

Experimental Investigation and Modeling of Bead Geometry and Residual Stresses during Submerged Arc Welding of HSLA Steels

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in CAD CAM Engineering

Submitted By

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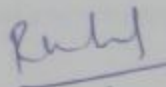
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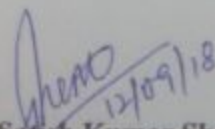
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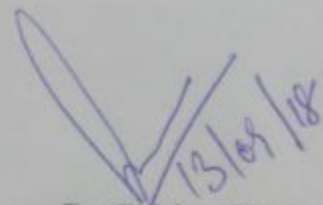
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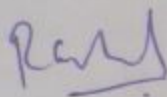
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ABSTRACT

Submerged arc welding (SAW) is a welding process used to join plates of higher thickness. In SAW process arc is formed between a continuously fed wire electrode and work piece. Weld is formed due to melting of wire and work piece and arc is shielded under a blanket of granular fusible flux. Flux melts during welding process and it provides protection to weld pool from atmospheric agents. Process parameters in SAW bear complex mathematical relationships and soft computing techniques are found to be useful for process modeling and optimization.

Bead geometry and penetration of metal are some of the important physical characteristics of a weldment. Various welding parameters like high arc-travel and low arc-travel affect bead geometry as it results in poor fusion of metal. Current, voltage and arc-travel length are responsible for depth of penetration. Other factors affecting penetration is arc-length and arc-force. Bead geometry characteristics play an important role to determine weldability of metal. Factors like open circuit voltage, trolley speed, contact tube to work piece distance, preheat temperature and wire feed rate are studied here.

Soft computing is an emerging approach to computing that closely resembles the ability of human mind to reason and learn from an environment of uncertainty and imprecision. In this present work, soft computing based model Artificial Neural Network (ANN) has been developed and implemented to model and optimize the SAW process. Experimentations based on design of experiment have been carried out for different process parameters. Dataset generated from experimentation was employed to create ANN model. ANN model uses ANN algorithm called back propagation neural network (BPNN) with Levenberg Marquardt (LM). A comparison of various ANN models using different number of layers and neurons was carried out and regression coefficient was found for it.

Residual stresses are the type of stresses which exist in a body when no external loads are applied on it. These types of stresses are created in welded joints due to non-uniform heating and cooling and shrinkage of molten metal. There will always be some amount of residual stresses present in any welded component. Tensile residual stresses are detrimental for component as it increases susceptibility of a welded part to premature failure. They accelerate failure due to fatigue and stress induced corrosion cracking. Parameters should be selected such that so as to reduce residual stresses which minimize and avoid failures of welded components. There are various factors which influence residual stresses present in welded joint. They are type of welding technique used, parameters of welding process and properties of metal being welded.

Study was undertaken to determine stresses in High strength low alloy steel plates by the help of X-ray diffraction (XRD) technique.

It is believed that the work presented here will add significant contribution to existing literature from view point of industrial importance and academic interest.

Key words: SAW, HSLA, Residual stresses, Simulation, XRD

TABLE OF CONTENTS

TOPIC	PAGE NO.
CERTIFICATE	ii
ACKNOWLEDGEMENT	iii
ABSTRACT	iv
TABLE OF CONTENTS	vi
LIST OF FIGURES	viii
LIST OF TABLES	x
NOMENCLATURE	xi
CHAPTER-1 INTRODUCTION	1
1.1 SUBMERGED ARC WELDING (SAW)	1
1.2 PRINCIPLE OF OPERATION	2
1.3 WELD BEAD GEOMETRY PARAMETERS	2
1.4 PARAMETERS AFFECTING BEAD GEOMETRY IN SAW	5
1.5 HIGH STRENGTH LOW ALLOY STEEL (HSLA)	7
1.6 PROPERTIES AND APPLICATIONS OF HSLA STEELS	8
1.7 RESIDUAL STRESSES	8
1.8 RESIDUAL STRESS MEASUREMENT	11
1.8.1 DESTRUCTIVE TECHNIQUES	11
1.8.2 NON DESTRUCTIVE TECHNIQUES	13
1.9 ARTIFICIAL NEURAL NETWORK	17
CHAPTER-2 LITERATURE REVIEW	19
2.1 LITERATURE REVIEW OF BEAD PARAMETERS AND ITS MODELING	19
2.2 OBSERVATIONS FROM LITERATURE	22
2.3 OBJECTIVES OF STUDY	23

CHAPTER-3 EXPERIMENTATION AND METHODOLOGY	24
3.1 MATERIALS AND METHODS	25
3.1.1 BASE AND FILLER MATERIAL COMBINATION	25
3.1.2 MACHINE SETUP AND WELDING PARAMETERS	25
3.2 RESPONSE SURFACE METHODOLOGY	26
3.3 PREPARATION OF SAMPLES	29
3.3.1 PREPARATION OF SAMPLES FOR BEAD GEOMETRY MEASUREMENT	29
3.3.2 PREPARATION OF SAMPLES FOR RESIDUAL STRESS MEASUREMENT	31
3.3.3 HEAT INPUT AND COOLING TIME CALCULATION	36
CHAPTER-4 RESULTS AND DISCUSSION	37
4.1 DEVELOPMENT OF MODEL USING ANN FOR BEAD GEOMETRY	37
4.2 COMPARISON OF MODEL RESULTS WITH ACTUAL VALUE OF BEAD GEOMETRY	42
4.2.1 COMPARISON FOR BEAD WIDTH (W)	42
4.2.2 COMPARISON FOR PENETRATION (P)	43
4.2.3 COMPARISON FOR REINFORCEMENT (R)	44
4.3 RESULTS FOR RESIDUAL STRESS	45
4.3.1 VARIATION IN RESIDUAL STRESSES WITH COOLING RATE	45
4.4 VALIDATION OF XRD ANALYSIS BY SIMULATION	47
4.4.1 VARIATION BETWEEN VALUES OF STRESSES FROM XRD AND SIMULATION	51
4.5 SUMMARY	52
CHAPTER-5 SUMMARY, CONCLUSIONS AND FUTURE SCOPE	53
5.1 SUMMARY	53
5.2 CONCLUSIONS	53
5.3 FUTURE SCOPE	54
REFERENCES	55

LIST OF FIGURES

Fig. no.	Description	Page no.
1.1	Submerged Arc Welding	1
1.2	Schematic of weld bead geometry parameters for bead on plate operation	3
1.3	Effect of welding current on bead profile	5
1.4	Effect of welding speed on weld bead	6
1.5	Effect of weld voltage on weld bead	6
1.6	Effect of Electrode size	7
1.7	Strain gauge arrangement in hole drilling method	13
1.8	Schematic of single angle diffraction technique	16
1.9	Schematic of X-ray diffractometer	17
3.1	Plan of research work	24
3.2 (a)	Weld bead on plate surface with slag layer	29
3.2 (b)	Weld bead on plate surface after removal of slag layer	30
3.3 (a)	Cross-section of cut part	29
3.3 (b)	Cross-section showing polished surface	29
3.3 (c)	Weld bead geometry is revealed after using Nital solution	29
3.4 (a)	Abrasive cutting machine	30
3.4 (b)	Open cover shield	30
3.4 (c)	Stereo zoom microscope	30
3.5	Schematic representation of the WEDM process	32
3.6 (a)	Plates in cross-section having weld bead	33
3.6 (b)	Weld bead on top of plate	33
3.7	ECOCUT WEDM with work piece on worktable and cover	34
3.8	CNC controller monitor to observe table position and feed rate	34
3.9 (a)	Wire feed mechanism with spool of wire	34
3.9 (b)	WEDM operation in progress	34
3.10 (a)	Schematic of work piece with weld bead	35

3.10 (b)	Work piece before and after machining	35
3.10 (c)	Schematic of HAZ and point location for XRD test	35
3.11 (a)	X' PERT PRO machine	35
3.11 (b)	EMPYREAN machine	35
4.1	Network architecture of the ANN model	40
4.2	Regression plot	41
4.3	Comparison for Bead width W	42
4.4	Comparison for Penetration P	43
4.5	Comparison for Reinforcement R	44
4.6	Variation of σ_{xx} with cooling rate	46
4.7	Variation of σ_{yy} with cooling rate	46
4.8 (a)	Picture of weld bead on plate	47
4.8 (b)	CAD model of plate	47
4.9	Loading details on plate	48
4.10	Interaction details on CAD model	48
4.11 (a)	Boundary conditions on plate on left face	48
4.11 (b)	Boundary conditions on bottom face	49
4.12	Meshing of the CAD model	49
4.13 (a)	Value of σ_{xx} from simulation	50
4.13 (b)	Value of σ_{yy} from simulation	50
4.14 (a)	Graphical trend of σ_{xx} from XRD analysis and simulation	51
4.14 (b)	Graphical trend of σ_{yy} from XRD analysis and simulation	51

LIST OF TABLES

Table No.	Description	Page No.
1.1	Weld bead geometry characteristics and its shape related parameters with significance	4
3.1	Chemical composition of base plate metal and consumable electrode wire	25
3.2	Chemical composition of flux	25
3.3	Process parameters with their levels used in experiment	26
3.4	Central composite rotatable designed experiments	28
3.5	Results of weld bead characteristics as per designed matrix of experiments	30
3.6	Features and properties of WEDM machine	33
3.7	Features and properties of XRD machine	35
4.1	Performance of different ANN structures	38
4.2	Experimental value, Predicted and Error value of the ANN	39
4.3	Value of process parameters in study for experiment trials	45
4.4	Values of residual stresses in MPa	45

NOMENCLATURE

σ_L	Stress in longitudinal direction
ε_L	Released strain
σ_P	Major Principal residual stress
λ	Incident ray wavelength
θ	Angle between incident and reflected beam
d	Interplanar spacing
ε_ψ	Strain components
E	Modulus of Elasticity
β	Principal stress direction
n	Reflection order

ACRONYMS

OCV	Open Circuit Voltage
DOE	Design of experiment
HAZ	Heat Affected Zone
HSLA	High Strength Low Alloy
SAW	Submerged Arc Welding
SMAW	Shielded Metal Arc Welding
ANN	Artificial Neural Network
RSM	Response Surface Methodology
FFNN	Feed Forward Neural Networks
BPNN	Back Propagation Neural Networks
CNC	Computer Numerical Control

CHAPTER-1

INTRODUCTION

There have been attempts to automate or mechanize arc welding process for the past many years. Idea was conceived to have a continuous coated electrode wire but it had various shortcomings. The coating will deteriorate with time on wire, was subjected to crushing forces when pass through rollers and it was difficult to make it in circular coils. Many methods were tried but they all failed. It was later proposed to have a layer of granular flux just ahead of the carbon electrodes and this method was successful in welding water pipes in California, U.S.A. [1].

1.1 SUBMERGED ARC WELDING (SAW)

SAW is a metal joining process in which granular and fusible flux covers and conceals the arc. Heat for the welding process is generated by the arc which lies between consumable wire electrode and the work piece. Figure 1.1 shows main parts of the machine. Arc is covered by a cover of flux or slag which is in a molten state.

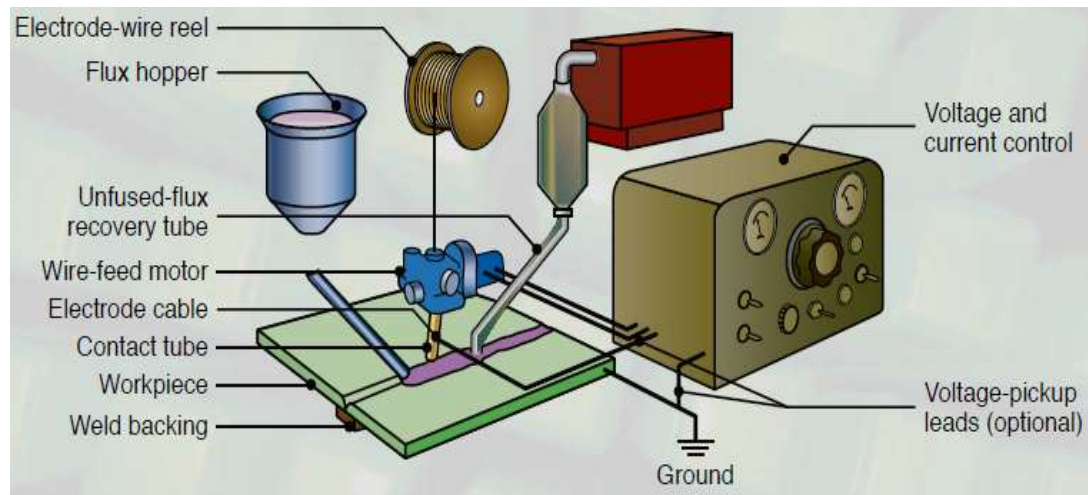


Fig. 1.1 Submerged Arc Welding [2]

This flux helps to refine weld metal and helps to save it from contamination due to atmosphere. There may be present some ingredients in flux which help to enhance the mechanical properties of the weld. Important parts of this welding process are namely flux hopper where flux is stored, spool of electrode wire and a control box to house electrical circuits. Control box has information

displayed which helps operator to determine values of welding current, voltage and speed of welding. By looking at the display the operator can change or vary them as per convenience. Movement of tractor can either be manual or automatic and controls are provided for this purpose. [1]

1.2 PRINCIPLE OF OPERATION OF SAW

Electrode is fed in this process by powered drive rolls. Arc is produced by the electric current which is then supplied to electrode via a contact tube. The current in this process can be that of direct current (DC) with electrode positive i.e. having reverse polarity, with electrode negative straight polarity or that has alternating current (AC). When welding operation is completed and weld metal has undergone solidification, the slag which remained un-fused is removed. The unfused slag may then be used depending on its condition. The slag which is solidified may be pulverized, resized and used to blend back in new flux. Submerged arc welding can be a semiautomatic and fully automatic operation. Fully automatic operation has gained popularity due to its advantages and hence it is widely used. Welder has controls of travel speed, placement of weld and direction of propagation of arc. Welding gun is used to transport flux and wire, which is used by operator to make the weld joint. The diameter of electrode wires are usually less than 2.4 mm which gives them flexibility and provide feed ability in the gun assembly. In case of manual operation, high skills are required because joint is hidden from plain view because of presence of flux layer. In SAW, direction and travel speed is maintained mechanically. Flux may be deposited in front of the arc, and any unfused flux can be collected by the help of vacuum recovery system.

In order to increase weld deposition rate, more than one wire is used which can be fed to the weld pool. Two electrodes are used in twin arc process where they are fed in same weld pool. Tandem arc SAW makes use of multiple electrodes which are arranged in one front of each other. In this process, each electrode has its own separate independent power supply. Optimized welding speed and bead shape can be achieved by varying spacing, configuration and nature of electric supply to the electrodes. [1]

1.3 WELD BEAD GEOMETRY PARAMETERS

In fabrication of oil and gas pipelines, high strength steel is preferred due to its fine grain structure. This steel shows high impact toughness at low temperatures and has high strength to weight ratio. In order to weld these types of steel, submerged arc welding (SAW) is the

preferable process. Heat input and deposition rate of SAW process depend on welding current, voltage, wire feed rate. Critical cooling time ($\Delta t_{8/5}$) of weld depends on preheating temperature and heat input imparted to process [3]. Heat input and $\Delta t_{8/5}$ directly affect behavior of welding joint as it affects weld bead geometry characteristics. Primary focus is to study effect of critical cooling time and heat input on weld characteristics and for that purpose weld characteristics like bead width, penetration, reinforcement, penetration and reinforcement area, width of heat affected zone and total weld area were directly measured from the weld. Values of shape relationship parameters were calculated via experiment. Bead width gives us the length of material which was deposited during fusion process. When fusion takes place, it alters properties of parent material and hence, it is advisable to involve minimum material as possible.

