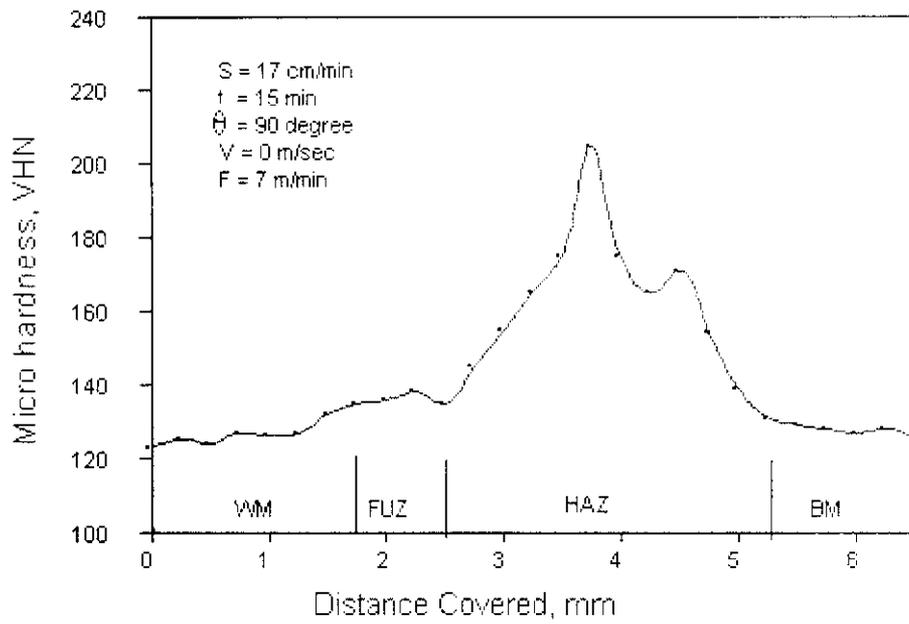


Fig. 5.25 Micro-Hardness Survey (Specimen No. 25)

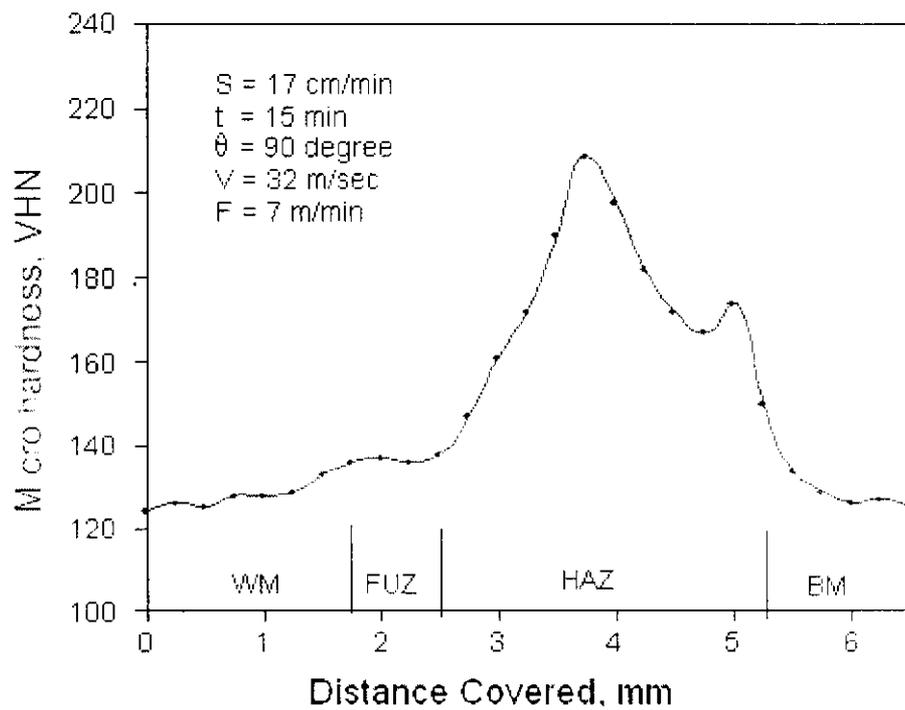


Fig. 5.26 Micro-Hardness Survey (Specimen No. 26)

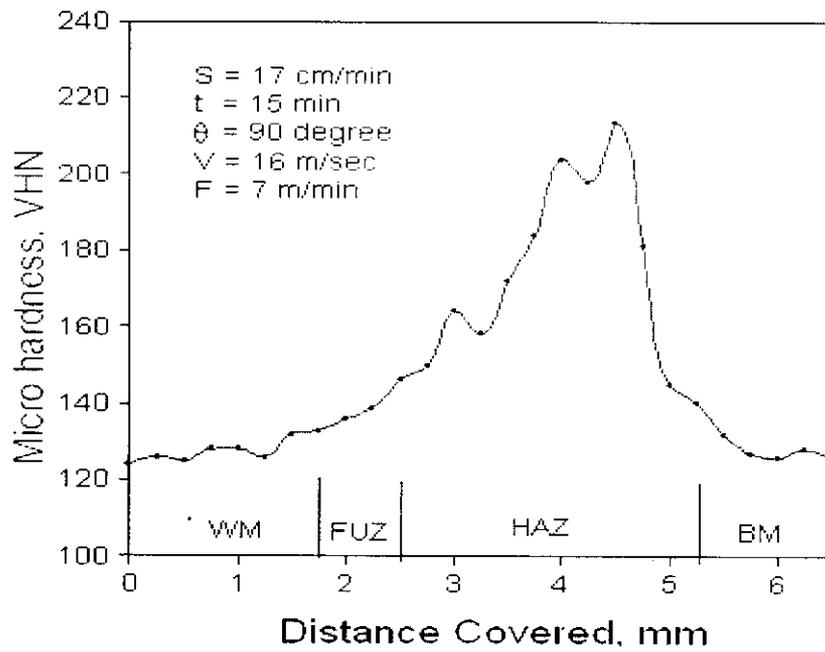


Fig. 5.27 Micro-Hardness Survey (Specimen No. 27)

