CHAPTER 1

INTRODUCTION

1.1 ALUMINIUM : AN INTRODUCTION

Aluminium is a silverish white metal that has a strong resistance to corrosion and like gold, is rather malleable. It is a relatively light metal compared to metals such as steel, nickel, brass, and copper with a specific gravity of 2.7g/cm^3. Aluminium is easily machinable and can have a wide variety of surface finishes. It also has good electrical and thermal conductivities and is highly reflective to heat and light. The typical tensile strength varies between 105 and 570 MPa. The wide range of ultimate tensile strength is largely due to different heat treatment and strain hardening conditions.

1.2 TYPES OF ALUMINIUM ALLOYS

1.2.1 Non-Heat-Treatable Aluminum Alloys - The strength of these alloys is initially produced by alloying the aluminum with additions of other elements. These alloys consist of the pure aluminum alloys (1xxx series), manganese alloys (3xxx series), silicon alloys (4xxx series) and magnesium alloys (5xxx series). A further increase in strength of these alloys is obtained through various degrees of cold working or strain hardening. Cold working or strain hardening is accomplished by rolling, drawing through dies, stretching or similar operations where area reduction is obtained. Regulating the amount of total reduction in area of the material controls its final properties. Material which has been subjected to a strain-hardening temper, may also be given a final, elevated temperature treatment called “stabilizing”, to ensure that the final mechanical properties do not change over time.

The letter “H” followed by numbers denotes the specific condition obtained from strain hardening.

The first number following the “H” indicates the basic operations used during or after strain hardening:

H1 – Strain hardened only

H2 – Strain hardened and partially annealed

H3 – Strain hardened and stabilized

The second number following the “H” indicates the degree of strain hardening:

HX2 – Quarter Hard

HX4 – Half Hard

HX6 – Three-Quarter Hard

HX8 – Full Hard

HX9 – Extra Hard

1.2.2 Heat-Treatable Aluminum Alloys - The initial strength of these alloys is also produced by the addition of alloying elements to pure aluminum. These elements include copper (2xxx series), magnesium and silicon, which is able to form the compound magnesium silicide (6xxx series), and zinc (7xxx series). When present in a given alloy, singly or in various combinations, these elements exhibit increasing solid solubility in aluminum as the temperature increases. Because of this reaction, it is possible to produce significant additional strengthening to the heat-treatable alloys by subjecting them to an elevated thermal treatment, quenching, and, when applicable, precipitation heat-treatment known also as artificial aging.

In solution heat-treatment, the material is typically heated to temperatures of 900 to 1050 deg F, depending upon the alloy. This causes the alloying elements within the material to go into solid solution. Rapid quenching, usually in water, which freezes or traps the alloying elements in solution, follows this process.

Precipitation heat-treatment or artificial aging is used after solution heat-treatment. This involves heating the material for a controlled time at a lower temperature (around 250 to 400 deg F). This process, used after solution heat-treatment, both increases strength and stabilizes the material.

1.3 APPLICATIONS

Aluminum 1100 alloy is widely used in fin stock, heat exchanger fins, spun hollowware, dials and name plates, decorative parts, giftware, cooking utensils, rivets and reflectors, and in sheet metal work.Aluminium alloys are widely used in engineering structures and components where light weight or corrosion resistance is required. Alloys composed mostly of aluminum have been very important in aerospace manufacturing since the introduction of metal skinned aircraft. Aluminum-magnesium alloys are both lighter than other aluminum alloys and much less flammable than alloys that contain a very high percentage of magnesium.

Figure 1.1 Applications of aluminium alloy

1.4 FRICTION STIR WELDING

Friction stir welding (FSW) is a new solid-state welding method developed by The Welding Institute (TWI) in 1991. The weld is formed by the excessive deformation of the material at temperatures below its melting point, thus the method is a solid state joining technique. FSW is considered to be the most remarkable and potentially useful welding technique for several materials, such as Al-alloys, Mg-alloys, brasses, Ti-alloys, and steels. The process uses the non consumable specially designed rotating tool which is inserted in to the material by giving the axial force and then translated along the joint line to make the weld.

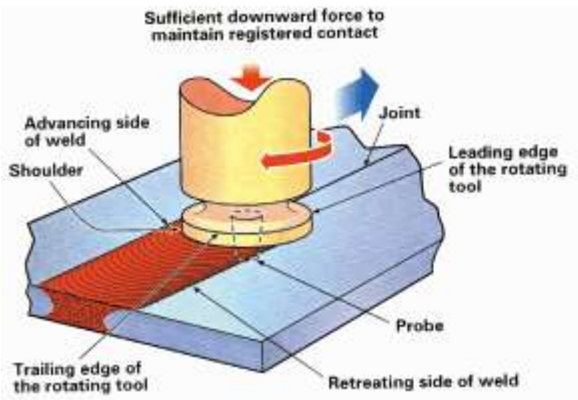


Figure 1.2 friction stir welding

CHAPTER 2

LITERATURE REVIEW AND PROBLEM FORMULATION

2.1 REVIEW OF LITERATURE

Solid state Welding is a fabrication process that joints two metals or non metals by producing frictional heat between them . This is generally achieved by stirring the tool metal against the work metal and feeding longitudinal movement to the tool to initiate the material flow and hence a strong joint. Stirring causes frictional heat which accelerates metal flow.