Reinforcement is material which is present in excess quantity than required to fill the joint. Excess reinforcement has negative effect on weld quality as it can lead to stress concentration and failure of joint. Stress carrying capacity of joint depends on penetration. A weld bead needs to have adequate penetration. But too much of penetration may lead to centerline cracking of weld due to transfer of C, S, P and Cu from base metal. Dilution is defined as ratio of cross-sectional area of weld metal below the original surface to total area of weld metal. Weld dilution affects mechanical properties of the weld as it is directly related to composition of weld metal.

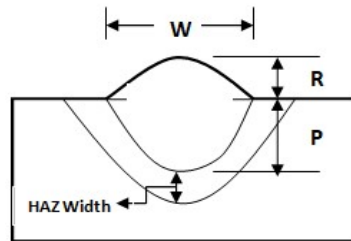


Fig 1.2 Schematic of bead geometry parameters for SAW bead on plate process [3]

Centerline cracking possibility in weld is dependent on weld penetration shape factor (WPSF) while external shape of weld is dependent on reinforcement form factor (WRFF). In any welding process HAZ is most critical part as it is the area more prone to embrittlement or weld cracking. In HAZ, there occur changes in microstructure because of thermal cycles of welding. Table 1.1 Summarizes weld bead geometry characteristics and its shape related parameters with significance.

Table 1.1 Weld bead geometry characteristics and its shape related parameters [3]

Weld bead parameters	Significance	Low level value	High level value
Penetration (P)	Necessary for stress carrying ability	Weld joint is weak	Responsible for centerline cracking
Reinforcement (R)	Improves strength of weld	Low strength due to less material	High stress concentration due to excess material
Bead width (W)	Signifies percentage parent metal involvement in welding	Improper fusion of parent and filler material	Surface cracks development
Dilution (D)	Responsible for chemical and mechanical properties of joint	Weak joint due to low penetration of metal	Solidification cracking in weld
Reinforcement form factor (WRFF)	Indication of external shape	Excessive material in reinforcement area	Concave surface of the weld
Penetration shape factor (WPSF)	Indicates probability for centerline cracking	Solidification cracking	Tendency of weld surface to crack

1.4 PARAMETERS AFFECTING BEAD GEOMETRY IN SAW

SAW is used to make large, long and repetitive welds as it is one of the most inexpensive and efficient process. The main hindrance is time and energy which goes into preparing the joint. All the joints should be lined up to have consistent gap in groove welds and backing plates need to be provided. Flux dams should be used to prevent spillage of flux. When all pieces are clamped, welding procedures and specifications should be studied and operators need to be consulted before welding procedure can begin. [2]

Variations and their effect on weld bead characteristics

Various parameters can be altered in SAW process like current, voltage, electrode stick out, travel speed of electrode, heating of work piece before welding, electrode size, flux depth and width. If any one of the above parameters is varied it will affect the shape, penetration and integrity of the weldment.

Welding current

Welding current influences parameters like weld deposition rate, penetration of metal and dilution. It is one of the most important welding variables. Increase in current at constant voltage decreases flux to wire ratio whereas decrease in current value, increases flux to wire ratio. When very low current is used, welds formed have higher width to depth ratios and they have little penetration. Welds which are made at high current have deep penetration. Low current is also responsible in producing less stable arc than the produced due to higher currents. Figure 1.3 shows effect of current variation on weld profile [2].

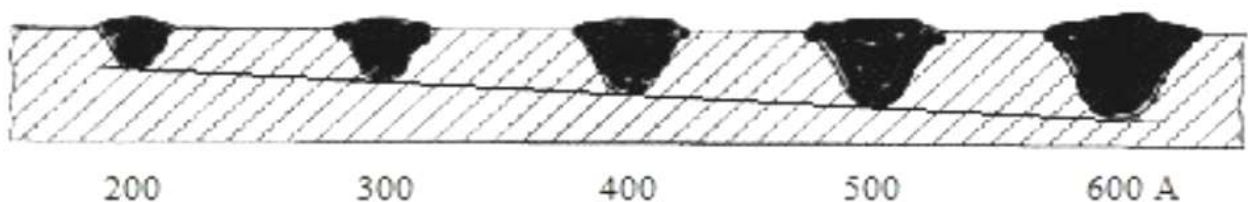


Fig. 1.3 Effect of welding current on bead profile [4]

Welding speed

When welding speed is decreased, penetration of metal and weld bead width increase. This is due to increase in heat input per length. Increase in electrode travel speed will lead to undercut and porosity and formation of crowned bead as shown in figure 1.4 [2].

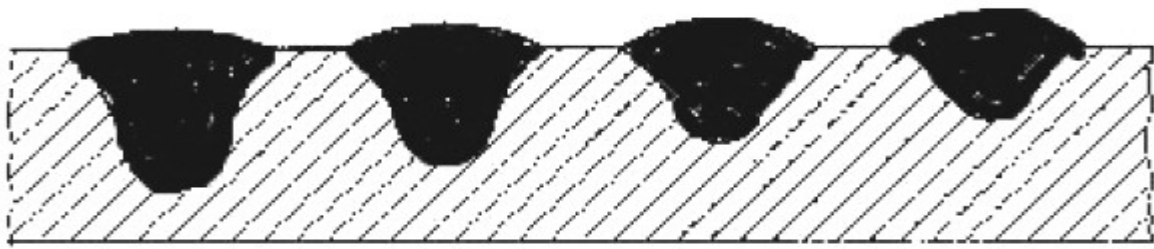


Fig. 1.4 Effect of welding speed on weld bead [4]

Voltage

When current is kept constant, increase in arc voltage leads to increase in flux to wire electrode ratio, whereas decrease in voltage will lead to reduction in flux to electrode ratio. Increasing arc voltage will lead to longer length of the arc which in turn leads to wider, flatter bead with decrease in penetration. Flux consumed tends to more in this case and the weld formed is flat hat in shape and they have low resistance to cracking. Decrease in voltage will produce arc which is unstable in nature and has a crowned bead and uneven profile where weld deposited meets plate metal [2].

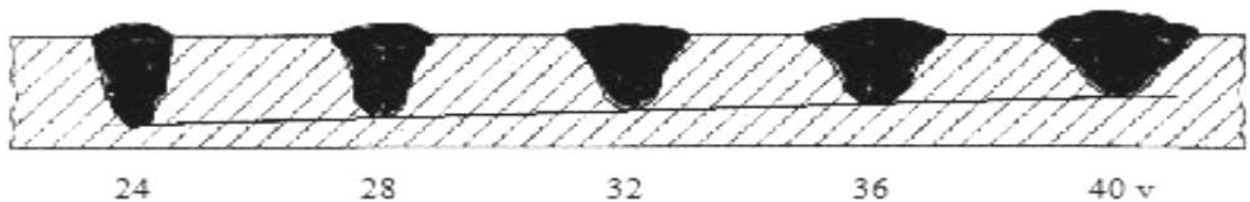


Fig. 1.5 Effect of weld voltage on weld bead [4]

Electrode stick-out

It refers to length of electrode, between end of contact tube and arc. Increase in electrode stick-out leads to reduction in energy supplied to arc which results in lower arc voltage. Now in order to obtain higher deposition, electrode stick-out should be increased along with proper voltage setting to maintain optimal arc length.

Size of electrode

Thickness of plate to be welded and size of weld determines the size of electrode to be used. If electrode of increased size is used we can get higher weld deposition rates, deeper penetration of metal and increase in weld size by increasing value of welding current. When welding current is kept constant, increase in electrode size can lead to wider and less penetrating bead. If our purpose is to bridge the gap present, we will use electrode of larger size. Effect of variation of size of electrode is shown in figure 1.6 [2].

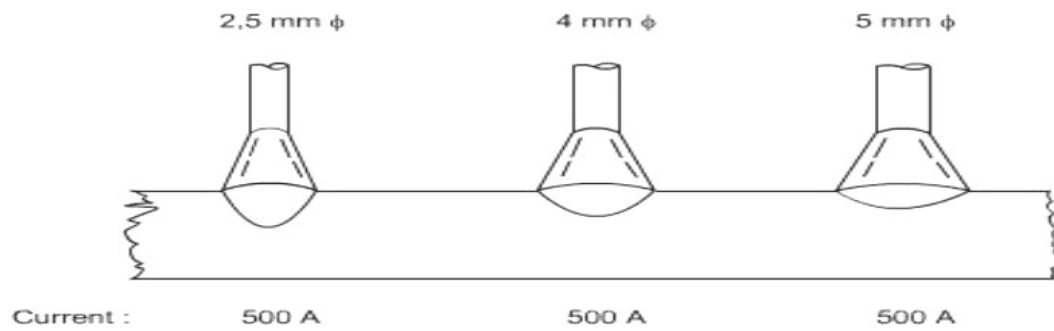


Fig. 1.6 Effect of Electrode size [4]

Flux

Flux is a compound or agent which helps to removing oxidation from metals to be welded. Zinc chloride, potassium chloride, borax are some of the common fluxes.

In metal joining processes subjected to high temperatures, main aim or purpose of using flux is to prevent oxidation of base and filler materials. Flux have tendency to become chemically active at high temperatures and they prevent creation of metal oxides. They are generally used in granular form.

Functions of flux are:

- To help in arc stability.
- Formation of slag to protect weld bead.
- Form a gas shield around the molten metal which is being deposited in arc gap.
- Helps in deoxidize weld pool.
- React with weld pool to provide weld of desired properties.

1.5 HIGH STRENGTH LOW ALLOY STEEL (HSLA)

HSLA steel is alloy steel which gives superior mechanical properties and is resistant to corrosion than normal carbon steel. When some desirable mechanical properties are desired in steel, than HSLA steels are made. The carbon content in them is kept between 0.05-0.25 percent so that they are easy to weld and retain formability. Other elements present in HSLA steels are phosphorous, copper, nickel, sulphur, niobium, vanadium and up to 2 percent manganese.

To impart strength to steel copper, titanium, vanadium and niobium are added. Yield strength is generally between 250-655 MPa. To increase corrosion resistance copper, silicon, nickel and chromium are added to the steel. To increase formability zirconium, calcium and some rare earth

elements are added. Due to presence of fine layers of ferrite and absence of pearlite, HSLA steels are resistant to rust when compared to other carbon steels.

1.6 PROPERTIES AND APPLICATIONS OF HSLA STEELS

For a small increment in price High Strength Low Alloy (HSLA) Steels impart higher strength to weight ratios over normal low carbon steels. As they are stronger, they are used in transport equipment components like pipelines where having reduced weight is of utmost importance. HSLA steels have thinner cross sections when compared to normal alloy steels and they were primarily developed for the automotive industry as it was possible to have reduction in weight without compromising on strength and dent resistance. [5]

When compared to structural carbon steel, HSLA steels need 25 to 30 percent more power in machining operations. They can handle large stresses and have better strength to weight ratio. They are also 20 to 30 percent lighter than carbon steel. Density of HSLA steel is around 7800 kg/m^3 . HSLA steel alloys have directionally sensitive properties in the sense that material exhibits different property when tested longitudinally or transversely in rolled direction. This effect is prominent in sheets having more thickness. [5]

HSLA Steels find their usage in automotive industry where reduction in weight is desired without affecting strength and dent resistance offered. Applications include door intrusion beams, automotive chassis members, mounting brackets, suspension parts, wheels and vehicle bumpers.

Mining equipment, oil exploration vessels, pipelines use HSLA sheets. For these applications, gage is specified. Structural forms (steels having 45000 to 50000 psi yield strength) are used in transmission tower, railway wagons, ship building and oil and gas rigs [5].

1.7 RESIDUAL STRESSES

Residual stresses are the stresses which are present in a body when no external load or forces are acting on it. They are also known as internal stresses or locked-in stresses. They are sometimes also referred as initial, inherent and reaction stresses.

Residual stresses can be classified into three types when taking case of a polycrystalline material. In first category comes residual stresses of ‘first type’ (macroscopic) which are almost homogeneous over the entire region of grains. Second category is residual stresses of ‘second

type' (microscopic) which are homogeneous over a small part of the material. The third category is residual stresses which are 'submicroscopic'. They are non-homogeneous and concentrated over a small region.

Residual stresses are generally classified as 'macro' and 'micro' stresses. First type of stresses can be classified as macro stresses where as micro stresses are combination of second and third type of residual stresses. In order to find total residual stresses at a particular point we take combination of first, second and third type.

Residual stresses are formed when a material undergoes changes in volume due to thermal expansion, plastic deformation and phase transitions in the material. Presence of these stresses can be detrimental to the performance and service life of component. There are stresses like compressive stresses which are deliberately introduced, like in shot peening which increases fatigue resistance.

Residual stresses are natural outcome of almost all manufacturing and fabrication processes. They can also form in processes like forging, rolling, drawing, machining or any process which undergoes different expansion or contraction in adjacent parts of body and where local yield strength is exceeded. Treatment process quenching produce residual stresses whereas stress-relieving heat treatments reduce them. Residual stresses are formed during welding process as metal undergoes localized expansion, which happens during welding operation. Molten metal takes up the heat during welding process and when the weldment cools, some areas cool more than others thereby causing residual stresses.

Residual stress formation in welded joint

When a material gets permanently deformed in a non-uniform manner residual stresses are formed. Due to uneven distribution of non-elastic strain, macroscopic strains are formed.

Processes which cause residual stresses in a component are casting, forging, extrusion, drawing and also fabrication processes like welding.

In case of multiphase materials, microscopic stresses are generated due to difference in thermal or elastic properties. They can be introduced in grains when material is subjected to heat, mechanical loading or due to chemical treatments. Sometimes when a material is subjected to mechanical loading, pileup of dislocations take place and this causes stresses to develop.

Similarly when there are present lattice defects in crystals like point or line defects, submicroscopic residual stresses are born in the material.

When a material undergoes cycle of rapid heating and cooling like in case of welding operation, shrinkage takes place and material undergoes phase transformation. Near the weld region, transient thermal stresses and non-elastic strains are generated. Depending on the type of welding technique, different types of residual stresses are produced. They also depend on welding parameter and properties of metals in welding operation.

Effect of residual stresses on welded joint

Residual stresses are present in any material which has undergone welding operation. In normal conditions the effects of stresses are not evident until the structure undergoes external loading or is exposed to some adverse environment. Tensile stresses need to be avoided as they may cause component failure due to fatigue, stress corrosion cracking etc. Compressive residual stresses are often beneficial as they mitigate the above defects and for this reason they are artificially created on the surface of the component.

In engineering, fatigue and stress corrosion cracking are the one of the most important modes of failure. These failures can be termed as surface sensitive phenomena. To protect component it is generally advised to evaluate surface residual stresses. But the study of fracture mechanics necessitates the measure of stresses at interior of the component. If compressive stresses are present in interior of the component then cracks generated on surface will not propagate inside. Hence knowledge and analysis of stress pattern is useful in assessment of crack propagation and in studies of fracture mechanics.

Failures of welded structures can prove to be fatal for the people working around it and it can cause shutdown of machinery. The failures can cause unnecessary cost buildup and affect economy of the company. There is always some amount of uncertainty in performance of welded structures. This uncertainty is due to lack of information about the residual stresses present in elements. Uncertainties are due to following reasons: (i) To get better performance newer materials are being used and (ii) Welding techniques are being modified to achieve better results and reliability. Failure of a component can be avoided or minimized if we can accurately predict the residual stresses present in the weldment. By this approach we can design and fabricate structures which are safe and reliable.

Welded components which are prone to get deformed upon machining due to presence of residual stresses should be stress relieved. Stress relieving removes deleterious residual stresses present in the component. In these cases residual stress measurements come handy to identify and study the stresses.