CHAPTER 6

HEAT FLOW ANALYSIS

HEAT FLOW ANALYSIS

6.1 Introduction

The maximum temperature attained due to thermal cycles during welding and the way in which a weld deposit cools from the liquid state is known to have profound effects on properties, homogeneity, microstructure and state of residual stress (~~Barlow et al. 1983~~) and (~~Murugan et al. 2001~~) of the weldments. There is now a model capable of estimating quantitatively the microstructure of the fusion zone of low-alloy steel welds deposited by arc welding techniques, as a function of the chemical composition of base plate. The austenite grain structure and the cooling curve of the fusion zone have, however, to be measured experimentally in each case. This clearly limits the usefulness of the model, the original aim of which was to enable the theoretical design of welding procedures

For many applications, an approximate knowledge of the maximum temperature and cooling time between specified temperatures is a sufficient characterisation of the weld deposit. On the other hand, a calculation of the microstructure requires a detailed knowledge of the maximum temperature and the cooling rate at any temperature where the austenite to ferrite transformation becomes thermodynamically possible

In this experimental work, an attempt has been made to rationalise maximum temperature and cooling curves obtained from the temperature-time history measured at the heat affected zone of the weldments. There is no reliable method for calculating such cooling curves as a function of GMAW process variables like Wire feed rate (F), welding speed (S), Time gap between passes (t), Angle of electrode (θ) and Velocity of cooling air (V). This is not surprising since the deposition process is by nature turbulent, with heat transfer between the arc plasma, flux, base metal and the molten deposit itself. Bearing these difficulties in mind, the aim of this work was to try and represent quantitatively the major variables controlling the maximum temperature and cooling behaviour of GMAW process of a given

The temperature variations during experiments were recorded using Data Acquisition System (DAS) with linearizer. Figs 6.2 and 6.3 show the photographs of DAS system with linearizer used in the experiment and a specimen fixed with thermocouples at bottom.

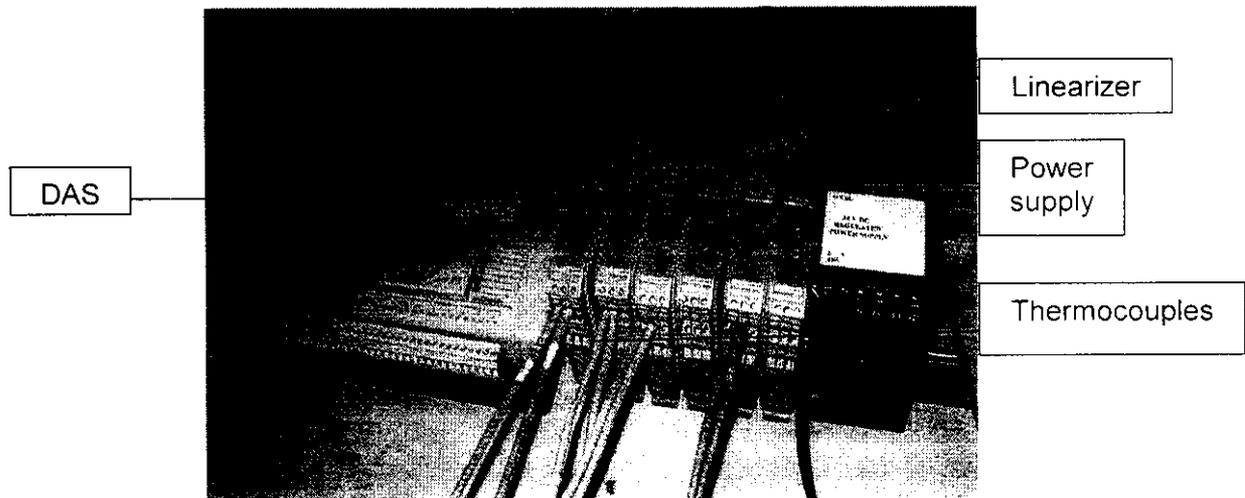


Fig. 6.2 Photograph of DAS System with Linearizer

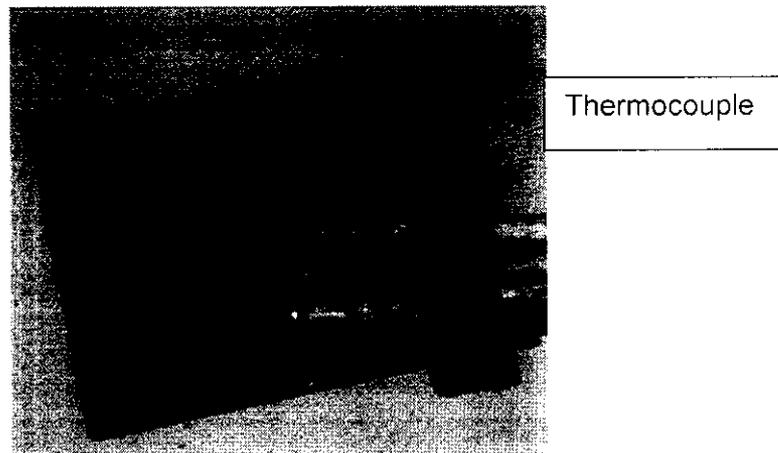


Fig. 6.3 Photograph Showing Thermocouple at the Bottom of the Specimen

The Data Acquisition System was programmed in such a way that temperature was recorded at a time interval 10 seconds. Sample temperature-time history recorded using the above experimental procedure (at four nodal points P, Q, R and S) is depicted

The experiments were carried out for different combinations of process variables (Table. 6.1) within their working range to study the effects of different process variables on temperature distribution.