With the advent of newer materials , stringent performance and quality requirements in the industry , engineers became increasingly aware of weld quality . The major factors which decide the quality of a joint are mechanical properties of the welded joint and distortion of the welded structure . The studies of the effects of various welding process parameters on mechanical properties have attracted many researchers to carry out further investigations. Design of experiment (DOE) combined with Response Surface Methodology (RSM) is a powerful statistical tool to determine and represent the cause and effect relationship between responses and input control variables influencing the responses as a two or three dimensional hyper surface. Recent developments in the evolution of artificial neural networks have been found to be useful in solving many engineering problems. In different fields of engineering , back propagation neural network has proved to be one of the best algorithms for predictive type of work .

2.1.1 INFLUENCE OF INPUT PROCESS VARIABLES ON THE MECHANICAL PROPERTIES

Jawdat et al [1] The friction stir welding process (FSW) is a variant of the linear friction stir welding process in which the material is being welded without bulk melting. The FSW parameters such as tool rotational speed, welding speed, welding tool shoulder diameter, and welded plate thickness play a major role in determining the strength of the joints. A central composite rotatable design with four factors and five levels was chosen to minimize the number of experimental conditions. Empirical relationships were established to predict the yield tensile strength and the hardness of friction stir welded alloys by incorporating independently controllable FSW process parameters. Response surface methodology (RSM) was applied to optimize the FSW parameters to attain maximum yield strength of the welded joints.

A. Gopi Chand et al [2] The main objective of this article is to find the optimum tool material for joining of a butt joint aluminium alloy AA6061.Three major factors at three levels namely tool material, rotational speed and axial force are considered for the present study. The uncontrollable factors include ultimate tensile strength percentage of elongation and hardness which can be converted signal to noise ratios by Taguchi method which is a multiple response process used to optimize the factors Further a three-dimensional model has been developed using Solid Works 2010 and by using ANSYS 13.0 Workbench, static structural analysis is done. The equivalent stress values for different combinations are noted from the response table and we get the optimum rank for the process parameters Hence the prediction of the optimum process parameters using Taguchi technique is investigated

D.Venkateswarlu et al [3] demonstrated The usefulness of tool designs and modeling methodology for predicting friction stir weld characteristics based on tool geometrical parameters The present investigation discusses the effects of threaded friction stir welding (FSW) tool geometries on AA7039 welds It is thought that for harder materials like AA7039, threaded FSW tools are useful A full factorial design matrix was utilized to manufacture 27 FSW tools having different levels of threaded pin diameter, shoulder diameter, and shoulder surface concavity Experiments were conducted to study the effect of these tools on AA7039 welds with respect to weld tensile strength, cross-sectional area, and % elongation A mathematical model was developed to predict the effects of the tool geometries using response surface regression analysis. The interaction effects of the control factors (tool geometrical parameters) on the responses such as weld strength, weld cross section, and % elongation were studied. The modeling methodology developed in this investigation was found to be adequate for predicting the effects of FSW tool geometrical factors on the weld.

Vinod Kumar et al [4] In the present work an effort has been made to study the influence of the welding parameters on mechanical properties in friction stir welding of aluminium. Three process parameters tool rotation speed, welding speed, and shoulder diameter were selected for present research work. Two level factorial design of eight runs was selected for conducting the experiments. The mathematical models were developed from the data obtained. The significance of coefficients and adequacy of developed models were tested by‘t’ test and ‘F’ test respectively. It has been observed that tensile strength decreases with increase in welding and tool rotation speed. Two Level Factorial Design is more convenient to investigate the interaction effects of parameters on the required response. The artificial aging of joints has very little effect on the mechanical properties of joints. The effects of process parameters on best mechanical properties have been represented in the form of graphs for better understanding

H. K. Mohanty et al [5]The weld properties of friction stir welding remains as an area of interest with respect to the effect of tool geometry and process parameters .In the present investigation effort has been made to understand the effect of important welding parameters such as tool rotational speed, traverse speed and probe geometries on various mechanical properties of AA1100 aluminum alloys Ultimate tensile strength, percentage of elongation and hardness were determined experimentally for this purpose. Analysis of variance (ANOVA) was used to observe the main effect of above mentioned parameters on mechanical properties. Regression relationships were developed to predict each output. The experimental and predicted values from the mathematical model were in close agreement**.**

D.H. Lammlein et al [6] A friction stir welding (FSW) tool geometry, consisting of a shoulder less conical probe, is investigated for application to closed contour welding, variable thickness welding and open-loop control welding. By use of a tapered retraction procedure and a ramped rotational velocity, a conical tool may facilitate material disengagement with minimal surface defects in applications which do not permit weld termination defects (e.g. pipes, pressure vessels, fuselages, nosecones). In addition, because the vertical position of the tool relative to the material surface is less critical with a conical tool than with other tool design It can be used in a open-loop fashion (i.e. without process force feedback control) and on materials whose thicknesses are highly variable .The use of a conical probe without a shoulder is not documented in the literature and it is the aim of this work to establish the conditions for mechanically sound welds Effective tool geometries and process variables are found via experimental analysis . It is concluded that this type of tooling is capable of producing acceptable welds when applied to butted aluminum plates and that similar methods would likely be effective in the applications described previously.