By changing welding parameters we can obtain stress free components by incorporating changes in process properties. This helps in development of new welding processes which can guide us in fabricating stress free products. By adding intentionally beneficial residual stresses we can reduce wastage and over design of materials which is generally associated with welding process. To make this possible we have to monitor residual stresses to study their magnitudes and distribution in weldments.

Quantitative measurement of residual stresses is useful in minimizing residual stresses by selecting optimum welding parameters. This can be achieved by optimizing welding heat inputs, diameter of electrodes used etc. weld joint design thus obtained can be useful to get stress pattern within acceptable limits and it can then be used to know effectiveness of stress relief heat treatment processes.

Primary causes for failure of steels are presence of tensile residual stresses in weldment. Frequent modes of failure can be attributed to intergranular stress corrosion cracking (IGSCC) and stress corrosion cracking (SCC). Dissimilar metal joints between ferritic steel pipes and austenitic steel is used widely in pipelines for crude transportation. Failure analysis carried on joints shows that maximum failure occurs in heat affected zone (HAZ) region. Therefore knowledge of residual stress profile of welded joints is useful in pipeline industries.

1.8 RESIDUAL STRESS MEASUREMENT

There are many techniques for measurement and analysis of residual stresses. These can be divided in two categories, destructive and non-destructive techniques.

The different techniques for measurement can be classified as follows:

- (i) Destructive techniques
- (ii) Non destructive techniques

1.8.1 DESTRUCTIVE TECHNIQUES

Stress relaxation technique is a destructive technique based on the fact that upon removal of a part of stressed body, it will result in redistribution of stress in removed as well as remainder of

the body. The redistribution is responsible for change in strain distribution whose magnitudes are related to stresses in the body. By using strain gauges, measurement of strain is done and from them, residual stresses are calculated [6].

Main disadvantage of this method is that the component has to be destroyed for analysis and at most the technique may be called semi-destructive. Specimens have to be cut either partially or entirely. The second disadvantage is that the measurement can be taken only for surface stresses. The stresses inside the component cannot be taken without destroying the sample.

Some of the Stress relaxation techniques are:

- (i) Dissection method
- (ii) Hole drilling method

Dissection method [7] is one of the earliest methods which is still used today to measure residual stresses. This method can be best applied to components having stress in one direction only or where stresses are present uniaxially.

In this method analysis becomes simple if transverse residual stress is negligible. Stress measured by linear strain gauges is

$$\sigma_L = E \varepsilon_L \quad (1.1)$$

Where σ_L : Stress in longitudinal direction

E : Modulus of elasticity

ε_L : Released strain

Hole drilling method [8] is used to measure residual stresses. This method can be called ‘semi-destructive’ in the sense that the size of hole is small with respect to thickness of component. Structural integrity of the component is not affected due to small hole and the hole can also be plugged after the measurement of residual stresses has been done.

Principle of hole drilling method is that the drilled hole does not relieve stresses in single direction as in the case of cutting. A special purpose strain gauge is used to measure the stresses. A hole is drilled through rosette centre and relieved stresses are measured in the principle directions [9]. Hole diameter is generally taken as 1.6 mm and depth of drilling is 2 mm.

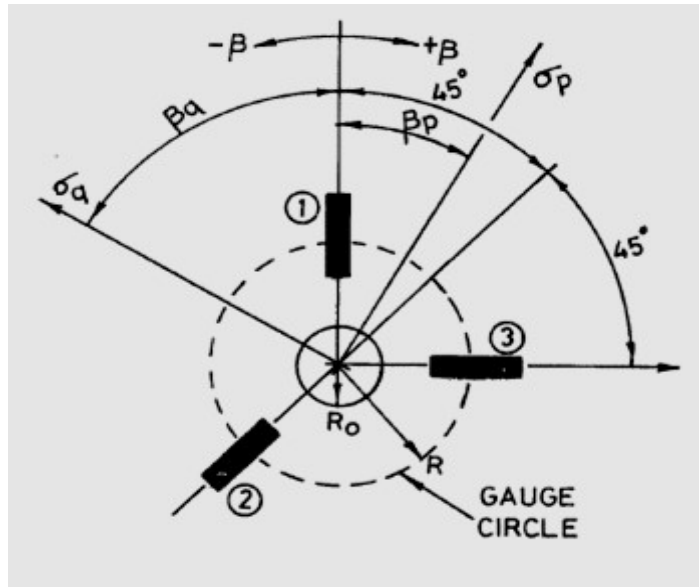


Fig. 1.7 Strain gauge arrangement in hole drilling method [6]

Where $\varepsilon_1, \varepsilon_2, \varepsilon_3$ are strain measured through strain gauges 1, 2, 3

σ_p = Major principal residual stress

β = Principal stress direction

Ultra high speed drilling technique is employed for drilling holes [10]. Other methods which can be used for precision drilling are electro-chemical milling and air –abrasive drilling techniques [11]. Electro-chemical milling is used for electrically conductive materials and high speed drilling which are not extremely hard.

1.8.2 NON DESTRUCTIVE TECHNIQUES

Diffraction techniques

One of the widely used non-destructive techniques for residual stress measurement is X-ray diffraction technique [14]. Portable equipments make possible use and measurement is possible on large objects in the field. In this technique, surface strains can be determined within area of 0.025 mm depth to 2 mm diameter. This technique can be used for quantitative analysis of macro as well as micro residual stresses separately.

Monochromatic X-ray beam is incident on the component and reflected beam is observed. This method makes use of Bragg's law which is given by equation:

$$n\lambda = 2d \sin \theta \quad (1.2)$$

λ – Wavelength of incident rays

θ – Angle between incident and reflected beam

d – Interplanar spacing

n – Reflection order ($n = 1, 2, 3 \dots$)

From above equation we can deduce that, if we know wavelength of X-ray, the value of ‘ d ’ is determined by measuring angle ‘ θ ’. When residual stresses are present value of ‘ d ’ changes which leads to shift in X-ray diffraction peaks. By using this method we can measure residual stresses in a component.

Reference directions X and Y are in surface plane and at right angles to each other. Z direction is perpendicular to surface plane. σ_x and σ_y are principal stresses and they are parallel to X and Y respectively [15]. Stress component in Z direction is zero and hence system is taken as biaxial. Strain components in X, Y and Z direction are ϵ_x , ϵ_y and ϵ_z respectively. $\epsilon_{\psi x}$ and $\epsilon_{\psi y}$ are strain components in XZ and YZ plane. By Hook’s law we get relation between stress and strain:

$$\epsilon_{\psi x} = \sigma_x \cdot \frac{1+\nu}{E} \cdot \sin^2 \psi - \frac{\nu}{E} (\sigma_x + \sigma_y) \quad (1.3)$$

$$\epsilon_{\psi y} = \sigma_y \cdot \frac{1+\nu}{E} \cdot \sin^2 \psi - \frac{\nu}{E} (\sigma_x + \sigma_y) \quad (1.4)$$

$$\epsilon_z = -\frac{\nu}{E} (\sigma_x + \sigma_y) \quad (1.5)$$

Where E – Youngs modulus of elasticity

From equation 1.3 and 1.5 we can write that

$$\epsilon_{\psi x} - \epsilon_z = \sigma_x \cdot \frac{1+\nu}{E} \cdot \sin^2 \psi \quad (1.6)$$

$$\sigma_x = \frac{E}{1+\nu} \cdot \frac{1}{\sin^2 \psi} (\epsilon_{\psi x} - \epsilon_z) \quad (1.7)$$

A crystalline material has many grains which are closely packed together albeit in random orientation. Atoms are arranged in a regular manner and they are equally spaced throughout the crystal. The distance between atomic planes called lattice spacing is constant for an unstressed crystal. The values of lattice spacing for wide variety of materials are known because of

extensive research been carried in this field. The values are available in reference books [16] and this data is provided along with instruction manual by residual stress measurement system manufacturer.

If specimen has internal stress then spacing between atomic planes changes with respect to direction of stress. By method of X-ray diffraction, spacing in crystals with respect to specimen surface can be measured. When crystal planes are parallel to surface plane and interplaner distance is d_z then,

$$\frac{d_z - d_o = \varepsilon_1}{d_o} \quad (1.8)$$

If measurement is made at angle ψ normal in XZ plane:

$$\frac{d_{\psi_x} - d_o}{d_o} = \varepsilon_{\psi_x} \quad (1.9)$$

Subtracting equation 1.9 from 1.8 and adding with combining with eq. 1.7,

$$\sigma_x = \frac{E}{1 + \nu} \cdot \frac{1}{\sin^2 \psi} \cdot \frac{(d_{\psi_x} - d_z)}{d_o} \quad (1.10)$$

Common methods of residual stress measurement by X-ray diffraction are:

- (a) Single angle method
- (b) Double angle method

Single angle method

One of the oldest methods for residual stress measurement is Single angle method [17]. The range of ψ is limited due to diffraction angle 2θ hence this method is less sensitive than two-angle method. Figure 1.8 shows schematic of single angle method. Beam of X-rays are made incident at an angle β and rays diffract from the component in picture to form a cone of emitting radiation. The diffracted rays are recorded and analyzed using detectors on sides of incident ray. Because of presence of residual stress, lattice spacing is varied in the crystal, which in turn results in change in angle of diffraction of X-ray beam.

Where the term $\frac{E}{1+\nu} \cdot \frac{1}{\sin^2 \psi}$ in above equation is a constant and is generally denoted as K. The term $d_{\psi x}$ is interplanar spacing and d_z is interplanar spacing in z direction. Two-angle method is faster and accurate when combined with position sensitive detectors (PSDs) as sample can be kept stationary and PSDs can be moved from one position to another.

Method to determine angle of diffraction

It is imperative to find diffraction angle accurately as it is an important factor in XRD stress measurements. Figure 1.9 shows schematic representation of diffractometer. Point X has source to emit X-rays which pass through point O. Detector D receives the diffracted X-ray beam. Diffraction will take place in those crystals whose lattice planes will be perpendicular to bisector. The component can be rotated about the axis so as to make lattice planes having angle with respect to plane in a position to diffract. Output to diffractometer is connected to a meter which generates voltage which is proportional to intensity of X-rays in beam. The voltage is then fed to an oscilloscope which has its X-axis synchronized to detector and Y-axis to X-ray intensity. When detector is scanned slowly over the diffracted beam region, we get a diffraction peak. This peak is shown in figure 1.9. In order to give accurate result, many angular peaks are recorded adjacent to maximum peak. A parabola is fitted to give readings of four or five more points.

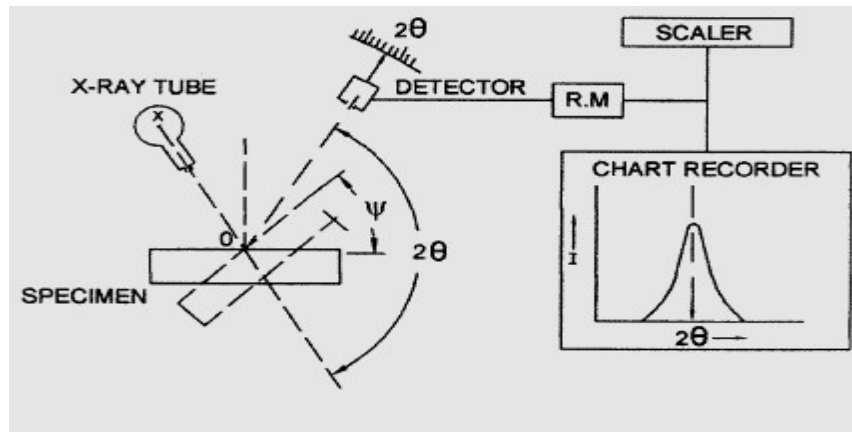


Fig. 1.9 Schematic of X-ray diffractometer [10]

1.9 ARTIFICIAL NEURAL NETWORK

Artificial neural networks (ANN) take inspiration from complexity of human brain thought process and structure. They are composed of parallel adaptive networks and derive computing ability by the help of elements called neurons. Each signal is passed through a neuron which acts as input and is then passed through a weighted pathway so as to generate a linear weighted

aggregation of signals [19]. Transformation takes place by activation function which generates the output signal for neuron. In training phase ANN gives approximation to underlying relationship between both the input and output variables of a process to random degree of accuracy. It is during testing phase that prediction capabilities of trained network are assessed. ANN is basically classified into two categories, namely, feed forward and recurrent type. In case of Feed Forward Neural Networks (FFNN), there is no presence of any cycle or loop and all the information passes in one direction from input to output layers through hidden layers. Back Propagation Neural Networks (BPNN) is one of the popular methods in variants of Feed Forward Neural Network.

Modeling using ANN

There is demand for increase in productivity in industries while maintaining uniform quality during production runs. This has lead to incorporation of computer based automation in industries. By the help of online process observation and monitoring, quality control is ensured in continuous process industries like petroleum and chemical etc. In these methods, process parameters linked to production are closely monitored and controlled instead of direct measurement of production output quality. This method is helpful in industries where process parameters bear direct relation to process variables. In case of industries having product manufacturing where process variables bear complex nonlinear relationships among multiple inputs and outputs values, it is difficult to construct a mathematical model. The above reasons make online monitoring difficult, in ensuring same output quality throughout production run. In conditions like these, soft computing is used to construct computationally intelligent systems in order to generate tools for process modeling and optimization.

Soft computing takes cue from human mind in order to learn in an environment of uncertainty and its skills to reason and argue [20]. Soft computing consists of various computing paradigms, notably among them are artificial neural networks (ANN), fuzzy set theory, genetic algorithm (GA). By inculcating the above soft computing methodologies, we are able to deal with uncertain process parameters and variables and learn to adapt in changing environment conditions for better performance. Soft computing techniques can be used to model input output relationship for any physical process. It can make suitable models for acting as supervisory control to observe online process control and in maintaining optimum product quality.

CHAPTER-2

LITERATURE REVIEW

This chapter covers the review of Submerged Arc Welding (SAW) and High Strength Low Alloy Steel (HSLA) Steels. Literature review of application of soft computing for modeling is also discussed.

2.1 LITERATURE REVIEW OF BEAD PARAMETERS AND ITS MODELING

Datta et al. [21] in this study optimization of SAW process was performed by having maximum number of slag-flux mixture in experiment that can be used without sacrificing any negative effect on bead geometry. Experiments being conducted having four different levels of parameters like welding current, slag-mixture percentage and flux basicity index.

Patnaik et al. [22] studied influence of parameters which may influence performance outputs such as deposition rate, dilution and hardness. The relationship between different control factors and outputs was established by using a nonlinear regression analysis.

Moi et al. [23] studied influence of slag-mix and varying the percentage as process variable. Main effect of slag-mix and effects of process parameters on bead geometry and heat affected zone (HAZ) have been evaluated by analysis of variance (ANOVA) method.

Elsayed & Chen [24] used Taguchi method for design of experiment and parameters to optimize the performance characteristic. It was observed that this method can reduce sensitivity of system performance to source of variation.

Myers & Montgomery [25] studied the use of quadratic response surface methodology so as to represent various process parameters in by the help of mathematical equations in submerged arc welding process.

Ghosh et al. [26] derived analytical solution model to predict transient temperature distribution on weld plate during SAW process. HAZ width calculation was done by analytical solution of the transient-three dimensional heat conduction equation.

Kumar et al. [27] used TAGUCHI experimental design to study effects of welding process parameters on micro hardness and microstructure of HAZ in weld. It was observed that micro hardness increases significantly with increase in welding current from 350A to 450A. Travel speed and arc voltage had negligible effect in relative comparison.

Prasad & Dwivedi [28] studied influence of weld process parameters like current and voltage on microstructure, hardness, and toughness in HSLA steels. Results were analyzed on the basis of net heat input on the welding process. It was observed that with increase in heat input, grain structure became coarser in weld as well as in heat affected zone. Hardness varied from weld centre line to base metal and peak hardness was observed in HAZ. It was noted that hardness reduces with increase in welding current and welding speed. Hardness of weld metal was found largely to be uniform.