Table. 6.1
Process variable combinations for heat flow analysis

Expt. No.	T Min	F m/min	S Cm/min	θ Deg	V m/sec
1.	15	6	17	90	16
2.	15	8	17	90	16
3.	15	7	15	90	16
4.	15	7	19	90	16
5.	5	7	17	90	16
6.	25	7	17	90	16
7.	15	7	17	70	16
8.	15	7	17	110	16
9.	15	7	17	90	0
10.	15	7	17	90	32

The graphical representation of the recorded temperature against time is depicted in the Figs. 6.4 to 6.13.

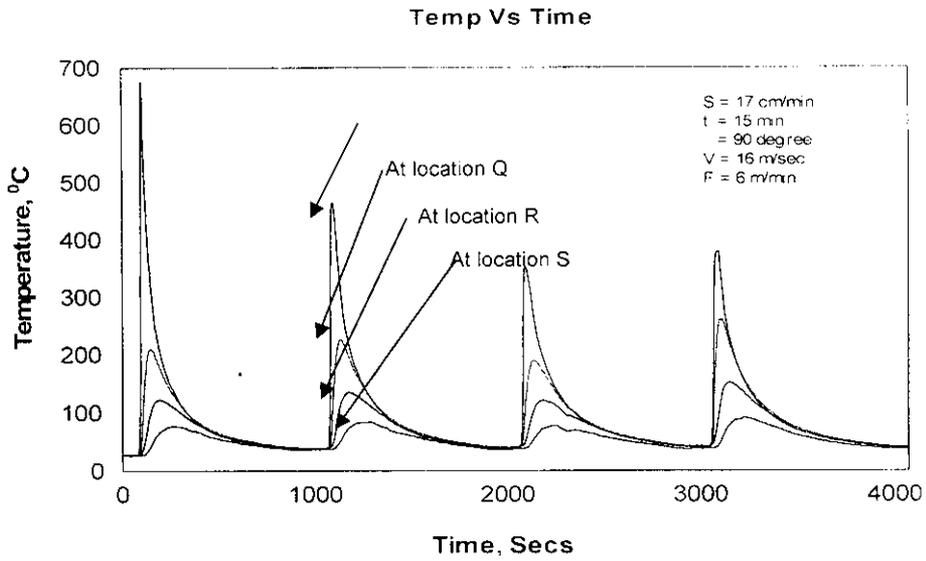