A. Pradeep et al **[7]** Experiments are conducted here, with a tool having a conical pin of 0.4mm clearance. The process parameters are optimized by using the Taguchi technique based on Taguchi's L9 orthogonal array. Experiments have been conducted based on three process parameters, namely, the tool rotational speed, tool tilt angle and travel speed. Tensile strength has been predicted for the Optimum welding parameters and their percentage of contribution in producing a better joint is calculated, by applying the effect of the signal-to-noise ratio and analysis of variance. Based on the study, the tool tilt angle is found to be the most significant variable over the other process parameters, and it enhances the quality of the weld on steel rather by the tool axis which is perpendicular to the work plate. The optimum tensile strength predicted through the ANOVA is 472 Mpa. Confirmation tests have been performed for the resulting optimum parameter and the average tensile strength was found to be 474 Mpa. A metallurgical analysis for the optimum parameter was performed on the specimens and typically two distinct Heat affected zones (HAZ) were observed with variation in the micro structure.

K. Elangovan et al **[8]** AA2219 aluminium alloy (Al-Cu-Mn alloy) has gathered wide acceptance in the fabrication of lightweight structures requiring a high strength-to-weight ratio and good corrosion resistance. Friction stir welding (FSW) process is an emerging solid state joining process in which the material that is being welded does not melt and recast. This process uses a non consumable tool to generate frictional heat in the abutting surfaces. The welding parameters such as tool rotational speed, welding speed, axial force, etc., and tool pin profile play a major role in deciding the joint strength. An attempt has been made to develop an empirical relationship between FSW variables to predict tensile strength of the friction stir welded AA2219 aluminum alloy. To obtain the desired strength, it is essential to have a complete control over the relevant process parameters to maximize the tensile strength on which the quality of a weldment is based. Therefore, it is very important to select and control the welding process parameter for obtaining maximum strength. To achieve this various prediction methods such as response surface method (RSM), analysis of variance (ANOVA), Students t-test, coefficient of determination, etc., can be applied to define the desired output variables through developing mathematical models to specify the relationship between the output parameters and input variables. Four factors, two levels central composite design have been used to minimize number of experimental conditions. The developed mathematical relationship can be effectively used to predict the tensile strength of FSW joints of AA2219 aluminium alloy at 95% confidence level.

2.1.2 APPLICATION OF FULL FACTORIAL DESIGN AND REGRESSION ANALYSIS FOR DESIGNING THE EXPERIMENTS AND DEVELOPING THE MATHEMATICAL MODEL

R. Palanivel et al **[9]**This paper presents a systematic approach to develop the mathematical model for predicting the ultimate tensile strength, yield strength, and percentage of elongation of AA6351 aluminium alloy which is widely used in automotive, aircraft and defence Industries by incorporating (FSW) friction stir welding process parameter such as tool rotational speed, welding speed, and axial force. FSW has been carried out based on three factors five level central composite rotatable design with full replications technique. Response surface methodology (RSM) is employed to develop the mathematical model. The developed mathematical model can be used effectively at 95% confidence level. The effect of FSW process parameter on mechanical properties of AA6351 aluminium alloy has been analyzed in detail.

P. Murali Krishna et al **[10]** The present study focused on the Taguchi experimental design technique of Friction Stir Welds of dissimilar alloys (AA2024-T6 and AA6351-T6) for tensile properties. Effect of process parameters, rotational speed, Traverse speed and axial force, on tensile strength was evaluated. Optimized welding conditions for maximize tensile strength were estimated in order to improve the productivity, weld quality. Non-linear regression mathematical model was developed to correlate the process parameters to tensile strength. The results were verified by conducting the confirmation tests at identified optimum conditions.

2.1.3 APPLICATION OF ANN FOR MODELLING OF PROCESS

Dr. K. Brahma Raju et al **[11]** conducted Experiments by varying the input parameters such as axial force, rotational speed and transverse speed, weld feed which play a key role in deciding the weld quality. A full factorial design was used for the experimental design. Three different types of neural network architectures namely Back Propagation Neural Network (BPNN) Radial Basis Function Network (RBFN) and Generalized Regression Neural Network (GRNN) have been used in predicting the tensile strength of the FSW process and a comparison is made between measured and predicted data. The results indicated that the predicted values are in good agreement with the experimental values. Hence the ANN technique is straight forward method used for prediction of tensile strength in FSW process and it can be applied to many engineering applications

D. Kanakaraja et al [12] The present work is a modelling study on different pin geometries of FSW tool using ANN in MATLAB. This work focuses on two methods such as artificial neural networks and Regression analysis to predict the tensile strength of friction stir welded 6061 aluminium alloy. An artificial neural network (ANN) model was developed for the analysis of the friction stir welding parameters of AA6061 plates. The Tensile strength of weld joints was predicted by taking the parameters Tool rotation speed, Weld speed and axial force as a function. A comparison was made between measured and predicted data. A regression model is also developed and the values obtained for the response Tensile strengths are compared with measured values. The graphs were plotted between Regression predicted values and Experimental data to show the accuracy of experimental results. It was found that among these methods ANN model is easier and effective methodology in order to find out the performance output and welding conditions.

Hasan Okuyucu et al [13] An Artificial Neural Network (ANN) model was developed for the analysis and simulation of the correlation between the friction stir welding (FSW) parameters of aluminium (Al) plates and mechanical properties. The input parameters of the model consist of weld speed and tool rotation speed (TRS). The outputs of the ANN model include property parameters namely: tensile strength, yield strength, elongation, hardness of weld metal and hardness of heat effected zone (HAZ). Good performance of the ANN model was achieved. The model can be used to calculate mechanical properties of welded Al plates as functions of weld speed and TRS. The combined influence of weld speed and TRS on the mechanical properties of welded Al plates was simulated. A comparison was made between measured and calculated data. The calculated results were in good agreement with measured data.