Gulenc & Kahraman [29] studied effect of welding on worn out parts which were welded using submerged arc welding process. Different types of welding wires and fluxes were used in this experiment. The welded parts were subjected to wear tests under different loading conditions and any change in hardness and microstructure was examined. Results showed that highest wear resistance was offered by hardest weld metal and least by least hard metal. Results showed that weld hardness and wear resistance were dependent on chemical composition of wire and flux used.

Chandel et al. [30] studied high deposition rate in SAW by using increased welding current. Twin arc, tandem arc, multiple wire variants of SAW were studied for it.

Pandey & Bharti [31] studied influences of SAW weld parameters and flux basicity index on weld chemistry. In this study different values of welding parameters and five fluxes were used. Welds were made as bead on plate experiment. It was observed that welding current and voltage have greater influence on weld composition.

Devis [32] studied effects of ten fluxes having different bases to measure composition after welding process. It was found out that weld-metal carbon content is independent of changes in composition of fluxes. Change in silicon content of the weld was greatly influenced by the value of basicity index.

Troyer & Mikurak [33] showed that addition of powder in SAW resulted in better use of heat imparted. For a given weld process, same bead size can be achieved in less number of passes thereby cutting down energy consumed in process. Welds which are made by lower heat input undergo higher cooling rate and width of HAZ is also less. Mechanical properties of such welds are also superior and also cost effective as less energy is consumed for process.

Beidokhti et al. [34] studied effect of addition of titanium on the weld metal of API 5L-X70 pipeline steel welded using SAW. The best combination of microstructure was obtained for 0.02-0.05% titanium. It was observed that Titanium inclusion improves toughness due to formation of acicular ferrite in microstructure.

Zrilic et al. [35] studied toughness and crack properties of joints in weld metal as well as in the HAZ. Crack sensitivity is ratio of impact energy for V-notched and pre-cracked specimens which enabled to compare microstructure of parent and weld metal. The results showed that toughness and ability to resist crack of weld metal was lower than those of parent metal and HAZ.

Ravi et al. [36] studied influences of MMR on fatigue life of HSLA steel welds. Butt joints were made by SMAW process and a CCT specimen was used to evaluate fatigue life of welded joints. Analysis of Variance (ANOVA) method was used to study significance of main and interaction value effects. Mathematical model was developed and used to predict fatigue life of HSLA steel welds by the help of regression analysis.

Tuma & Sednak [37] studied interaction between two adjacent weld bead matrix and soft weld metal inclusions. It was seen that the interaction produces local brittle zone (LBZ), which causes local unstable fracture behavior. Low hardness region formation was attributed to process of multi pass welding and reheating. Local strength mis-match caused yielding and strain hardening and it contributed significantly to unstable fracture behavior.

Ravi et al. [38] studied strength of filler materials when compared to that of parent material depending on application and use of welded structures. Butt joints were fabricated by SMAW process. Fatigue crack growth was tested at constant amplitude loading.

Bhole et al. [39] studied effects of alloy addition in the process of SAW. Nickel (Ni), molybdenum (Mo) was added to study their effect on impact toughness of API HSLA-70 steel welded using SAW. Addition of Ni resulted in low impact toughness and increase of Mo promoted formation of high toughness.

Galantucci et al. [40] employed ANN to establish relationship between quality of welds obtained and the process parameters of the experiment to weld A16110 T61 alloy sheets. Computerized image processing was used to recognize any defect or imperfections in the weld cross section. ANN system adopted here was proved to have close tolerance level in quality levels measured when compared by experimental methods.

Luo et al. [41] used BPNN to diagnose faults during welding process. By using acoustic signals, features extracted were input to ANN so that after training identification could be made between normal and abnormal welds.

Yilbas et al. [42] conducted welding of wedge surfaces having inclination angle of 18° and also normal surfaces and they were examined by drop out flatness of surface.

Tsai et al. [43] employed a BPNN model for prediction and analysis of various cutting parameters in welding like depth of penetration, width of the heat affected zone (HAZ). Input

variables of BPNN were current, frequency and speed of torch. A genetic algorithm (GA) was developed defined by user objective function in order to find the optimal parameters which lead to fast welding speed and with least heat affected zone (HAZ) width.

Nguyen et al. [44] made extensive survey and presented analytical solutions for moving heat sources in plates, cylinders and spheres in simulation of weld pool and residual stresses. They assumed that conduction played important part in thermal analysis of weldment. Estimation for welding process was more difficult having multiple pass welding.

Stamenkovic and Vasovic [45] performed a 3D welding simulation and predicted residual stresses induced due to welding. This process was used to butt weld two carbon steel plates. Simulation was considered to be sequentially coupled thermo-mechanical analysis. Filler material deposition was achieved by having element birth and death technique in simulation.

Tahami et al. [46] examined effect of plate thickness on residual stresses formation when butt welding steel plates. Analysis result showed that value of residual stresses increases with increase in plate thickness. Residual stress affected zone was also found to be exhibit same pattern. The effect of welding-electrode speed using element birth and death of elements was studied and it was seen that simulation of butt welding gave results within accepted region. It was seen in analysis that longitudinal residual stress in weld axis changed to tensile from compressive when plate thickness was increased.

Mohammadreza et al. [47] considered a carbon dioxide laser beam delivering thermal loading to a thin disc of steel to simulate welding and compare ensuing stresses obtained experimentally. The metallurgical transformations have been taken into account and the FE results agreed with the experimental ones, including temperatures and distortions.

Ramamurti et al. [48] proposed that high tensile residual stress in regions near the weld may lead to brittle fracture, fatigue, stress corrosion and cracking in weldment. Compressive residual stress and initial distortion may reduce buckling strength thereby weakening joint. Annealing of weldment is needed for to lower the risk of brittle fracture during the service of the structure. Unfortunately, such a post-weld heat treatment (PWHT) may also lead to a deterioration of mechanical properties of the metal. It would therefore be of interest to try and predict and compare the stresses induced in the material.

2.2 OBSERVATIONS FROM LITERATURE

After reviewing the existing literature regarding submerged arc welding, it was found that very few comprehensive studies have been reported for investigating the effect of various process

parameters on weld bead geometry for HSLA steels. It was also observed that very few studies have been reported for modeling the stochastic process like SAW using soft computing methods. Application of ANN in validating bead geometry has been sporadically covered for steel plates and even less in case of HSLA steel plates. Soft computing technique like ANN is important in modeling and optimization of weld bead characteristics.

Scant information is available for simulation for HSLA steels weld joints. Residual stresses are responsible for failures at later stage because stresses induced due to high temperature gradient cause deformation and failure of the welded structure. It becomes necessary to have a reliable method to measure them directly with minimum experimental time. Residual stresses can play a significant role in explaining and preventing failure of a component.

Papers studied had problems in simulation of welds due to dynamic nature of welding process. Literature survey showed that modeling of residual stresses in weld was difficult due to high computation time required by the computers and even if we created fine mesh around weld, results were approximate at best.

Scant studies have been done for analysis of residual stresses for HSLA steel. As welding process involves many different parameters, need is there to have methods which can easily predict stresses in weldments.

2.3 OBJECTIVES OF STUDY

The objective of this study is to model the process parameters of SAW to predict the bead geometry parameters using the ANN technique. The process parameters varied during welding are open circuit voltage, trolley speed, contact tube to work piece distance, preheat temperature and wire feed rate. After finding the bead geometry for the experiments, modeling and validation of results is done by Artificial Neural Network (ANN). For the modeling of residual stresses locked in the weld bead, ABAQUS is used and results obtained are verified by conducting the confirmatory experiments and measuring the residual stresses using XRD.

CHAPTER- 3

EXPERIMENTATION AND METHODOLOGY

In this chapter, discussion is done about materials and methods adopted to undertake welding operation. Figure 3.1 shows the plan of work as followed in this research work. Work carried out in this M.E. thesis is completely based on the experimental work carried out by Sharma [3] for his Ph.D. research work. Results for bead geometry parameters are taken to further analyze the SAW process simulation for residual stresses. For better understanding of the work, details of base as well as filler material, SAW process details and methodology adopted by Sharma [3] for his work and methodology of this thesis research work are discussed in the following sections.

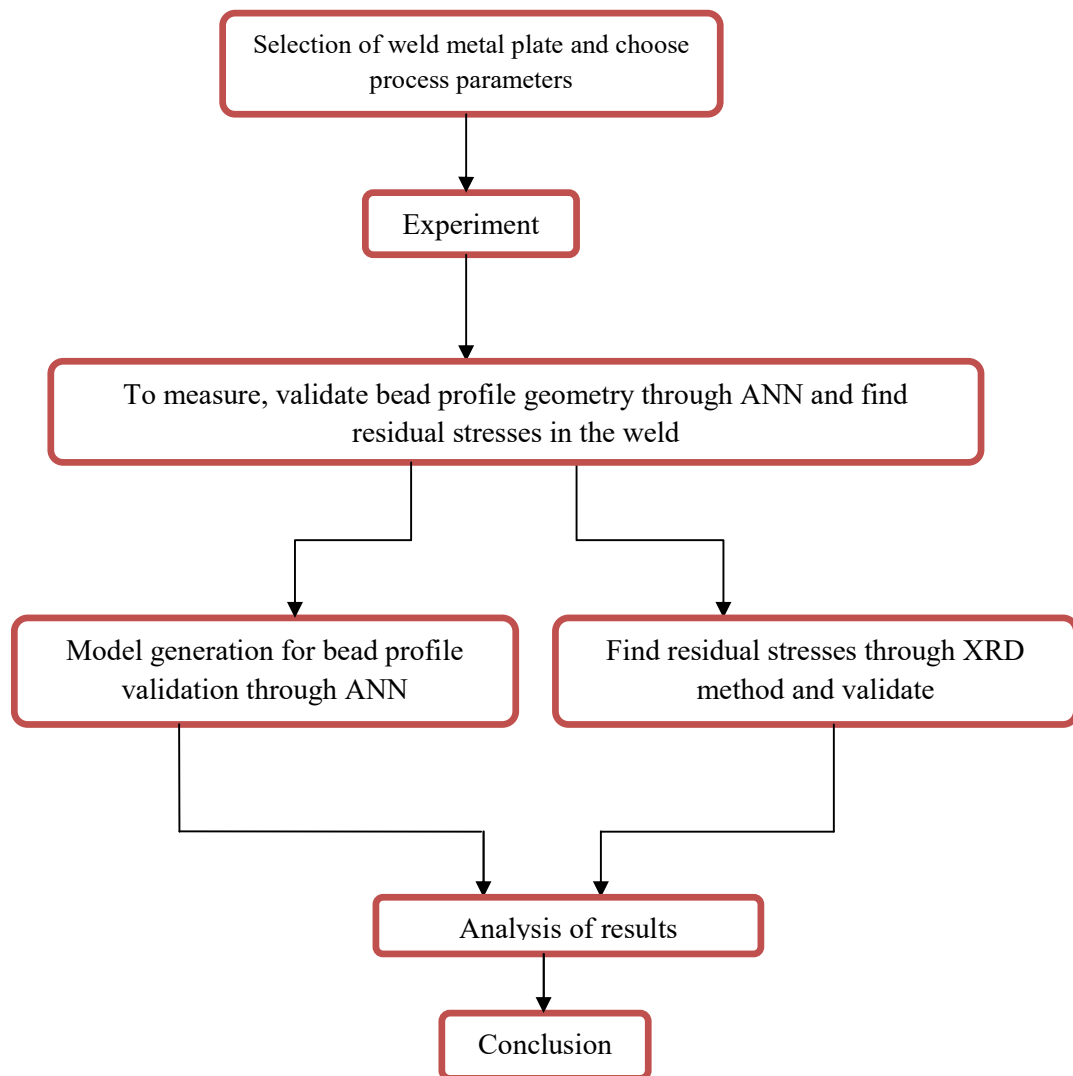


Fig. 3.1 Plan of research work

3.1 MATERIALS AND METHODS

To find weld bead characteristics in relation to preheating temperature and heat input, beads were laid on plane surface of API 5L X80 micro-alloyed high strength steel plates. Dimensions of plates were 300mm × 75mm × 24mm. Filler and flux was selected according to AWS A5.23: EF3EG classification.

3.1.1 BASE AND FILLER MATERIAL COMBINATION

Table 3.1 gives chemical composition of plate and electrode wire.

Table 3.1 Chemical composition of base plate metal and consumable electrode wire [3]

Element	Fe	C	Si	Mn	S	P	Ni	Cr	Mo
API X80	97.39	0.053	0.225	1.59	0.005	0.0095	0.189	0.103	0.259
Electrode wire	96.37	0.13	0.22	1.73	0.004	0.007	0.93	0.03	0.53
Element	Al	Cu	Ti	Nb	Co	V	Pb	Zr	B
API X80	0.036	0.057	0.018	0.036	<0.01	0.018	<0.01	<0.006	<0.0005
Electrode wire	0.002	0.04	-	-	-	0.01	-	-	-

Filler wire of 4mm diameter (OE-SD3 1Ni 1/2Mo) and fluoride based flux (OP 121 TT/W) was used in the experimentation. Chemical composition of flux used is shown in table.

Table 3.2 shows chemical composition of flux used in the SAW process.

Table 3.2 Chemical composition of flux [3]

Main Constituents	SiO ₂ + TiO ₂	CaO + MgO	Al ₂ O ₃ + MnO	CaF ₂	Basicity
%age	15	40	20	25	3.1

3.1.2 MACHINE SETUP AND WELDING PARAMETERS

ESAB-CPRA 800 (S) DC power source was used in experimental procedure to lay down weld bead on HSLA steel plate surface. The DC power source used was of constant voltage type. The power source used has self adjusting arc length control. The constant voltage power used gives steady arc length as any change in current with change in arc voltage alters burn off rate so as to oppose change in arc length. DC electrode positive (DCEP) polarity is used in submerged arc

welding as it gives maximum penetration with best surface appearance. It also gives resistance to porosity [3]. Plates were kept in heating chamber of electric furnace for uniform preheating temperature. In this study, five variables were selected for variation of parameters. They were selected so as to change the heating and cooling rate of welding process. Open circuit voltage, trolley speed, contact tube to work distance, preheating temperature and wire feed rate were the parameters changed in the experiments which were based on CCRD. Process variables were selected on the basis of studies and experiments [3]. The process parameters are shown in table 3.3.

Table 3.3 Process parameters with their levels used in experiment [3]

Process Parameters	Units	Levels				
		-2	-1	0	+1	+2
Open circuit voltage	Volt	30	32	34	36	38
Trolley Speed	cm/min	25	30	35	40	45
Contact Tube to Work piece Distance	mm	24	28	32	36	40
Preheat temperature	°C	60	120	180	240	300
Wire feed rate	mm/s	20	25	30	35	40

3.2 RESPONSE SURFACE METHODOLOGY

Fractional factorial techniques are used where there are many factors involving number of layers and where conducting numerous experiments is not possible. Limitations of fractional factorial method are that interaction takes place between only those factors about which we have some past information or knowledge. If we wish to study effects of interaction between some new factors about which no study has been done, fractional factorial design prove to be unsuccessful. Central composite rotatable design (CCRD) method of response surface methodology is useful for the above mentioned cases. By using CCRD method using half fraction, the numbers of times we have to design and perform experiments are reduced to 32 in total. Advantage of using this method is reduced prediction error and improved estimation of quadratic effects when compared to face-centered CCD. Another advantage of a CCRD method is that the variance of predicted values obtained of process response is in equal distance in all directions from centre of design.

RSM is useful in processes which are influenced by many process variables. It is a collection of different statistical and mathematical techniques used for modeling and analysis of experimental

problems. In initial stages relationship between response and variables is unknown and in that case linear model is used to find an approximate relationship. Drawback of using a linear model is that it suffers from lack of fit due to interaction between variable values and surface curvature.