Fig. 6.4 Temperature distribution for wire feed rate (F) = 6 m/min

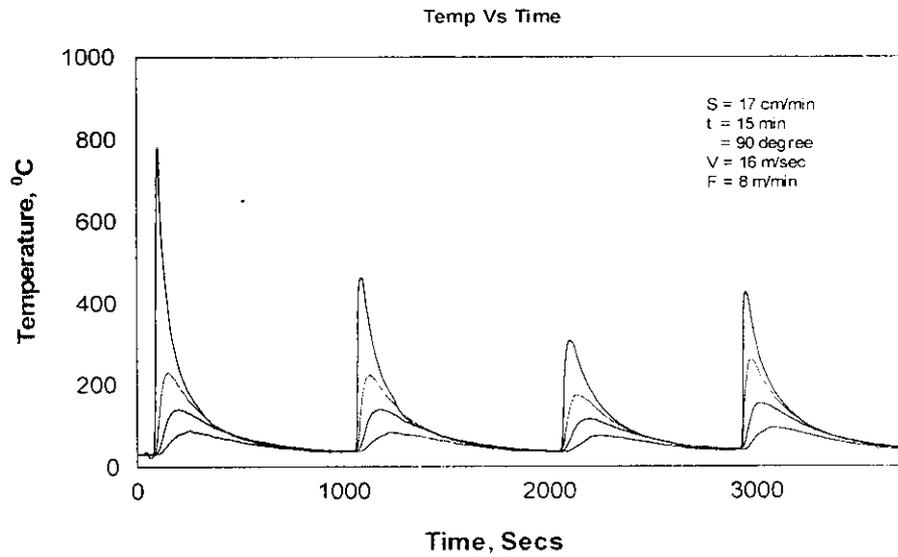


Fig. 6.5 Temperature distribution for wire feed rate (F) = 8 m/min

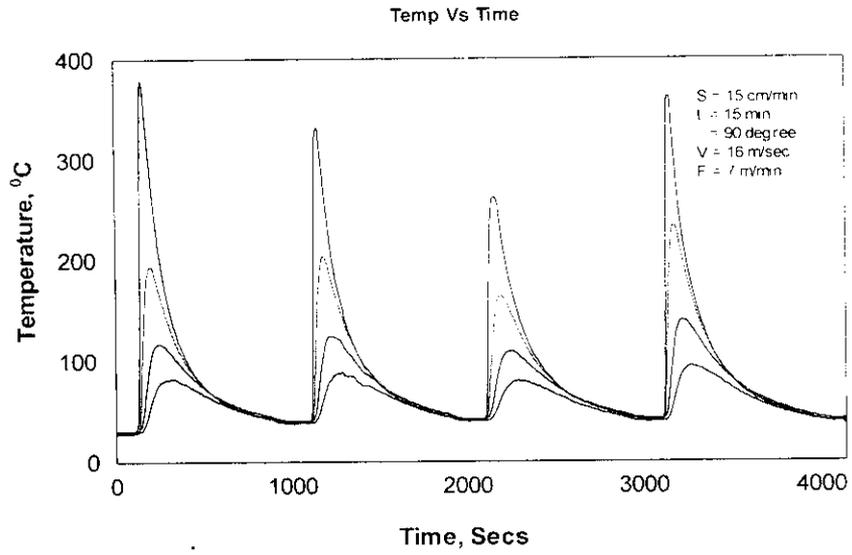


Fig. 6.6 Temperature distribution for welding speed (S) = 15 cm/min

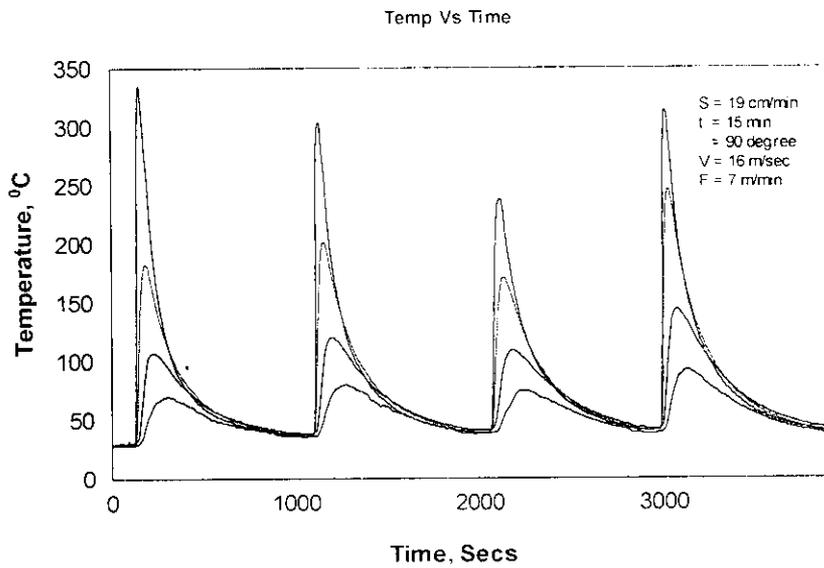
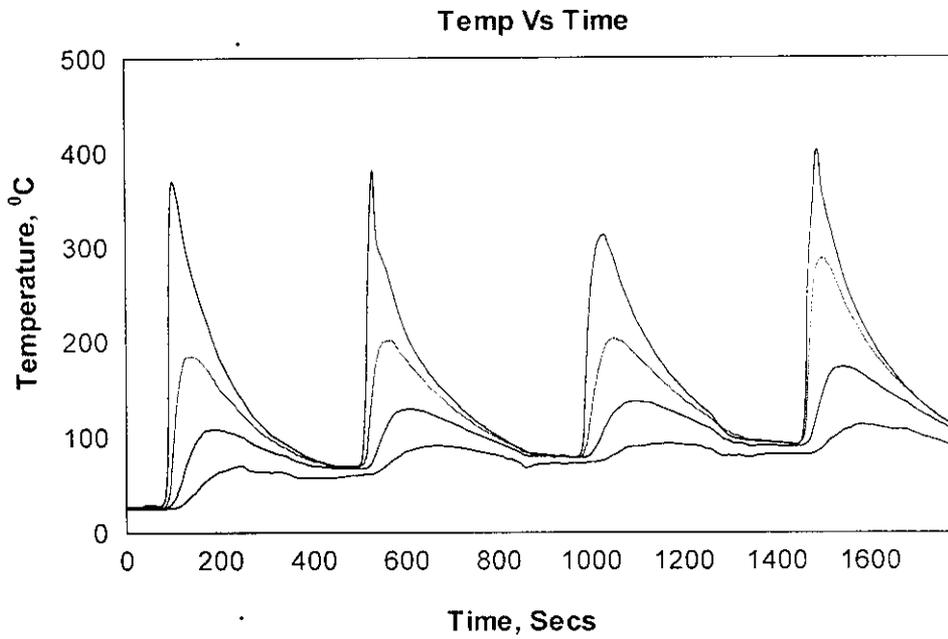
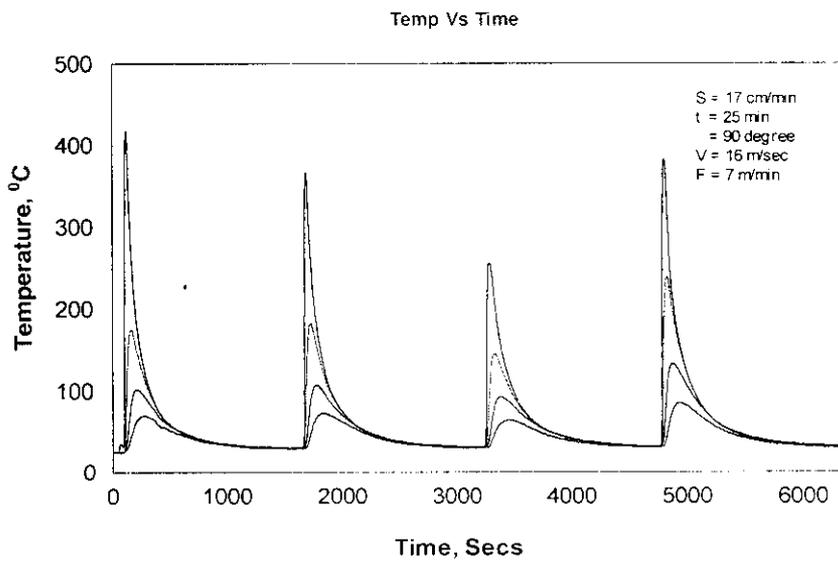