Sasidhar Muttineni et al **[14]** The present paper deals with the modelling FSW process using neural networks. A three layered feed forward neural network (NN) has been used to model the FSW of aluminium alloys. It is important to note that the connection weights and bias values of the NN are optimized with the help of a binary coded genetic algorithm (GA). The training of the NN with the help of GA is a time consuming process. Hence, offline training has been provided to optimize the connection weights and bias values of the neural network. Once, the training is over, the GA trained neural network will be used for online prediction of the mechanical properties of FSW process at different operating conditions

Nuran Bradley et al **[15]** The experimentation is an application of treatments to experimental units, and then measurement of one or more responses. It is a part of scientific method. It requires observing and gathering information about how process and system works. In an experiment, some input x's transform into an output that has one or more observable response variables y. Therefore, useful results and conclusions can be drawn by experiment. In order to obtain an objective conclusion an experimenter needs to plan and design the experiment, and analyze the results. There are many types of experiments used in real-world situations and problems. When treatments are from a continuous range of values then the true relationship between y and x's might not be known. The approximation of the response function y = f (x1, x2,…,xq) + e is called Response Surface Methodology. This thesis puts emphasis on designing, modelling, and analyzing the Response Surface Methodology. The three types of Response Surface Methodology, the first-order, the second-order, and three-level fractional factorial, will be explained and analyzed in depth. The thesis will also provide examples of application of each model by numerically and graphically using computer software.

A.Suresh Babu et al **[16]** Friction Stir Welding is a novel green solid state joining process particularly used to join high strength aerospace alloys which are otherwise difficult to weld by conventional fusion welding. Unlike other solid state joining technique, in Friction stir welding a third body contact by tool will generate the additional interface surfaces and finally all the surfaces are coalesced with each other by applied pressure and temperature and form solid state weld. This review paper addresses the overview of Friction stir welding which includes the basic concept of the process, microstructure formation, influencing process parameters, typical defects in FSW process and some recent applications. The paper will also discuss some of the process variants of FSW such as Friction Stir Processing, Friction stir Spot Welding.

J. I. Cole et al **[17]** Application of the latest developments in materials technology may greatly aid in the successful pursuit of next generation reactor and transmutation technologies. One such area where significant progress is needed is joining of advanced fuels and materials. Rotary friction welding, also referred to as friction stir welding (FSW), has shown great promise as a method for joining traditionally difficult to join materials such as Al alloys. This relatively new technology, first developed in 1991 has more recently been applied to higher melting temperature alloys such as steels, nickel-based and titanium alloys. An overview of the FSW technology is provided and two specific nuclear fuels and materials applications where the technique may be used to overcome limitations of conventional joining technologies are highlighted.

A. K. Lakshminarayanan et al **[18]**The FSW process parameters such as tool rotational speed, welding speed, axial force, play a major role in deciding the weld quality. Two methods, response surface methodology and artificial neural network were used to predict the tensile strength of friction stir welded AA7039 aluminium alloy. The experiments were conducted based on three factors, three-level, and central composite face centered design with full replications technique, and mathematical model was developed. Sensitivity analysis was carried out to identify critical parameters. The results obtained through response surface methodology were compared with those through artificial neural networks

Milan Vukčević et al [19] The paper presents the optimization of forces of welding process. The joining of the aluminium alloy sheets 6082-T6, with the thickness of 7.8 mm is performed. The area of research of process parameters is current and under-explored. The paper includes experimental researches performed on the basis of the adopted experimental plan. Values that are varied in the experiment are: welding speed, rotation speed of tools, angle of pin slope, pin diameter and diameter of shoulder. During the experiment the following was carried out: measurement of the forces that occur during the course of the friction stir welding process (downward force, longitudinal forces and side force), as well as other relevant values. The process of optimization was performed using the Box - Wilson gradient method and the model of the FSW process was obtained

2.1.4 INFLUENCE OF PROCESS VARIABLES ON THE METALLURGY OF WELDED SPECIMEN

G. Buffa et al [20] discusses the effects of the thermal and mechanical actions on the residual stress field occurring in friction stir welding (FSW) of AA7075-T6 were investigated. Both numerical and experimental analyses were carried out to highlight the metallurgical phenomena and induced residual stresses in FS welded blanks The welding process was simulated using a continuous rigid-viscoplastic finite element model (FEM) in a single block approach through the software DEFORM-3DLagrangian implicit code designed for metal forming processes. Then, the temperature histories at each node of the FE model were extracted and transferred to a further FE model of the joint considering an elasto-plastic behavior of the AA7075-T6 material The map of the residual stress were extrapolated from the numerical model along several directions. Thus the cut-compliance methodology was used to compare the residual stress profiles with those of the numerical model. The numerical-experimental comparisons have shown the tool.

Yuh J. Chao et al [21] discusses about the heat generated by friction between the tool and the work piece In the friction stir welding (FSW) process, This heat flows into the work piece as well as the tool. The amount of heat conducted into the work piece determines the quality of the weld, residual stress and distortion of the work piece. The amount of the heat that flows to the tool dictates the life of the tool and the capability of the tool for the joining process. heat transfer of the FSW process into two boundary value problems steady state BVP for the tool and a transient BVP for the work piece. physical values of the process the temperatures in the work piece and the tool are measured. Using the measured transient temperature fields finite element numerical analyses were performed to determine the heat flux generated from the friction to the work piece and the tool detailed temperature distributions in the work piece and the tool are presented Discussions relative to the FSW process are then given. In particular, the results show that the majority of the heat generated from the friction, i.e., about 95%,is transferred into the work piece and only 5% flows into the tool and the fraction of the rate of plastic work dissipated as heat is about 80% As much as on tool temperatures, for various welding speeds.