Thus a second order model when used can improve the optimization process by introducing a second order polynomial model in RSM while neglecting further higher order terms as given in equation. The quadratic model is defined as-

$$y = \beta_0 + \sum_{i=1}^k \beta_i x_i + \sum_{i=1}^k \beta_{ii} x_i^2 + \sum_{i < j} \beta_{ij} x_i x_j + \varepsilon \quad (3.1)$$

Where y denotes desired output response, x_i denotes process variables, k is number of design variables, β is regression coefficient, ε denotes error observed in response.

In this study, application of RSM with CCRD is discussed. Here, preheating temperature, open circuit voltage, welding speed of torch, electrode stick out length and electrode wire feed rate are the variables whose influence on weld bead characteristics of X80 HSLA steel plate is observed. The above 5 variables have been changed while performing submerged arc welding (SAW) process in accordance to CCRD as shown in table 3.4 in coded and actual values. The process variables influencing study were selected after studying their influence through single factor experiments and their values were thus chosen after observing preliminary experiments and past literature data. Coded values at different levels were assigned to actual value at all levels using equation

$$x_i = \frac{X_i - X_0}{\Delta X_i}; \text{ or } \text{Coded value} = \frac{\text{Uncoded(Actual) value} - \text{Mean value}}{\text{Incremental value}} \quad (3.2)$$

By using above method, conversion of actual values to coded values brings variables used in experiment to same order of magnitude. This makes regression analysis easy and productive. Table 3.4 shows values of different weld parameters arranged according to CCRD method.

Table 3.4 Central composite rotatable designed experiments [3]

Run No.	Standard No.	Process Parameters in coded values					Process Parameters in Actual values				
		A	B	C	D	E	A	B	C	D	E
1	12	1	1	-1	1	-1	36	40	28	240	25
2	26	0	0	0	0	2	34	35	32	180	40
3	28	0	0	0	0	0	34	35	32	180	30
4	11	-1	1	-1	1	1	32	40	28	240	35
5	16	1	1	-1	1	1	36	40	36	240	35
6	01	-1	-1	-1	-1	1	32	30	28	120	35
7	32	0	0	0	0	0	34	35	32	180	30
8	03	-1	1	-1	-1	-1	32	40	28	120	25
9	30	0	0	0	0	0	34	35	32	180	30
10	10	1	-1	-1	1	1	36	30	28	240	35
11	14	1	-1	1	1	-1	36	30	36	240	25
12	17	-2	0	0	0	0	30	35	32	180	30
13	20	0	2	0	0	0	34	45	32	180	30
14	08	1	1	1	-1	-1	36	40	36	120	25
15	19	0	-2	0	0	0	34	25	32	180	30
16	31	0	0	0	0	0	34	35	32	180	30
17	24	0	0	0	2	0	34	35	32	300	30
18	27	0	0	0	0	0	34	35	32	180	30
19	15	-1	1	1	1	-1	32	40	36	240	25
20	02	1	-1	-1	-1	-1	36	30	28	120	25
21	23	0	0	0	-2	0	34	35	32	60	30
22	06	1	-1	1	-1	1	36	30	36	120	35
23	13	-1	-1	1	1	1	32	30	36	240	35
24	22	0	0	2	0	0	34	35	40	180	30
25	07	-1	1	1	-1	1	32	40	36	120	35
26	09	-1	-1	-1	1	-1	32	30	28	240	25
27	29	0	0	0	0	0	34	35	32	180	30
28	05	-1	-1	1	-1	-1	32	30	36	120	25
29	25	0	0	0	0	-2	34	35	32	180	20

30	21	0	0	-2	0	0	34	35	24	180	30
31	18	2	0	0	0	0	38	35	32	180	30
32	4	1	1	-1	-1	1	36	40	28	120	35

3.3 PREPARATION OF SAMPLES

Before commencement of welding operation, the plates were thoroughly cleaned to avoid any contamination like dust, rust, oil, moisture etc. Presence of any contamination may result in weld defect in later stages.

3.3.1 PREPARATION OF SAMPLES FOR BEAD GEOMETRY MEASUREMENT

Weld bead on the surface of plate is shown in figure 3.2. After deposition of bead was done, a small cross-section was cut for measurement of bead geometry parameters. Cutting of weld pieces was performed by using an abrasive cutter as shown in figure 3.4(a). The pieces were polished using emery papers with grades 100 to 1200. Super polishing was done using alumina suspension on velvet cloth. To reveal bead geometry parameters, Nital solution having concentration of 5% was used (5 ml HNO_3 in 95 ml ethanol) to polish the surface [3].



Fig. 3.2 Weld bead on plate surface (a) with slag layer deposit (b) after removal of slag layer [3]



Fig. 3.3 Cross-section of cut part (a), polished surface (b) and (c) weld bead geometry is revealed after using Nital solution [3]



Fig. 3.4 (a) Abrasive cutting machine, (b) open cover shield, (c) stereo zoom microscope [3]

After welding operations were done, samples were cut from plates and bead geometry characteristics were measured, their results are shown in table 3.5.

Table 3.5 Results of weld bead characteristics [3]

Run No.	W (mm)	P (mm)	R (mm)
1	16.15	7.86	5.50
2	13.74	10.20	6.60
3	17.18	7.50	5.48
4	10.48	8.80	7.56
5	14.26	10.20	6.36
6	14.90	9.78	7.30
7	16.20	7.54	5.80
8	16.10	7.44	4.70
9	19.20	7.50	4.90
10	15.90	11.80	7.30
11	21.90	7.40	4.80
12	6.70	7.75	6.70
13	12.10	8.50	5.30
14	15.76	7.46	4.32
15	19.44	9.70	7.00
16	18.00	7.45	5.00
17	12.70	9.00	5.50
18	17.80	7.60	5.20

19	12.87	8.14	5.06
20	18.84	7.80	5.00
21	17.86	7.72	5.80
22	17.00	10.10	7.80
23	11.14	9.50	8.00
24	16.50	8.00	7.38
25	10.50	8.24	7.70
26	11.58	8.44	6.16
27	17.00	7.62	5.15
28	19.34	7.00	4.92
29	19.28	6.00	3.50
30	13.70	8.80	5.00
31	13.74	9.00	5.70
32	12.24	9.40	5.50

3.3.2 PREPARATION OF SAMPLES FOR RESIDUAL STRESS MEASUREMENT

Wire Electrical Discharge Machining (WEDM) is one of the important non-traditional machining process, capable of producing complex two and three dimensional shapes under close tolerances, precision and accuracy which is demanded by manufacturing industries. WEDM is used in automobile, aeronautical, tool and die industries in areas of material machining [49]. WEDM has grown leaps and bounds since its introduction in the year 1969.

D.H. Dulebohn applied optical-line follower system which was capable of controlling the shape of component to be machined automatically. After the year 1975, its popularity was increasing as industries started to recognize the importance of capabilities of WEDM process. By the end of 1970s, computer numerical control (CNC) system was incorporated in WEDM process which brought about major revolution in the machining process [50].

Basic scheme of wire electrical discharge machining (WEDM) process

Typical WEDM setup consists of wire, worktable, electrical control device, power supply, wire feed drive unit and dielectric supply system. Basic scheme of WEDM system [51] is exhibited in Fig. 3.5. The CNC system performs various functions like sequential cutting operation,

manufacture part modeling, CNC code generation, wire feed rate, table movement, dielectric circulation etc. Input to CNC system is given by keyboard.

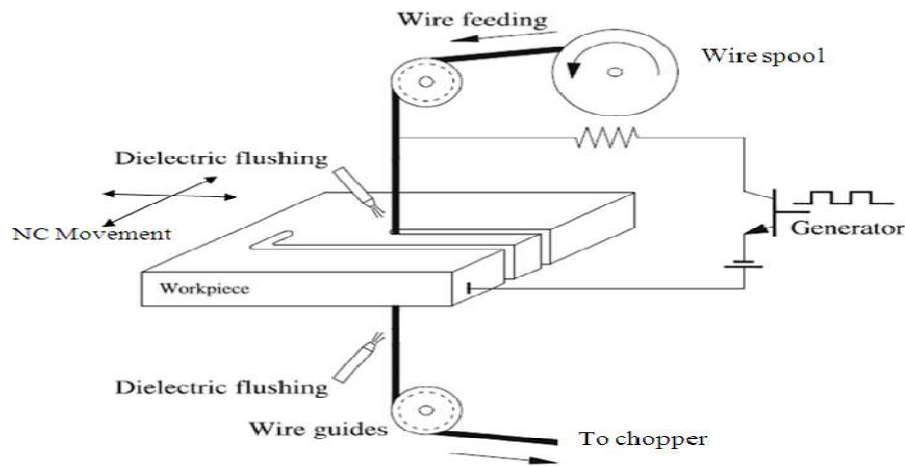


Fig. 3.5 Schematic representation of the WEDM process [51]

The work piece is clamped on the worktable and table is free to move along X and Y-axis directions. The wire electrode is continuously fed from wire supply spool system and passes through guide where required current is imparted to it under tension. Used wire is collected in a chopper bin. The path traversed information of X-Y table and U-V table is passed to the controller with the help of a NC program.

A series of electrical pulses generated by the pulse generator unit is applied between the work piece and wire electrode. This causes erosion of material and the process is continuously repeated by moving worktable in predetermined path. Path traversed is decided by controller and it moves it in X-Y direction. As machining is in progress, distilled water is used to flush the work piece. Distilled water acts as dielectric medium which passes through nozzles on both sides of work piece. To prevent ionization of water, ion exchange resin is used to maintain conductivity of dielectric.

Machine setup and process parameters

From the plates having bead on surface, small piece for the measurement of bead geometry parameters was cut having weld in the centre. Cutting of weld pieces is carried out using abrasive cutter as shown earlier in figure 3.4(a). This piece was polished with emery papers of different grades starting from 100 to 1200 number of SiC abrasive followed by super polishing

using alumina suspension on velvet cloth. To reveal the bead geometry parameters, 5% concentrated Nital solution (5 ml HNO₃ in 95 ml ethanol) is applied on the polished surface. [3]

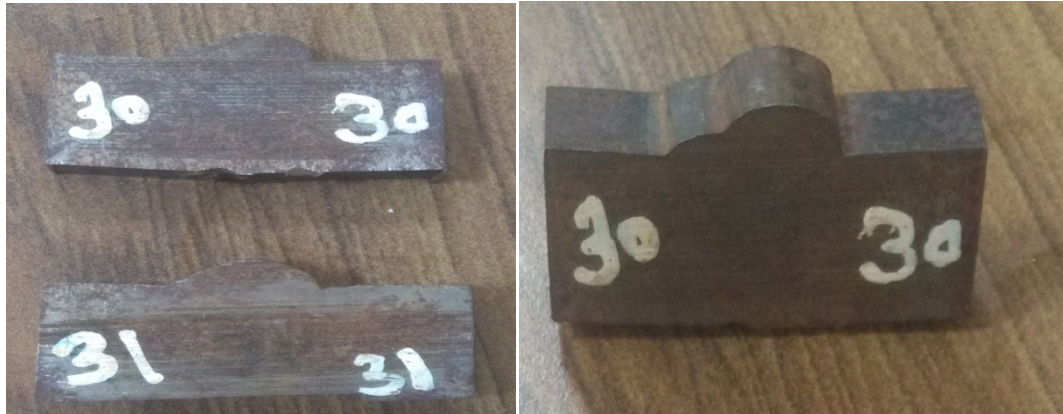


Fig. 3.6 (a) Plates in cross-section having weld bead (b) Weld bead on top of plate

Machine and part programming

WEDM machine used to cut pieces in required dimension was that of Ecocut of Electronica group. Salient features of this model are

Table 3.6 Features and properties of WEDM machine

S. no.	Features	Properties
1	Travel X-Y	250×350 mm
2	Max. work piece height	150 mm
3	Max. table size	370×600 mm
4	Max. cutting speed	70 mm ² /min.
5	Taper	± 5° over 50 mm
6	Best surface finish	1.2 μ Ra

Dimension required of sample work piece for XRD analysis was 22×22×5 mm. There were total 5 samples pieces selected for the analysis. The pieces had weld bead at different places at the plate. They were cut so as to have portion of weld bead on which XRD analysis could be performed.



Fig. 3.7 ECOCUT WEDM with work piece on worktable and cover [Courtesy- Echo Tool Engineering, Bhopal]

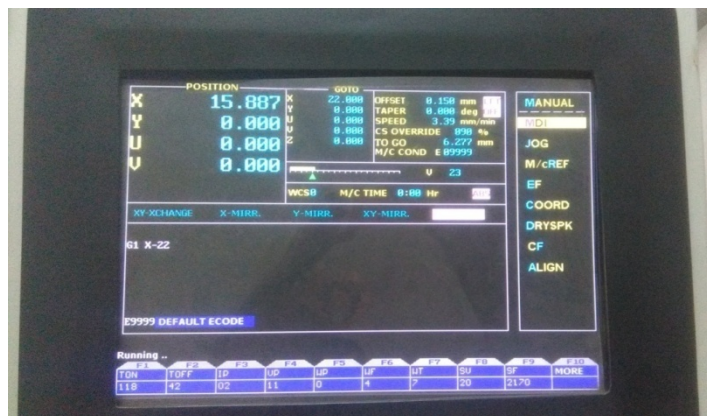


Fig. 3.8 CNC controller monitor to observe table position and feed rate



Fig. 3.9 (a) Wire feed mechanism with spool of wire and (b) operations in progress



Fig. 3.10 (a) Schematic of work piece with weld bead, (b) Work piece before and after machining and (c) Schematic of HAZ and point location for XRD test

XRD machine setup

Details of machine used to analyze the samples and perform analysis is shown in table 3.7

Table 3.7 Features and properties of XRD machine

S. No.	Make and characteristics	Properties
1	PANalytical, The Netherlands	(1) X' Pert Pro (2) EMPYREAN
2	Specification	X-Ray tube with Cu target. (Anode Material)
3	Wavelength	– 1.54184 Å
4	X-ray generator	40KV & 30 mA / 45kv & 40 mA

Figure 3.11 shows the machine setup for XRD analysis.



Fig. 3.11 (a) X' PERT PRO (b) EMPYREAN

3.3.3 HEAT INPUT AND COOLING TIME CALCULATION

Heat input in any arc welding process depends on arc voltage, welding current, welding speed and electrode stick-out. In this study, these very process parameters were taken to change heat input values. The power source used in this study was that of constant voltage. Welding current adjusts itself according to slight change in wire feed rate. Heat input per unit length of welding is determined using equation 3.1.

$$HI = \eta \frac{V \times I \times 60}{N \times 1000} \text{ (kJ/mm)} \quad (3.3)$$

Where η = arc efficiency, V = average arc voltage (V), I = average welding current (A), N = trolley speed (mm/min).

To find out average values of voltage and current, V-I transient data is recorded using data acquisition system. Process efficiency for submerged arc welding is taken to be 85%. Cooling rate is calculated by the equation 3.4. Cooling rate is given in °C/s.

$$\Delta t_{8/5} = \frac{HI}{2\pi} \left(\frac{1}{500 - T_0} - \frac{1}{800 - T_0} \right) \quad (3.4)$$

CHAPTER-4

RESULTS AND DISCUSSION

4.1 DEVELOPMENT OF MODEL USING ANN FOR BEAD GEOMETRY

Artificial neural networks (ANNs) have emerged as a revolutionary new field of computing. It has been successfully made its foray in study in various fields of studies [51]. In this process, experimental and ANNs results are compared. Studies have been published in which properties and parameters of SAW were discussed. The neural network efficiency and performance depends on number of hidden layers and also on number of input neurons. In this regard, there has been exhaustive research work been carried out to study effect of hidden layers (2 to 3) and number of neurons in hidden layer (15 to 30) for optimal prediction of weld bead geometry. Researchers have put forward approaches that use trial and error in order to determine the number of hidden layers and neurons [52].