Fig. 6.7 Temperature distribution for welding speed (S) = 19 cm/min



**Fig. 6.8 Temperature distribution for
Time between passes (T) = 5 min**



**Fig. 6.9 Temperature distribution for
Time between passes (T) = 25 min**

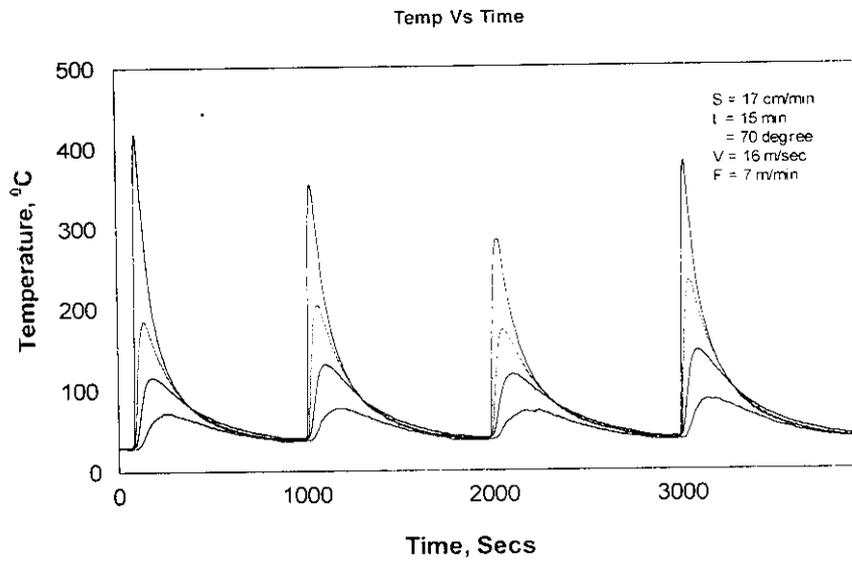


Fig. 6.10 Temperature distribution for angle of electrode (θ) = 70 degree

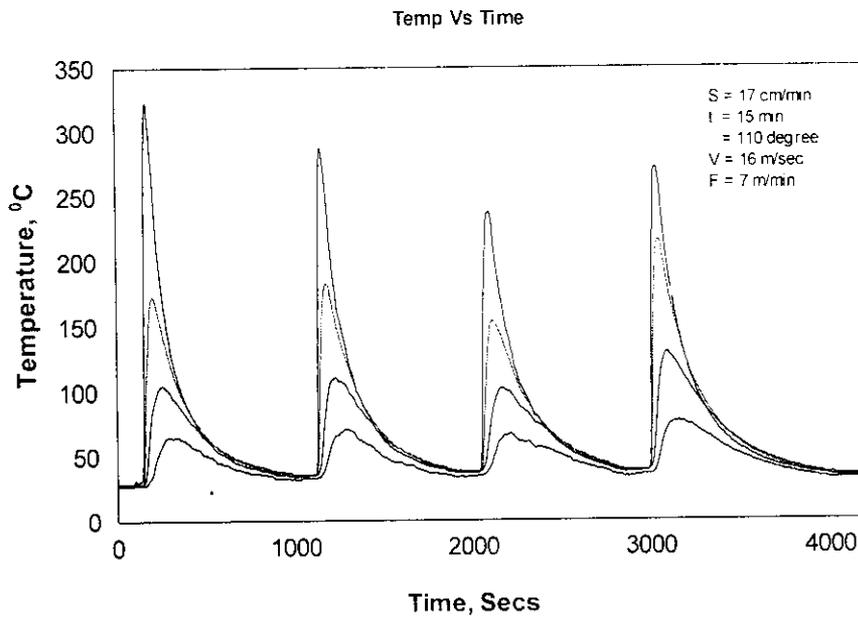
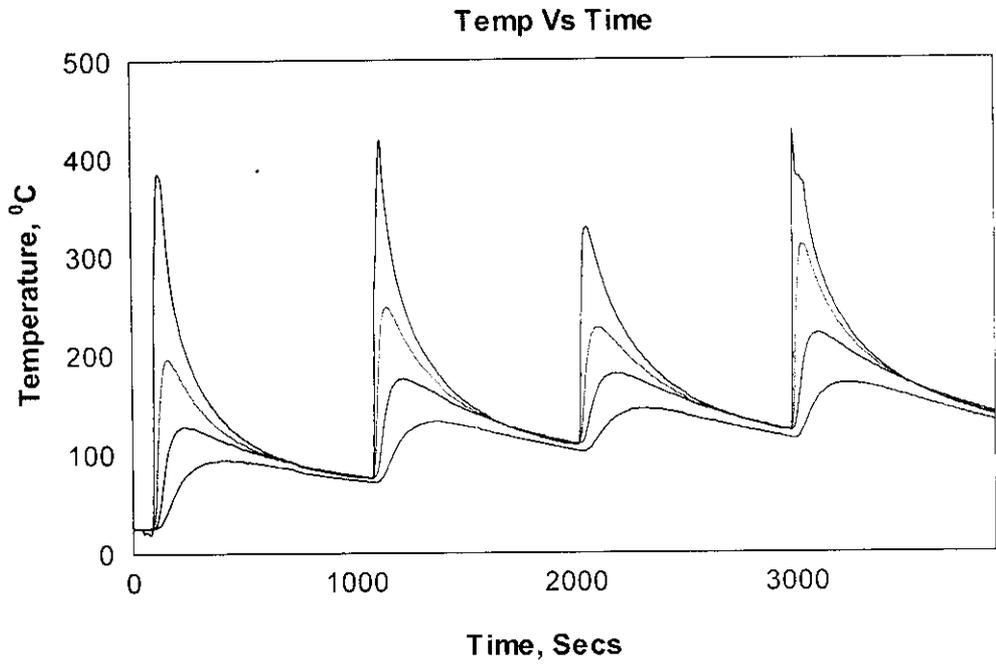
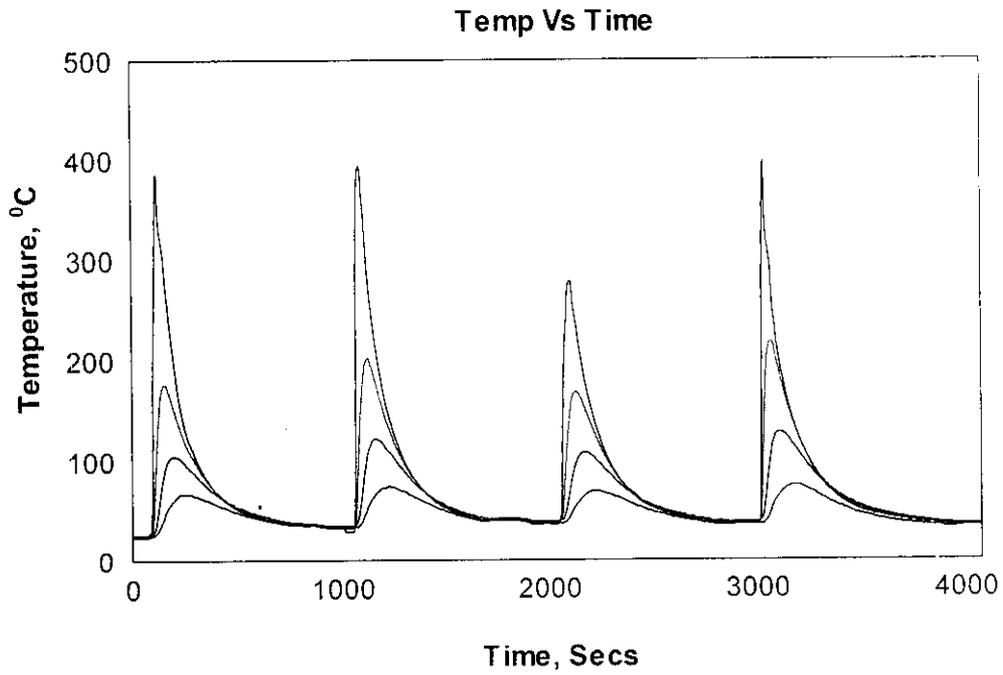


Fig.6.11 Temperature distribution For angle of electrode (θ) = 110 degree



**Fig. 6.12 Temperature distribution
For velocity of cooling air (V) = 0 m/min**



**Fig. 6.13 Temperature distribution
For velocity of cooling air (V) = 32 m/min**

Results and Discussion

During each pass, the temperature at the measuring point increases, reaches a maximum value and then decreases (Christensen 1965). The point nearest to the centre line of the weld experiences the maximum temperature.

In multi-pass welding, weld beads are laid along different lines parallel to the centre line of the weld, in the V – shaped joining edge of the plates. In pass 1 and pass 2 weld beads are laid in line that coincides with the center line of the weld, in pass 3, it was laid closer to the side of the plate in which the temperature was measured and in pass 4, it was laid on the other side of the plate. Because of this the temperature measured during 3rd pass is lower than during 4th pass irrespective of other controlling parameters. During the cooling phase of any pass, the cooling rate is steep during initial stage but not in the later stages

6.3 Effect of welding process parameters on maximum temperature rise

For any weld pass, the highest and lowest temperatures can be found from the experimental results. The difference between these two values will give the maximum temperature rise attained at the locations P, Q, R, and S (point at which the temperature is measured). The maximum temperature rise at different passes and at different locations can be obtained. The maximum temperature rise at different welding process parameters is given in figs. 6.14 to 6.18.