Mohamed Assidi et al [22] The accurate 3D finite element simulation of the Friction Stir Welding (FSW) process requires a proper knowledge of both material and interface but friction, the key phenomenon of this process, is quite difficult to model and identify. According to the extreme encountered conditions and the highly coupled nature of the material flow, simple tribological tests are not representative enough, so the welding process itself has been utilized in most analyses of the literature, although its complexity has led to use simplified numerical models and approaches. The recent development of more accurate 3D simulation software which allows the entire complexity of the FSW process, makes it possible to follow a much more rigorous inverse analysis (or calibration) approach. FSW trials are conducted on an Al 6061 aluminum plate with an unthreaded concave tool. Forces and tool temperatures are accurately recorded at steady welding state, for different welding speeds. The numerical simulations are based on an Arbitrary Lagrangian Eulerian (ALE) formulation that has been implemented in the Forge3s F.E. software. The main feature of the numerical approach is to accurately compute the contact and frictional surface between the plate and the tool. A first study using Norton's friction model show the great sensitivity of welding forces and tool temperatures to friction coefficients, the need to take into account the changes brought to the contact surface by slight friction variations (thanks to the ALE formulation), the possibility to get very accurate calibrations on forces, and the impossibility to properly render the tool temperature profile. On the other hand, the use of Coulomb's friction model allows obtaining realistic temperature profiles and so calibrating a friction coefficient that offers an excellent agreement with experiments, on forces

Ahmed Khalid Hussain et al [23] Friction Stir Welding (FSW) is a solid state welding process in which the relative motion between the tool and the work piece produces heat which makes the material of two edges being joined by plastic atomic diffusion. This method relies on the direct conversion of mechanical energy to thermal energy to form the weld without the application of heat from conventional source. The rotational speed of the tools, the axial pressure and welding speed and the (weld time) are the principal variables that are controlled in order to provide the necessary combination of heat and pressure to form the weld. These parameters are adjusted so that the interface is heated into the plastic temperature range (plastic state) where welding can take place. During the last stage of welding process, atomic diffusion occurs while the interfaces are in contact, allowing metallurgical bond to form between the two materials. The functional behaviour of the weldments is substantially determined by the nature of the weld strength characterized by the tensile strength, metallurgical, surface roughness, weld hardness and micro hardness. In this project an attempt is made to determine and evaluate the influence of the process parameters of FSW on the weldments. The Vickers hardness, tensile strength and radiography are considered for investigation by varying tool speed, tool feed and maintaining constant depth of penetration of weld. Experiments were conducted on AA6351 Aluminium alloy in a CNC Vertical Machining Centre. The output factors are measured in UTM, Vickers hardness tester and Radiography equipment. Results show strong relation and robust comparison between the weldment strength and process parameters. Hence FSW process variable data base is to be developed for wide variety of metals and alloys for selection of optimum process parameters for efficient weld.

K. Panneerselvam et al **[24]** In this study, an attempt has been made to understand the mechanism of FSW and the role of tool pin profile, rotation speed and welding speed in Nylon 6 plates. Experiments were performed at rotational speed of 600-1200 r/min, Welding speeds of 10-40 mm/min, and FSW tool pin profiles of Triangular, square, Threaded and Grooved pin profiles. This has been done by understanding the material flow pattern in the weld regime. Optical microscopy was used to evaluate the micro structural characteristics and Rockwell hardness is observed in weld joints. Weld zone microstructure were investigated using different images of optical microscopy. The micro structure and Rockwell hardness of the welded region was created by Grooved pin profile with welding speed of 10 and 20 mm/min and rotation speed of 800 and 600 r/min identified as correct FSW parameters to avoid defects in Nylon 6 plates.

S.K. Chionopoulos et al [25] Friction stir welding (FSW) is a solid state welding process for joining aluminium and other metallic alloys and has been employed in aerospace, rail, automotive and marine industries. The welding parameters and tool pin profile play a major role in defining weld quality. In this investigation an attempt has been made to understand the influence of rotational and travel speed on friction stir processed (FSP) zone formation in AA5083 aluminium alloy plates. Eight different sets of parameters were used to fabricate the joints. In each case the formation of the FSP zone was revealed by macroscopic observation. The obtained welded samples were examined using optical microscopy in order to define the different joined zones and to identify possible defects. Micro hardness measurements were taken on cross sections of the specimens and were correlated with the FSP zone formation. The optimal parameters corresponded to welding zones without any defects or other discontinuities. In any case, the welding tool had no detritions due to the process.

Strauss et al [26] This paper examines the relationship between tool wear and process parameter in Friction Stir Welding (FSW) of a Metal Matrix Composite (Al 359/SiC/20p). FSW Matrix Composites (MMCs) are super abrasive materials which consist of ceramic particles dispersed throughout a larger metal matrix. Fusion welded MMC joint characterized by porosities in the heat affected zone, disturbances in the particle distribution which translate to a reduction in weld strength, and the formation deleterious theta phase (Al4C3) caused by localized melting. Though these effects can be somewhat mitigated through careful control of heat input, a solid –state joining process more viable alternative. However, FSW of MMCs is severely complicated by rapid tool wear, a consequence of the contact between the tool and abrasive particles which give the material its enhanced strength. The Taguchi method, a statistical analysis technique frequently used in manufacturing engineering , is used to characterize the degree of influence that rotation speed, traversal rate, and length of the weld joint have on wear in FSW of MMCs . The result of this analysis is an empirically derived equation which expresses the dependence of tool wear on the specified process parameters. The software PASW and cross- validation techniques are used to assess the predictive capabilities of the multiple regression models.