Many computational experiments were performed with several combinations to find the right number of hidden layers and number of neurons. The structure of various neural networks is shown in Table 4.1. The appropriate structure for optimal bead geometry is found out by trial and error method. For this research the best ANN structure was found to be 5-18-13-3. This structure has 5 neurons in input layer; 18 in first hidden layer; 13 neurons in second hidden layer; 3 in the output layer). The results are summarized in Table 4.2 and the optimal is bold face. The five neurons of input layer were taken as input parameters of experimental work and three neurons in output layer were related as response variables for the three parameters (Penetration, height and weld width). The neurons of one layer provide input to the next layer neurons when the network is run. This process continues and the results are obtained from the output layer. The ANN was modeled using Neural Network Toolbox of MATLAB software. The architecture of MATLAB model is shown in Fig 4.1. The algorithm used for Neural Network training was Levenberg-Marquardt. This algorithm is many times faster than steepest descent algorithm, gradient descent and gradient descent with momentum. Logarithmic Sigmoidal transfer functions were used in all hidden layers and pure linear transfer functions for output layer.

Table 4.1 Performance of different ANN structures

Experiment no.	ANN structure	Training function	Transfer function	R-correlation coefficient
1	5-10-15-3	Trainlm	Logarithmic sigmoidal	0.95612
2	5-12-17-3	Trainlm	Logarithmic sigmoidal	0.98365
3	5-14-15-3	Trainlm	Logarithmic sigmoidal	0.98124
4	5-15-19-3	Trainlm	Logarithmic sigmoidal	0.97125
5	5-16-18-3	Trainlm	Logarithmic sigmoidal	0.98201
6	5-11-19-3	Trainlm	Logarithmic sigmoidal	0.96763
7	5-13-11-3	Trainlm	Logarithmic sigmoidal	0.977029
8	5-17-14-3	Trainlm	Logarithmic sigmoidal	0.98242
9	5-19-11-3	Trainlm	Logarithmic sigmoidal	0.98946
10	5-18-13-3	Trainlm	Logarithmic sigmoidal	0.99428

In the above table 4.1, Iteration number 10 gave the closest result to actual values and validating the model.

Table 4.2 shows weld bead characteristics values obtained from welding experiments and those obtained from ANN model. Differences in values are also tabulated.

Table 4.2 Experimental value, Predicted and Error value of the ANN

Run. No.	Actual W (mm)	Predicted W (mm)	Error E For W	Actual P (mm)	Predicted P (mm)	Error E for P	Actual R (mm)	Predicted R (mm)	Error E for R
1	16.15	16.12372	0.026284	7.86	7.07086	0.78914	5.5	5.259333	0.240667
2	13.74	13.74	4.04E-11	10.20	10.2	6.91E-11	6.6	6.6	-1.62E-11
3	17.18	18.045	-0.865	7.50	7.5125	-0.0125	5.48	5.145	0.335
4	10.48	10.48	1.55E-11	8.80	8.8	1.02E-10	7.56	7.56	-2.15E-11
5	14.26	14.26	3.99E-11	10.20	10.2	8.33E-11	6.36	6.36	-1.29E-11
6	14.90	14.8973	0.002696	9.78	9.200938	0.579062	7.3	6.608934	0.691066
7	16.20	18.045	-1.845	7.54	7.5125	0.0275	5.8	5.145	0.655
8	16.10	16.1	8.94E-12	7.44	7.44	7.86E-11	4.7	4.7	-2.44E-11
9	19.20	18.045	1.155	7.50	7.5125	-0.0125	4.9	5.145	-0.245
10	15.90	15.9	3.77E-11	11.80	11.8	9.57E-12	7.3	7.3	-3.90E-12
11	21.90	21.9	4.23E-11	7.40	7.4	6.09E-11	4.8	4.8	-2.47E-11
12	6.70	9.312502	-2.6125	7.75	7.566105	0.183895	6.7	7.261464	-0.56146
13	12.10	12.1	-1.30E-11	8.50	8.5	-7.93E-12	5.3	5.3	-2.60E-13
14	15.76	15.76	-1.09E-10	7.46	7.46	-6.30E-13	4.32	4.32	-1.95E-11
15	19.44	19.44	6.82E-11	7.86	9.7	-5.24E-13	7	7	1.13E-11
16	18.00	18.045	-0.045	10.20	7.5125	-0.0625	5	5.145	-0.145
17	12.70	12.7	2.21E-11	7.50	9	-8.57E-11	5.5	5.5	1.85E-11
18	17.80	18.045	-0.245	8.80	7.5125	0.0875	5.2	5.145	0.055
19	12.87	12.7943	0.075695	10.20	8.127949	0.012051	5.06	5.781157	-0.72116
20	18.84	18.84	6.50E-12	9.78	7.8	8.47E-11	5	5	-2.86E-11
21	17.86	17.86	2.11E-11	7.54	7.72	-5.28E-11	5.8	5.8	2.17E-11
22	17.00	17	8.01E-12	7.44	10.1	4.47E-12	7.8	7.8	-1.08E-12
23	11.14	11.01726	0.122741	7.50	8.860559	0.639441	8	7.876477	0.123523
24	16.50	16.5	2.23E-11	11.80	8	-9.57E-11	7.38	7.38	-5.00E-12

25	10.50	10.5	1.72E-11	7.40	8.24	4.20E-11	7.7	7.7	-3.69E-12
26	11.58	10.55315	1.026855	7.75	8.036422	0.403578	6.16	5.615567	0.544433
27	17.00	18.045	-1.045	8.50	7.5125	0.1075	5.15	5.145	0.005
28	19.34	19.34	-7.45E-11	7.46	7	1.68E-10	4.92	4.92	-3.70E-11
29	19.28	19.28	-5.66E-11	7.86	6	1.00E-10	3.5	3.5	-7.53E-12
30	13.70	13.7	4.46E-11	10.20	8.8	5.20E-11	5	5	-6.91E-12
31	13.74	15.67295	-1.93295	7.50	8.60714	0.39286	5.7	5.337428	0.362572
32	12.24	12.48655	-0.24655	8.80	9.37822	0.02178	5.5	4.479212	1.020788

Fig. 4.1 shows 18 neurons in first hidden layer and 13 in second hidden layers. This iteration gave the best result.

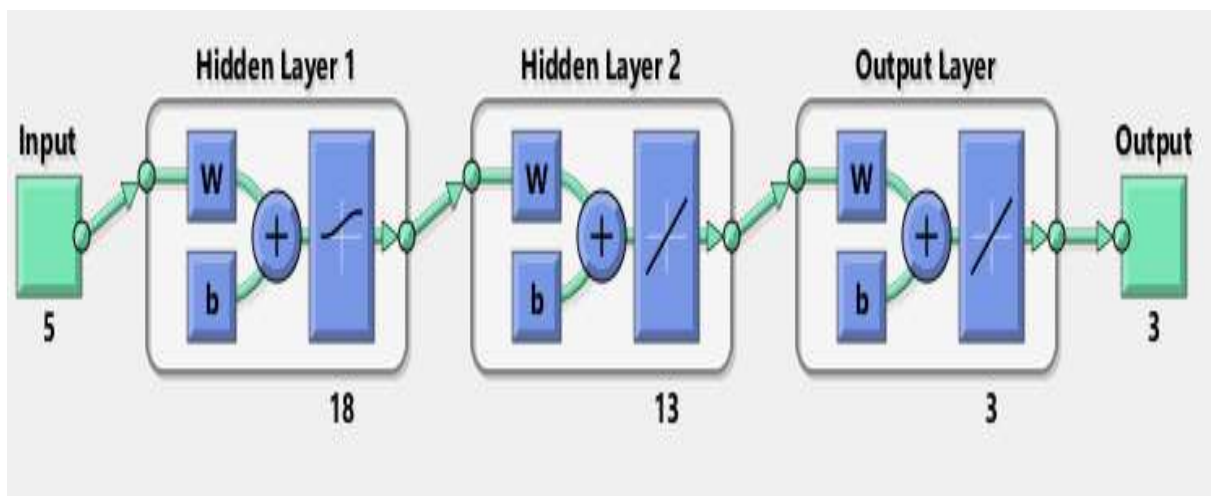


Fig. 4.1 Network architecture of the ANN model

Figure 4.2 shows the regression in terms of value of 'R' (correlation coefficients) for training, validation, testing and value of the model are **0.99287**, **0.99876** and **0.99731** respectively. There is almost 100% semblance or agreement between observed and predicted values.

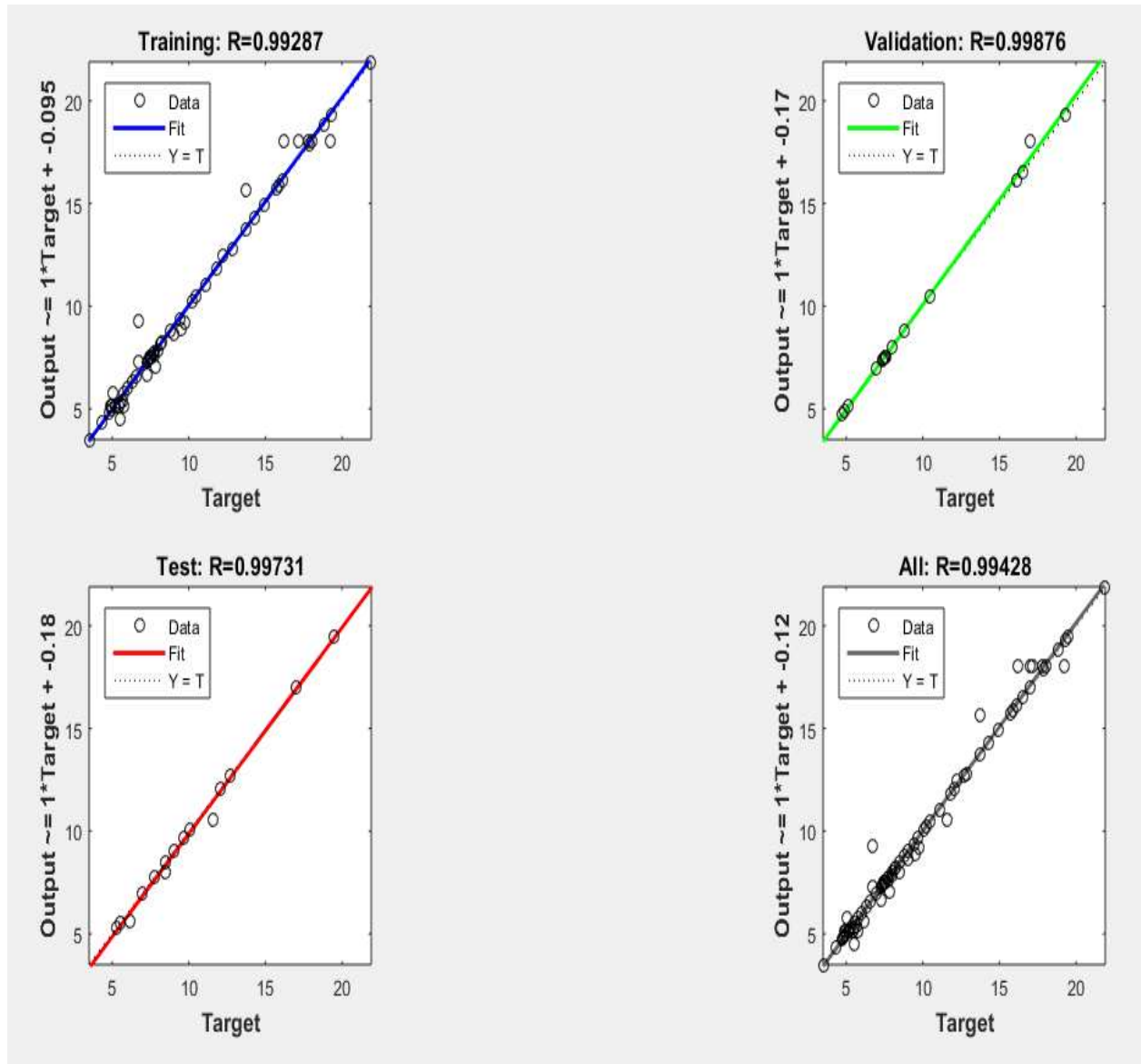


Fig. 4.2 Regression plot

4.2 COMPARISON OF MODEL RESULTS WITH ACTUAL VALUES OF BEAD GEOMETRY

Figure 4.3 shows variation of actual bead width obtained from experiments to that of predicted bead width obtained from ANN model.

4.2.1 COMPARISON FOR BEAD WIDTH (W)

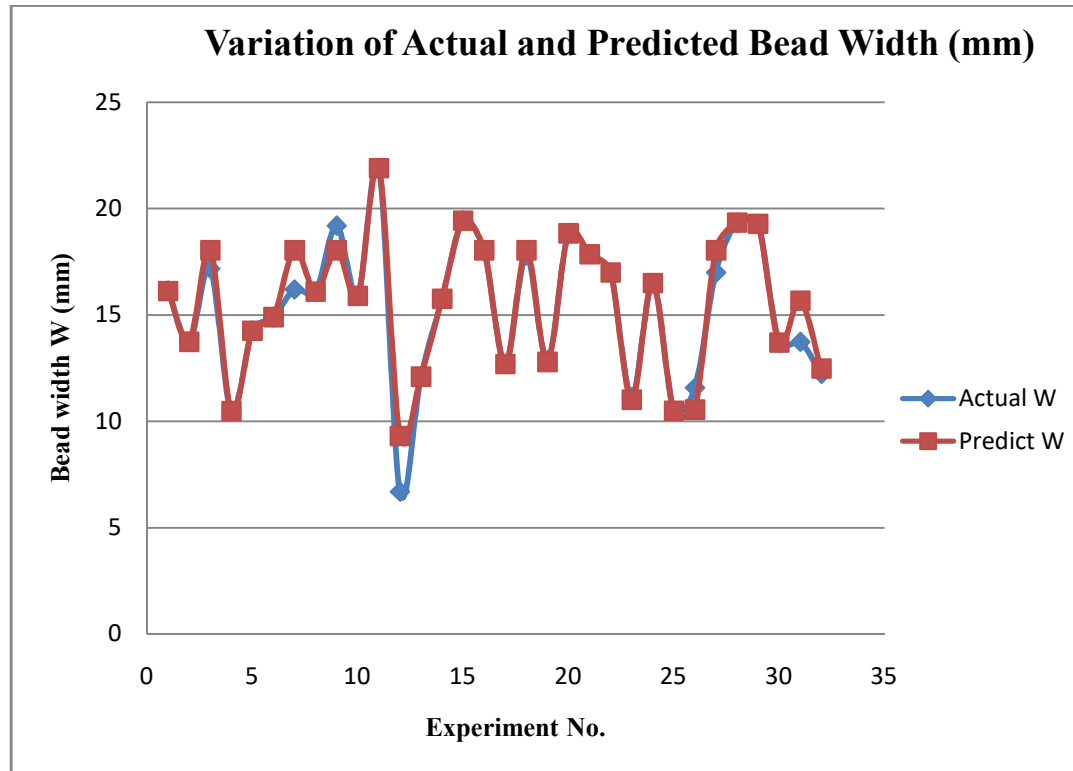


Fig. 4.3 Variation of Actual and Predicted Bead width W (in mm)

From the above figure 4.3 we analyze that, predicted value of bead width follows the trend line of values of actual bead width value. The maximum difference of error between the two values at experiment run is that of **1.155** which is **6.01%** of actual value in real experiment run.