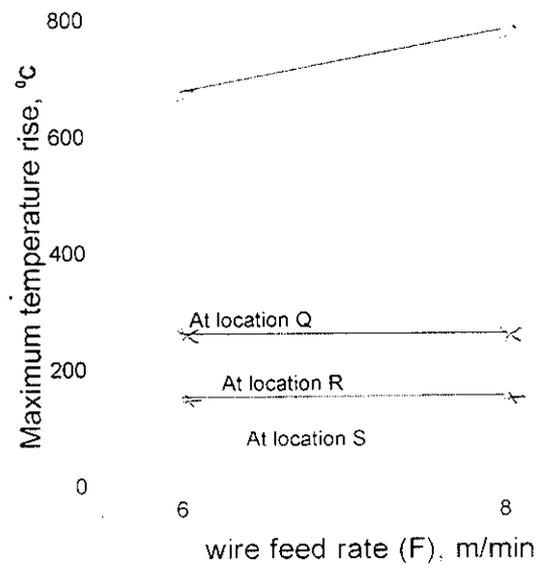


Fig. 6.14 Effect of wire feed rate on maximum temperature rise during first pass

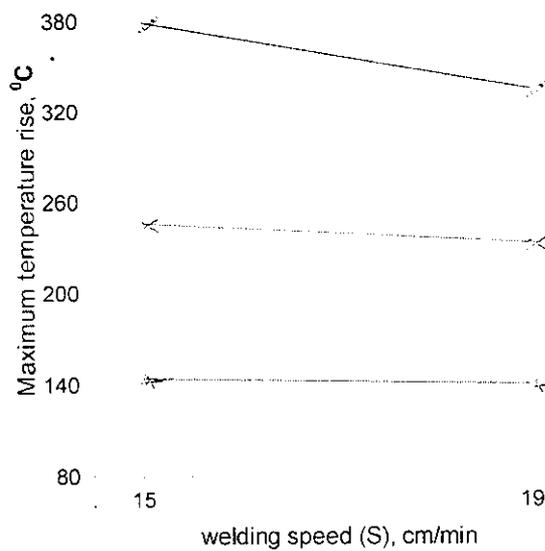


Fig. 6.15 Effect of welding speed on maximum temperature rise during first pass

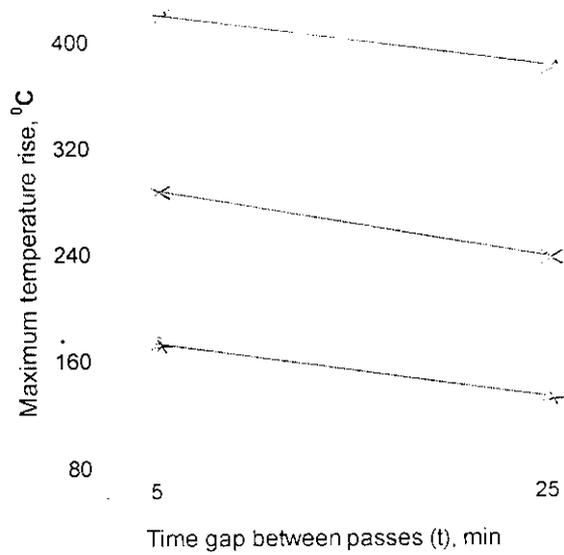


Fig. 6.16 Effect of time gap between passes on maximum temperature rise during second pass

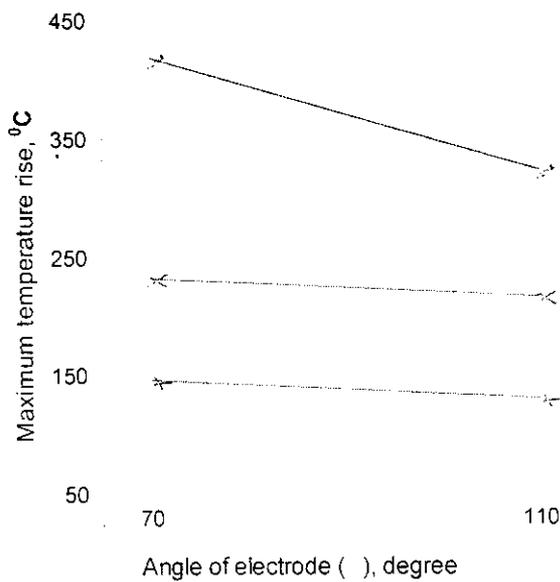


Fig. 6.17 Effect of angle of electrode on maximum temperature rise during first pass

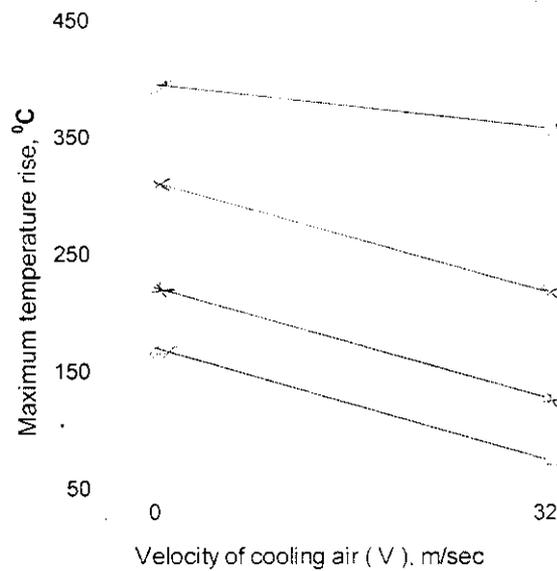


Fig. 6.18 Effect of velocity of cooling air on maximum temperature rise during second pass

The maximum temperature rise at a location closer to center line of the weld is more as compared to that at far away locations. This may be due to low heat flux at these locations, since heat flux at any location is equal to the weld heat input minus the heat lost due to surface convection between the location and the center line of the weld.

From the figs. 6.14 to 6.18, it can be seen that the maximum temperature rise varies uniformly with distance from the center line of the weld. The maximum temperature rise expected at any other point lying in between can be read directly from these curves

6.4 Effect of wire feed rate

Figs. 6.4 and 6.5 represent the temperature distribution for different wire feed rate (F) i. e. 6 m / min and 8 m/min. Fig. 6.14 represents the effect of wire feed rate on maximum temperature rise during first pass.

The highest temperature during any weld pass is more when F is 8 m/min as compared to that when ' F ' is 6 m/min. This may be because of higher heat input due to higher value of ' F '.