T. DebRoy et al [**27]** discusses the unsuitability of Friction stir welding for hard alloys because of premature tool failure. A scheme is created which exploits the physical three-dimensional heat and mass flow models, and implements them into a fast calculation algorithm, which when combined with damage accumulation models, enables the plotting of tool durability maps which define the domains of satisfactory tool life. It is shown that fatigue is an unlikely mechanism for tool failure, particularly for the welding of thin plates. Plate thickness, welding speed, tool rotational speed, shoulder and pin diameters and pin length all affect the stresses and temperatures experienced by the tool. The large number of these variables makes the experimental determination of their effects on stresses and temperatures intractable and the use of a well tested efficient FSW model a realistic undertaking. An artificial neural network, trained and tested with results from a phenomenological model is used to generate tool durability maps that show the ratio of the shear strength of the tool material to the maximum shear stress on the tool pin for various combinations of welding variables. These maps show how the thicker plates and faster welding speeds adversely affect tool durability and how that can be optimized

2.2 IDENTIFIED GAPS IN THE LITERATURE

From the literature review it is observed that independent work has been done in development of mathematical models for welding process , their modelling through neural network and metallurgical studies have been carried out independently. But an integrated approach of studying the effects of various welding process variables on mechanical properties using 2 level full factorial design , use of regression analysis to develop mathematical models for predicting the mechanical properties , modelling of the process through ANN and studying the influence of process parameters on the metallurgy of the welded specimen in Friction stir welding of Aluminium plates is found very less in the literature .The present research work attempts to address this issue.

2.3 MOTIVATION AND OBJECTIVE

The motivation of this project was to study the FSW process in its totality and to explore the potential of controlling the process so as to get desired outputs by simply manipulating the input process variables. To be able to successfully use a process in industry it is imperative that we have a robust way of controlling the outputs as per our needs.

The main objective of this project was to understand the influence of process variables such as tool rotational speed , weld speed, and tool pin diameter and to quantify the relationships through development of mathematical models co-relating the two . Further prediction of the mechanical properties was done through ANN by developing neural network architecture. The effect of welding parameters on metallurgy was also studied.

2.4 STATEMENT OF THE PROBLEM

"Effect of the welding parameters on mechanical properties and metallurgy in FSW process on aluminium alloys 1100 "

The research work describes the development of mathematical models through experimental observations made on Aluminium alloy 1100 using RSM and development of neural network architecture for modelling the FSW process to predict the mechanical properties for a given set of inputs. The metallurgical aspects of the welded metal were also studied and an attempt was made to co-relate the observed the values with the input process variables.

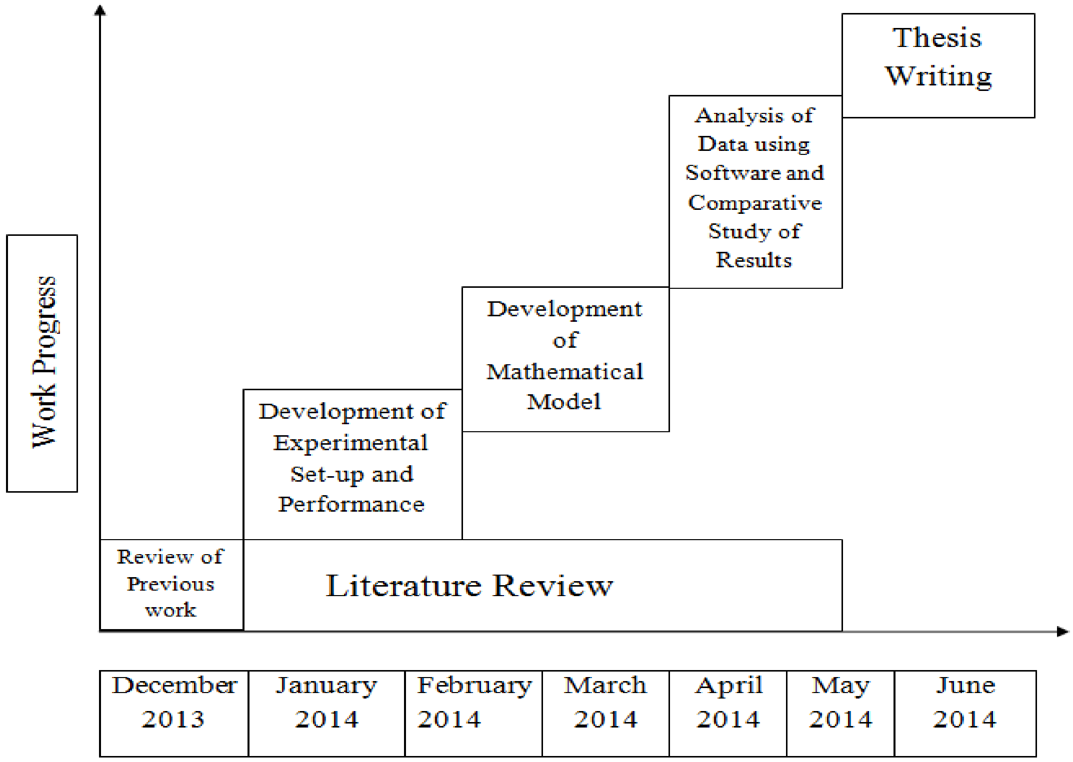
2.5 PLAN OF INVESTIGATION

The research work was planned to be carried out in the following steps:

1. Identification of important process control variables.
2. Deciding the working range of the process control variables, viz. Tool rotational speed, weld speed, tool pin diameter.
3. Developing the design matrix.
4. Conducting the experiments as per the design matrix.
5. Recording the responses viz. Tensile strength, hardness at weld nugget, hardness at thermo mechanically affected zone, Temperature at weld nugget and Temperature at thermo mechanically affected zone.
6. Development of mathematical models
7. Checking the adequacy of the models
8. Finding the significant of co efficient
9. Developing the final proposed model
10. Plotting of graphs and drawing conclusions

11. Development of an ANN architecture to model and to predict the mechanical properties
12. Comparison of performances of mathematical models ,experimental model and ANN models
13. Metallurgical analysis to study the micro structure of the welded material with the process variables
14. Discussion of the results.

2.6 PROJECT PLAN



CHAPTER 3

THEORY AND EXPERIMENTATION

3.1 FRICTION STIR WELDING

3.1.1 INTRODUCTION

Friction Stir Welding is a novel green solid state joining process particularly used to join high strength aerospace modelling alloys which are otherwise difficult to weld by conventional fusion welding. Like other solid state joining technique, in Friction stir welding a third body contact by tool will generate the additional interface surfaces and finally all the surfaces are coalesced with each other by applied pressure and temperature and form solid state weld. Friction stir welding is used for joining low melting point alloys like Aluminium, copper, magnesium etc., The process uses the non consumable specially designed rotating tool which is inserted in to the material by giving the axial force and then translated along the joint line to make the weld.

3.1.2 WORKING PRINCIPLE OF FSW PROCESS

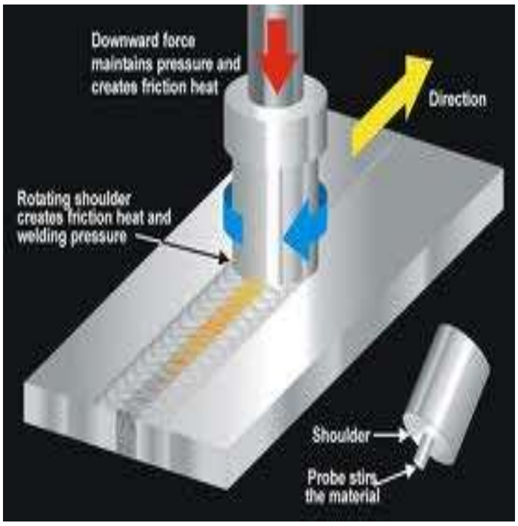


Figure 3.1 schematic view of the FSW process

A constantly rotated non consumable cylindrical-shouldered tool with a profiled probe is transversely fed at a constant rate into a butt joint between two clamped pieces of butted material. The probe is slightly shorter than the weld depth required, with the tool shoulder riding atop the work surface. The basic principle of the process is shown in the Figure 3.1 Frictional heat is generated between the wearresistant welding components and the work pieces. This heat, along with that generated by the mechanical mixing process and the adiabatic heat within the material, cause the stirred materials to soften without melting. As the pin is moved forward, a special profile on its leading face forces plasticized material to the rear where clamping force assists in a forged consolidation of the weld. This process of the tool traversing along the weld line in a plasticized tubular shaft of metal results in severe solid state deformation involving dynamic recrystallization of the base material.

3.1.3 MOTIONS IN FRICTION STIR WELDING

There are two types of motions involved in friction stir welding.

a. Tool Rotary motion: It is the main motion provided by the milling machine to the cutting tool to cause relative motion between the tool and the work piece so that the face of the tool approaches the work piece material.
b. Work piece Transverse motion: This motion is given to work piece by the machine which, when added to tool rotary motion leads to welding of metal.

3.1.4 PROCESS VARIABLES

FSW involves complex material movement and plastic deformation. Welding parameters, tool geometry, and joint design exert significant effect on the material flow pattern and temperature distribution, thereby influencing the micro structural evolution of material. In this section, a few major factors affecting FSW process, such as tool geometry, welding parameters, joint design are addressed. The strength of Friction stir welds depends on the following process parameters. They are

- Spindle speed /Tool Rotational Speed
- Feed rate/weld speed
- Depth of penetration
- Tool tilt
- Tool design
- Welding forces
- Flow of material
- Generation and flow of heat

a. Spindle Speed:

The spindle speed is the rotational frequency of the spindle of the machine, measured in revolutions per minute (RPM). The preferred speed is determined based on the material being cut. Excessive spindle speed will cause premature tool wear, breakages, and can cause tool chatter, all of which can lead to potentially dangerous conditions. Using the correct spindle speed for the material and tools will greatly affect tool life and the quality o the surface finish. The speed at any point on the periphery (outside edge) of a cutter must always be equal to the ideal speed for the material for it to work at its optimum performance. The spindle speeds may be calculated for all machining operations once the welding speed is known. The rotation of tool results in stirring and mixing of material around the rotating pin and the translation of tool moves the stirred material from the front to the back of the pin and finishes welding process. Higher tool rotation rates generate higher temperature because of higher friction heating and result in more intense stirring and mixing of material. However, it should be noted that frictional coupling of tool surface with work piece is going to govern the heating. So, an increase in heating with increasing tool rotation rate is not expected as the coefficient of friction at interface will change with increasing tool rotation rate. The ratio of influence of tool speed and weld speed is 4: 3 which was found by experimental results. In addition to the tool rotation rate and traverse speed, another important process parameter is the angle of spindle or tool tilt with respect to the work piece surface. A suitable tilt of the spindle towards trailing direction ensures that the shoulder of the tool holds the stirred material by threaded pin and move material efficiently from the front to the back of the pin.