4.2.2 COMARISON FOR PENETRATION (P)

Figure 4.4 shows variation of actual penetration obtained from experiments to that of predicted value obtained from ANN model.

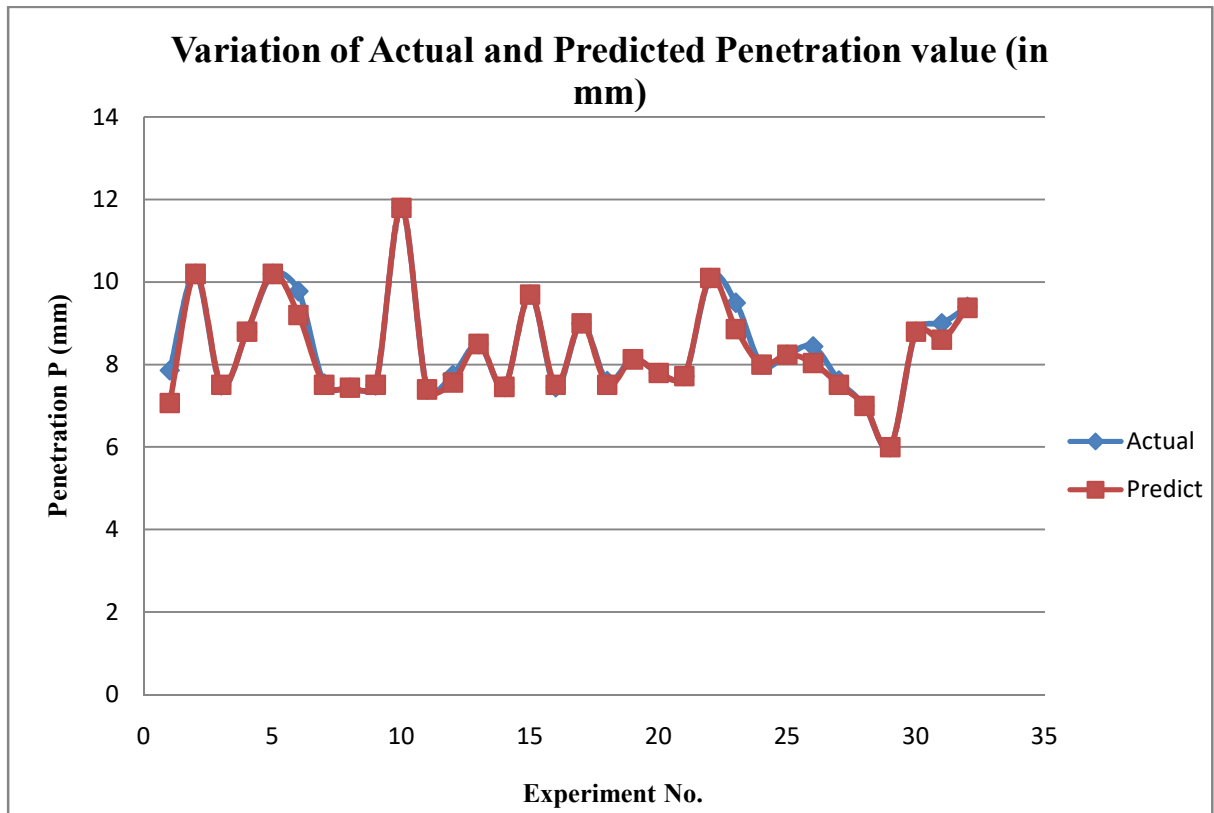


Fig. 4.4 Variation of Actual and Predicted Penetration P (in mm)

From the above figure 4.4 we analyze that, predicted value of penetration follows the trend line of values of actual penetration value. The maximum difference of error between the two values at experiment run is that of **0.78** which is **4.82%** of actual value in experiment runs.

4.2.3 COMPARISON FOR REINFORCEMENT (R)

Figure 4.5 shows variation of actual penetration obtained from experiments to that of predicted value obtained from ANN model.

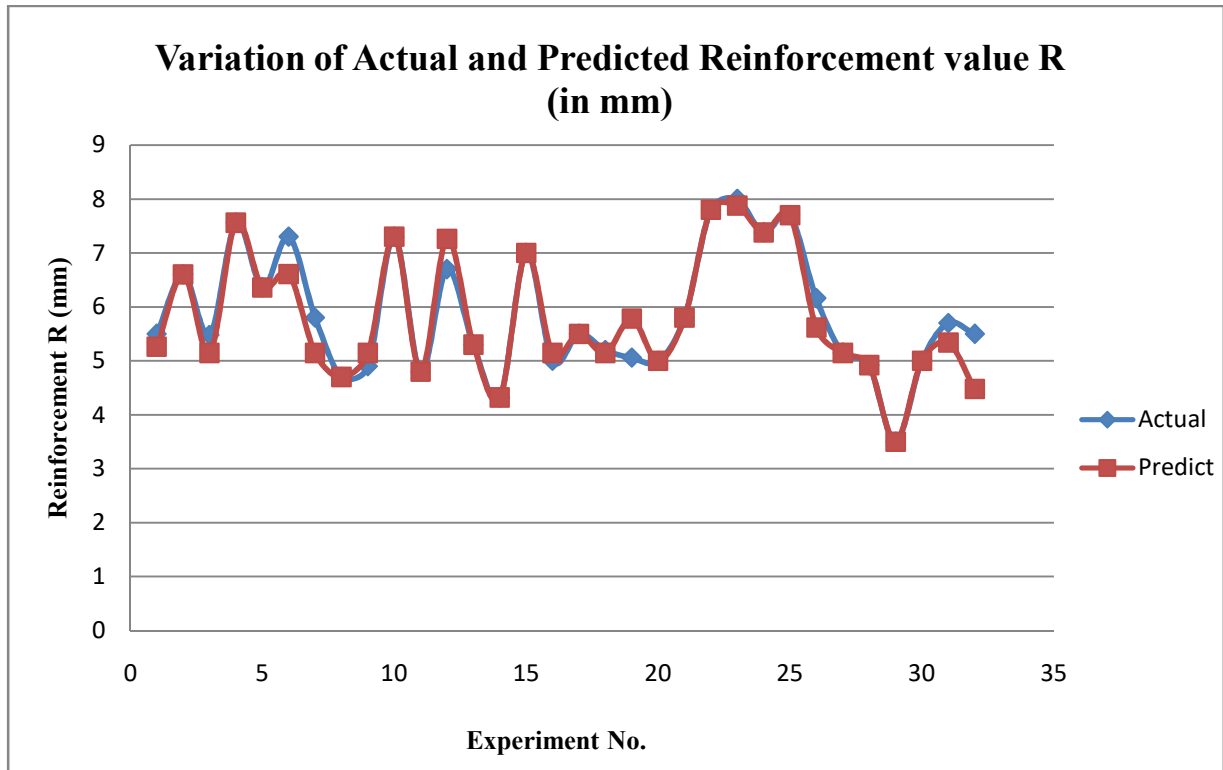


Fig. 4.5 Variation of Actual and Predicted Reinforcement (in mm)

From the above figure 4.5 we analyze that, predicted value of reinforcement follows the trend line of values of actual reinforcement value. The maximum difference of error between the two values at any experiment run is that of **0.691066** which is **9.4%** of the actual value.

Fig.4.3, Fig.4.4 and Fig.4.5 compare the variation of penetration, reinforcement height and weld width using ANN (Artificial Neural Network). Back propagation neural network is used for modeling the weld bead geometry (penetration, reinforcement height and weld width) and the analysis carried out for this confirms that artificial neural network is a powerful tool which can be used for the analysis and modeling of experiments.

The results obtained using Neural Network Tool indicate that neural network can yield fairly accurate results.

4.3 RESULTS FOR RESIDUAL STRESSES

There were in total 5 samples. Each sample had 2 readings to be taken for calculation of stresses. One of the points to be tested was in immediate vicinity of weld fusion zone and other was at a distance from the weld bead. Results obtained are shown below. All the values of stresses are in MPa. Table 4.3 shows values of various process parameters for experiment trials. Samples were selected on the basis of cooling rate. Value of cooling rate was calculated using Rosenthal equation for thick plates. Cooling temperature range selected was between temperatures 800 to 500 °C, as metallurgical changes are more prominent in this range. Negative terms denote that stresses are compressive in nature and positive term denotes tensile nature.

Table 4.3 Values of process parameters in study for experiment trials

Trial experiment	OCV (in volt)	Trolley speed (in cm/min)	Tube to work piece distance (in mm)	Preheat temperature (in °c)	Wire feed rate (in mm/s)	Cooling rate (in °C/s)
1	34	35	32	180	30	20.9
2	36	30	28	120	25	24.74
3	34	35	32	180	20	26.96
4	34	35	32	80	30	33.46
5	34	35	32	25	30	38.73

4.3.1 VARIATION IN RESIDUAL STRESSES WITH COOLING RATE

Table 4.4 shows values of residual stress σ_{xx} and σ_{yy} with respect to cooling rate of the weld.

Table 4.4 Values of residual stresses in MPa.

Experiment no.	Value of σ_{xx} in region near HAZ	Value of σ_{yy} in region near HAZ
1	-603.7	-801.1
2	-365.4	-465.0
3	-78.6	-410.1
4	107.9	-32.0
5	114.7	-3.7

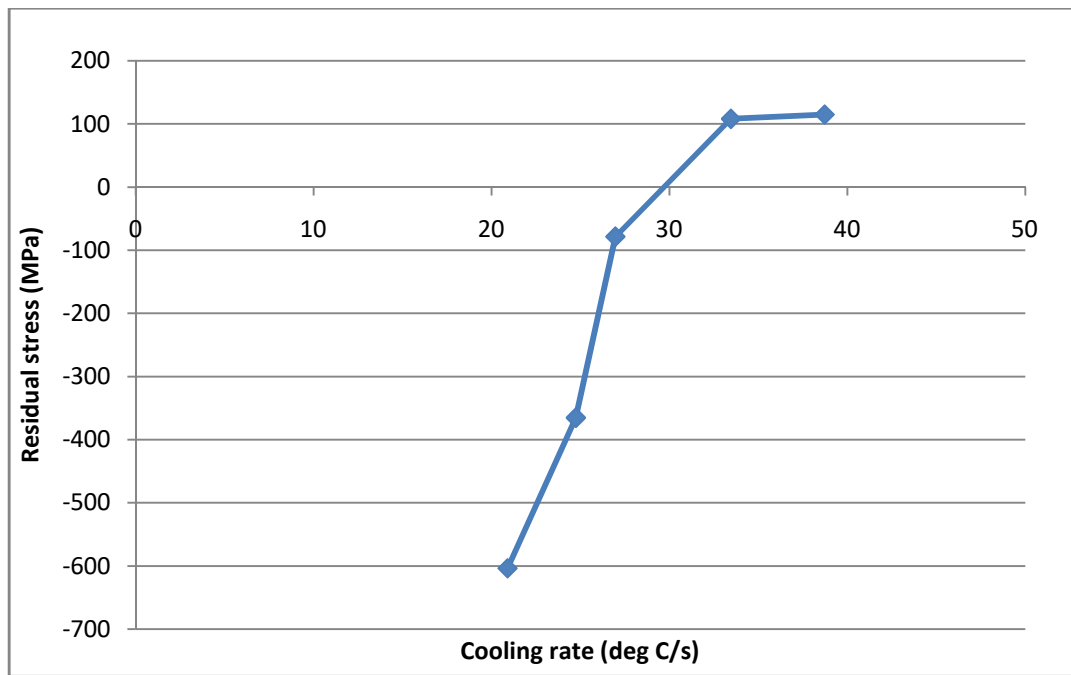


Fig 4.6 Variations of σ_{xx} stresses with cooling rate

Observing the graph in Fig. 4.6 we deduce that stresses decrease in value with increase in cooling rate of the plates. The trend also shows that nature of stresses changes from compressive to tensile with increase in cooling rate value.

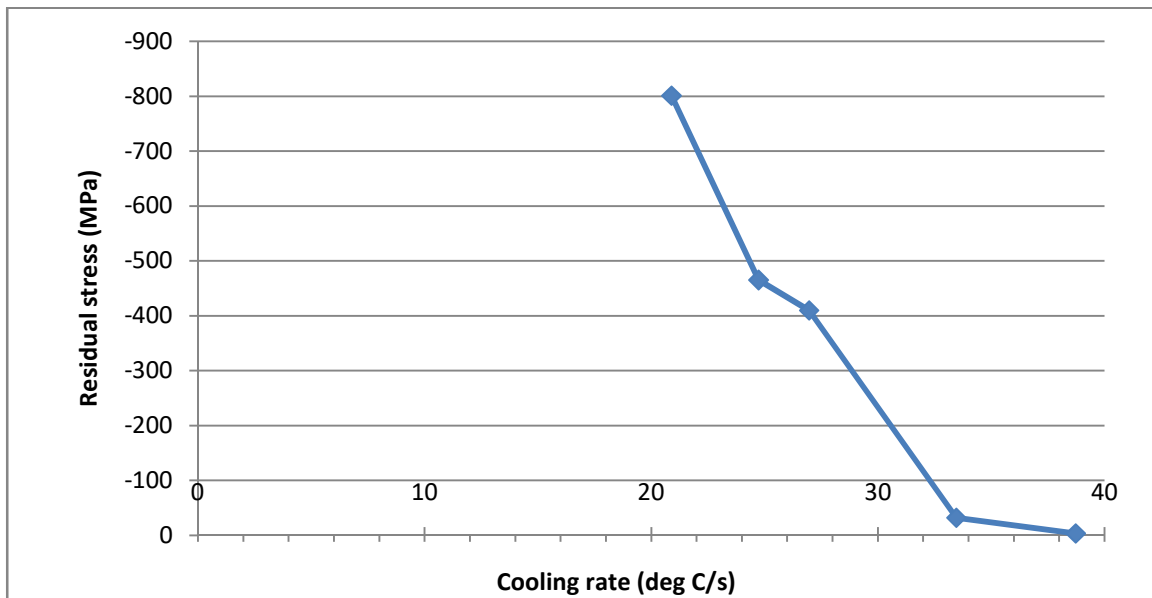


Fig 4.7 Variations of σ_{yy} stresses with cooling rate

Observing the graph in Fig. 4.7 for residual stress in y direction, we can deduce that stresses decreases in value with increase in cooling rate of the plates. The trend shows that nature of stresses changes from compressive with increase in cooling rate.

The reason behind these trends can be understood by understanding the relation between heat input of welding and cooling rate. As per the Rosenthal Equation higher cooling rate indicates the lower heat input of the welding operation. This lower heat input affects the lesser area around the weld and therefore lesser residual stresses in the joint.

4.4 VALIDATION OF XRD ANALYSIS RESULTS BY SIMULATION

Objectives of simulation-

To perform finite element simulation of submerged arc welding and predict residual stresses generated due to thermal expansion of the part.



Fig 4.8 (a) Picture of weld bead on plate and (b) CAD model of plate

Loading details-

Submerged arc welding involves moving arc which provides heat to the work piece and fusion zone is formed. As the arc generating electrode moves, melt pool keeps on forming in the welding direction. To simulate the heat addition process, a user subroutine called DFLUX is created in ABAQUS. With the help of subroutine moving arc source is created with required power input into the work piece.