The highest temperature during second pass and third pass is less than that of during first pass when ' F ' is 8 m/min. This may be due to the reason that during the first pass more weld metal is deposited and hence the thermal resistance between the next pass bead and the location of temperature measurement are increased.

The maximum temperature rise at location (P) increases with the increase in ' F '. The slope of this increasing trend decreases with the increase in the distance of location of thermocouple from the weld center line. This may be due to the fact that the heat flux at location (S) during first pass is equal to the heat flux at location (P) minus the convection losses between these locations. As the convection loss is directly proportional to temperature potential, the heat loss is more for higher value of ' F '. Hence the heat flux at location (S) further gets reduced. Due to this fact the slope of the maximum temperature rise is less at location (S).

6.5 Effect of welding speed

Figs. 6.6 and 6.7 represent the temperature variation at different welding speed (S), i.e. 15 cm/min and 19 cm/min. Fig. 6.15 represents effect of welding speed on maximum temperature rise during first pass.

The highest temperature during any pass is higher when $S = 15$ cm/min compared to that when $S = 19$ cm/min. This may be because of higher heat input rate due to lower value of ' S '.

The maximum temperature rise at location (P) decreases with the increase in F . This may be due to the heat input per unit length decreases with the increase in welding speed.

6.6 Effect of time gap between successive passes

Figs. 6.8 to 6.9 represent the temperature distribution for different time gap between successive passes (t), i. e. 5 min. and 15 min. Fig. 6.16 represents the effect of time gap between passes on maximum temperature rise.

The highest temperature during any weld passes decreases with the increase in ' t '. The maximum temperature rise during second pass decreases at location 'P' with the increase in ' t '. This may be due to the fact that the more heat loss due to more cooling time for higher time gap between successive passes is more.

However the slope of this decreasing trend gets reduces when the distance of location from the center line of the weld increases. And at location (S) slight increasing trend is experienced. This may be due to the reason that higher time gap between successive passes allows more heat to propagate to the location (S). From the temperature – time graphs we know that the cooling rate is low as compared to that of heating rate at any location. Hence, before all the propagated heat gets dissipated, the next wave of heat flow reaches the location and increases the temperature further.

6.7 Effect of angle of electrode to work piece: (Push welding or pull welding)

Figs. 6.10 and 6.11 represents the temperature distribution at different angular position of electrode (θ), i. e. $\theta = 70^\circ$ (pull welding) and $\theta = 110^\circ$ (push welding). Fig. 6.17 represents the effect of angular position of electrode to work piece on maximum temperature rise.

Slight increase in the highest temperature in any weld pass is experienced for push welding ($\theta = 110^\circ$) as compared to that for pull welding ($\theta = 70^\circ$). This may be because of the preheating of the metal by the arc in push welding position.

The maximum temperature rise experiences slight increasing trend at closer location but slight decreasing trend at far away location with the increase in ' θ '.

6.8 Effect of velocity of cooling air

Figs. 6.12 and 6.13 represents the temperature distribution at different velocity of cooling air $V = 0$ m/sec and $V = 32$ m/sec. Fig. 6.17 represents the effect of velocity of cooling air on maximum temperature rise.

The highest temperature is same during first pass since all the welding process parameters are same during first pass. Decrease in the highest temperature in the subsequent weld passes is experienced for velocity of cooling air ($V=0$ m/sec) as compared to that velocity of cooling air ($V=32$ m/sec). This may be because of the higher cooling rate of the metal by forced cooling reduces the temperature to very low. Hence the temperature rise in the subsequent passes will be less compared to that during first pass.

The Decreasing trend of maximum temperature rise is less at closer location but slightly higher at far away location with the increase in velocity of cooling air. This may be because of higher temperature potential at closer locations compared to that at far away locations.

CHAPTER 7

RESULTS AND DISCUSSIONS

7.1 Micro Hardness Survey

- The micro hardness value in the weld metal zone was not affected much by the process parameters and was almost equal to that of unaffected base metal.
- It was found that micro hardness value were higher in the grain growth zone of HAZ for all specimen irrespective of the heat input rate and welding conditions.
- The micro hardness values were higher for low heat input specimens than that of high heat input specimen.
- The PMH value increases by 4.2 VHN as V increases from 0 m/sec to 32 m/sec.
- The PMH value increases by 11.2 VHN as F increases from 6 m/min to 8 m/min.
- The PMH value decreases by 4.3 VHN as S increases from 15 cm/min to 19 cm/min
- The PMH value decreases when time gap between passes increases
- The PMH value increases by 12 VHN as angle increases from 70 degrees to 110 degrees.

7.2 Heat flow analysis

- Experimental temperature distribution data have been established for Gas Metal Arc welding of 16 mm thick structure steel plates for four passes.
- Results of maximum temperature rise and cooling rate will be useful in the estimation of likely changes in the microstructure, phase transformation and consequent changes in mechanical properties of the base plate.
- The temperature – time history results presented in this work will be useful for the validation of the theoretical and FEA simulation of heat flow in multi-pass welds.
- The effects of the process variables on maximum temperature and its change are more predominant at locations closer to the weld center line than that far of locations.
- Even though the temperature is more during subsequent passes cooling rate during first pass is more compared to that of during subsequent passes.
- For all the process variables and for all passes the cooling rate first increases, reaches the maximum value and then decreases.
- The maximum temperature rise decreases from 380°C to 350°C as V increases from 0 m/sec to 32 m/sec.
- The maximum temperature rise increases from 680°C to 790°C as F increases from 6 m/min to 8 m/min.

CHAPTER 8

REFERENCES

REFERENCES

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