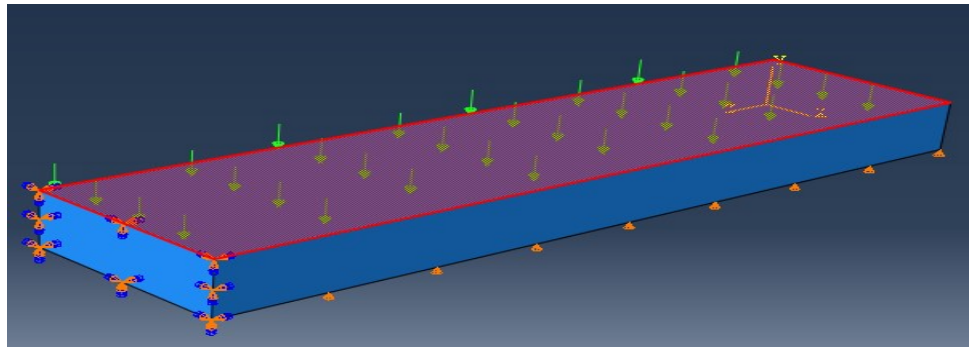


Fig. 4.9 Loading details on plate

Interaction details-

As the work piece is getting heated there will be some heat losses to the environment via convection. Heat convection is defined at all the surfaces of work piece with ambient temperature of 25°C and convection coefficient of $30 \text{ W/m}^2 \text{ K}$.

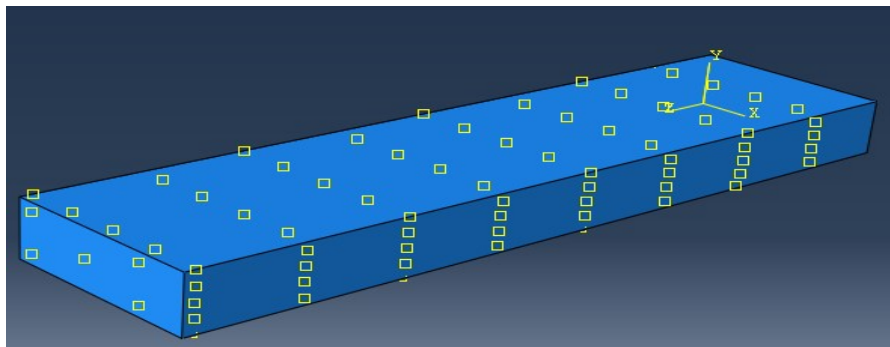


Fig. 4.10 Interaction details on CAD model

Boundary conditions

To constraint the work piece during finite element analysis boundary conditions are applied. Work piece is constraint in vertical and in-plane direction.

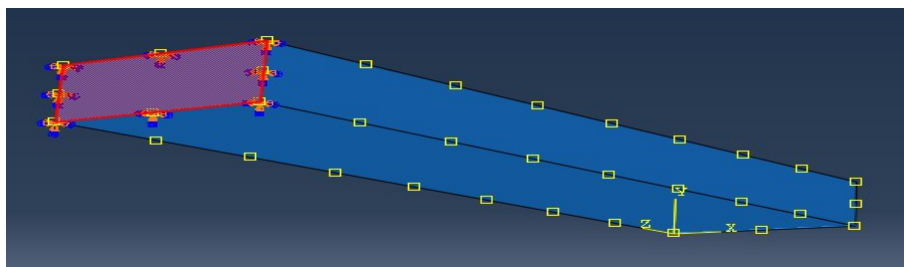


Fig. 4.11(a) Boundary conditions on plate on left face

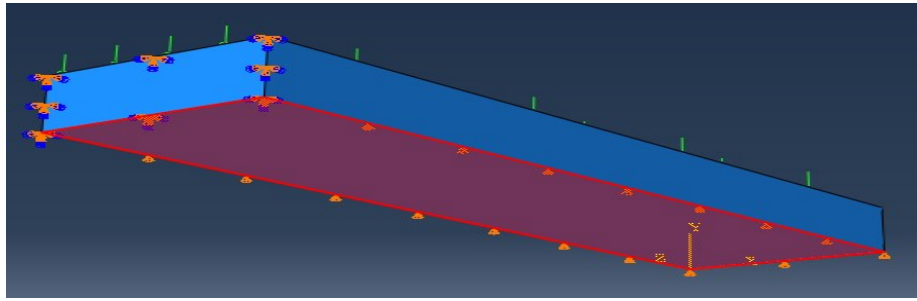


Fig. 4.11 (b) Boundary conditions on plate on bottom face

Step and meshing details-

Present analysis involves temperature and displacement calculation at the elements. Therefore coupled temperature displacement analysis is performed and elements are also selected correspondingly.

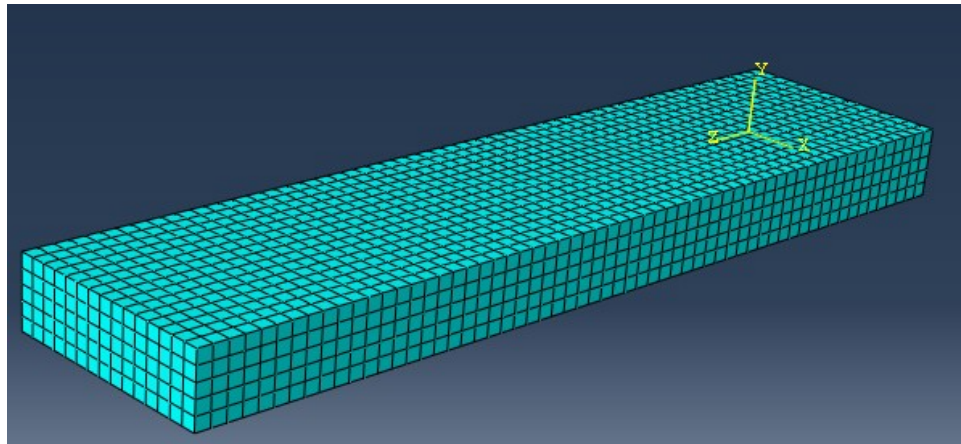


Fig. 4.12 Meshing of the CAD model

Values of σ_{xx} and σ_{yy} obtained from simulation

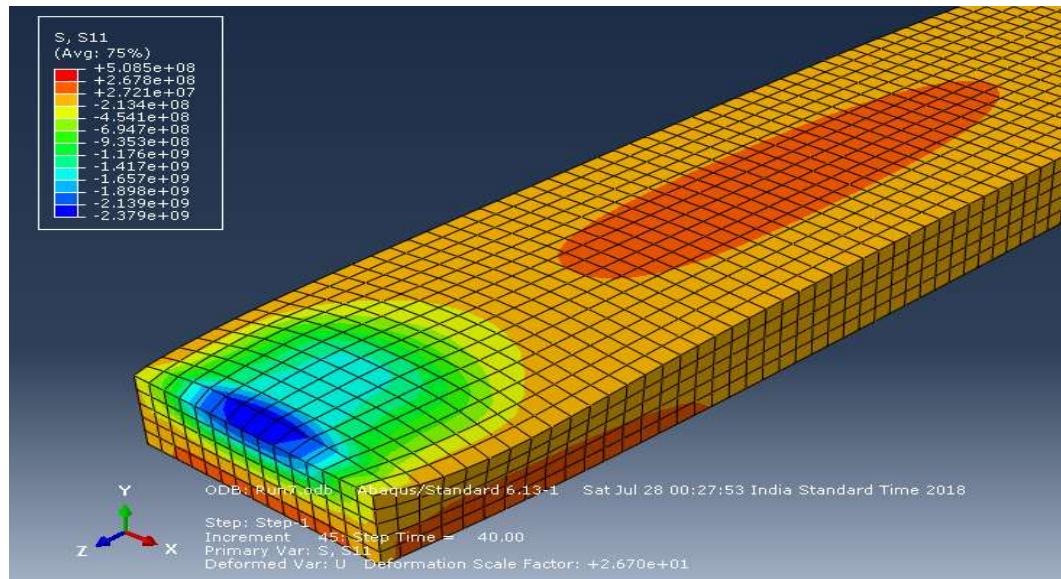


Fig. 4.13 (a) Value of σ_{xx} from simulation

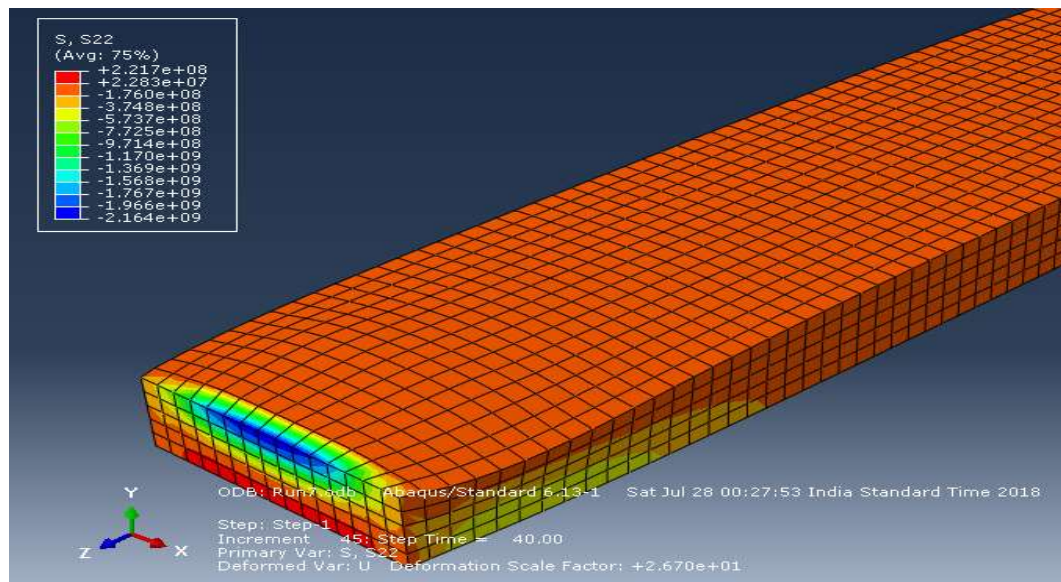


Fig. 4.13 (b) Value of σ_{yy} from simulation

4.4.1 Variation between values of stresses obtained from XRD and simulation

We observe from figure 4.14 (a) and (b) that the values of stresses obtained from XRD analysis and that obtained from Simulation closely follow each other in a definite trend, thereby validating the simulation model.

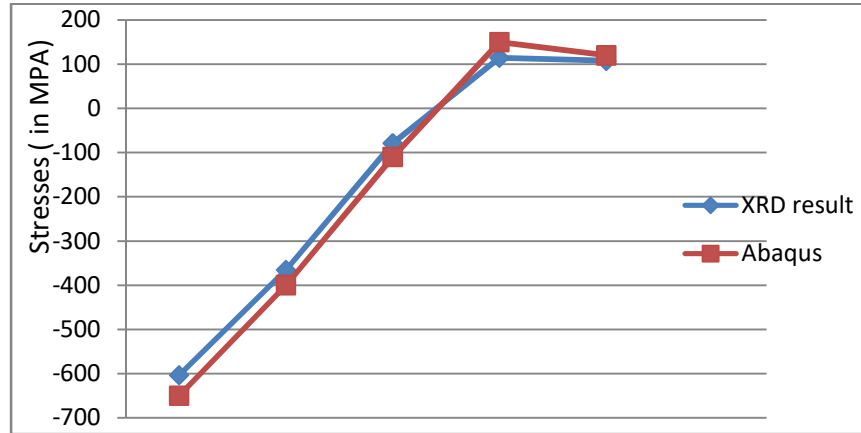


Fig. 4.14 (a) Graphical trend of σ_{xx} from XRD analysis and simulation

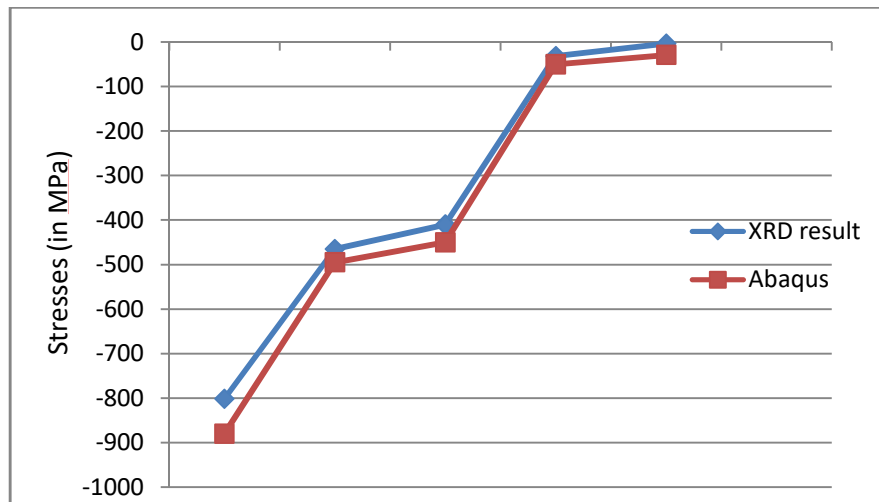


Fig. 4.14 (b) Graphical trend of σ_{yy} from XRD analysis and simulation

4.5 SUMMARY

Following points are deduced from results-

There were total ten ANN model structures. Five input values were taken for bead parameters namely open circuit voltage, trolley speed, contact tube and work piece distance, preheat temperature and wire feed rate. Three output values for bead characteristics bead width, penetration and reinforcement were taken.

Each model had two hidden layers. The model chosen for accurate prediction had eighteen neurons in first hidden layer and thirteen in second hidden layers. Out of ten models, the one selected was found to be 99.428% accurate. Maximum difference between predicted and actual value was 6.01%, 4.82% and 9.4% for weld bead width, penetration and reinforcement respectively.

Model made using ANN was able to closely predict values of bead geometry within close tolerances. During investigation of residual stresses in samples, types of stresses were found to be tensile and compressive in nature. Stresses found near weld bead had tensile as well compressive stresses in them.

CHAPTER-5

SUMMARY, CONCLUSIONS AND FUTURE SCOPE

5.1 SUMMARY

Study of weld bead characteristics with relation to heat input and preheating temperature for SAW process was studied by laying beads on plane surface of API 5LX80 HSLA steel plates. Effect of five input parameters was studied on bead geometry profile micro-alloyed high strength pipeline steel plates. In order to lay down the beads on the surface of HSLA steel plates, ESAB-CPRA 800 (S) DC power source was used. DC power source was of constant voltage type. To change heat and cooling rate of the SAW process, five variables with variation at five levels were selected. The process parameters were open circuit voltage, trolley speed, contact tube to work distance, preheating temperature and wire feed rate. Different values of bead width, penetration and reinforcement was recorded for different combination of input parameters.

Artificial Neural Network Tool was employed to generate output values with the help of algorithms for ten number of iterations to find the weld bead characteristics values. Result showed close approximation between experimental and simulation data thereby proving effectiveness of ANN in determining bead characteristics from input parameters data values.

XRD 2 θ method was employed to find magnitude and nature of stresses in weld bead. The presence of tensile and compressive stresses was more prominent in region near weld bead whereas majorly compressive stresses were found in region away from weld.

5.2 CONCLUSIONS

The present study was carried to study effects of input parameters on weld bead characteristics of SAW and validate the results by the help neural network tool of MATLAB. Input parameters which were varied in experiment run were open circuit voltage, trolley speed, contact tube and work piece distance, preheating temperature and wire feed rate.

The following conclusions have been drawn from the study-

- ANN can predict and validate the values of weld bead characteristics accurately with minimal error so as to give values within acceptable region.
- Regression coefficient of value 0.998 is indication of effectiveness of ANN as a powerful analysis tool.
- Stresses in the region of weld bead were of mixed nature, some tensile and some being compressive.

5.3 FUTURE SCOPE

In addition to present work mentioned above, further research work can be carried out in following directions:

- In addition to above studied effect of five input parameters, there are other parameters like electrode diameter, different types of flux, preheating of flux etc. which can be varied so as to see their individual and combined effects.
- Study can be done to evaluate toughness and hardness of joints by adding metal powders.
- Flux having different compositions can be taken and there effects on mechanical properties can be studied along with evaluating stresses present.

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