The best speed depends on the following conditions:

- Weld strength and quality of the weldment required – Higher quality of weld and strength can be obtained at high speed operations.
- Material to be welded – Hard material requires high speed operation.
- Size of weld. Large welds require low speed operation.
- Thickness of the work piece to be welded.

b. Feed Rate

Feed rate is the velocity at which the cutter is fed, that is, advanced against the work piece. It is expressed in units of distance per revolution for turning and boring (typically inches per revolution (ipr). but it is often expressed in units of distance per time for milling (typically inches per minute (ipm) .

c. Depth of penetration

The insertion depth of pin into the work pieces (also called target depth) is important for producing sound welds with smooth tool shoulders. The insertion depth of pin is associated with the pin height. When the insertion depth is too shallow, the shoulder of tool does not contact the original work piece surface. Thus, rotating shoulder cannot move the stirred material efficiently from the front to the back of the pin, resulting in generation of welds with inner channel or surface groove. When the insertion depth is too deep, the shoulder of tool plunges into the work piece creating excessive flash. In this case, a significantly concave weld is produced, leading to local thinning of the welded plates. It should be noted that the recent development of ‘scrolled’ tool shoulder allows FSW with 08 tool tilt. Such tools are particularly preferred for curved joints. Preheating or cooling can also be important for some specific FSW processes. For materials with high melting point such as steel and titanium or high conductivity such as copper, the heat produced by friction and stirring may be not sufficient to soften and plasticize the material around the rotating tool. Thus, it is difficult to produce continuous defect-free weld. On the other hand, materials with lower melting point such as aluminium and magnesium, cooling can be used to reduce extensive growth of recrystallized grains and dissolution of strengthening precipitates in and around the stirred zone.

d. Tool tilt and plunge depth

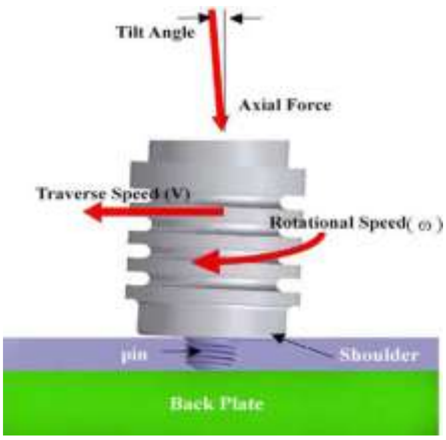


Figure 3.2 plunge depth and tilt of the tool.

Tilting the tool by 2–4 degrees, such that the rear of the tool is lower than the front, has been found to assist this forging process. The plunge depth needs to be correctly set, both to ensure the necessary downward pressure is achieved and to ensure that the tool fully penetrates the weld. Given the high loads required, the welding machine may deflect and so reduce the plunge depth compared to the nominal setting, which may result in flaws in the weld.

On the other hand, an excessive plunge depth may result in the pin rubbing on the backing plate surface or a significant under match of the weld thickness compared to the base material. Variable load welders have been developed to automatically compensate for changes in the tool displacement while TWI has demonstrated a roller system that maintains the tool position above the weld plate.

e. Welding forces

During welding a number of forces will act on the tool:

- A downwards force is necessary to maintain the position of the tool at or below the material surface. Some friction-stir welding machines operate under load control but in many cases the vertical position of the tool is preset and so the load will vary during welding.
- The traverse force acts parallel to the tool motion and is positive in the traverse direction. Since this force arises as a result of the resistance of the material to the motion of the tool it might be expected that this force will decrease as the temperature of the material around the tool is increased.
- The lateral force may act perpendicular to the tool traverse direction and is defined here as positive towards the advancing side of the weld.
- Torque is required to rotate the tool, the amount of which will depend on the down force and friction coefficient (sliding friction) and/or the flow strength of the material in the surrounding region (sticking friction).

In order to prevent tool fracture and to minimize excessive wear and tear on the tool and associated machinery, the welding cycle is modified so that the forces acting on the tool are as low as possible and abrupt changes are avoided. In order to find the best combination of welding parameters, it is likely that a compromise must be reached, since the conditions that favors low forces (e.g. high heat input, low travel speeds) may be undesirable from the point of view of productivity and weld properties.

3.1.5 FSW TOOL

FSW tool is considered as a heart of the welding process which has two primary parts namely shoulder and pin, which heats the work piece material by friction. Shoulder part of the tool frictionally heats the portion of the work piece and induces the axial downward force for welding consolidation. Three types of shoulder end surfaces are normally used, flat, convex, concave shoulder end. Shoulder end surfaces can also have features like scrolls, ridges, knurling, grooves and concentric circles in order to increase the weld quality and material mixing .Probe is the part of the tool which is inserted in to the work piece by axial force which shears the material in front of the tool and moves the same behind the tool .Probe end shape may be made as a flat (or) domed surface. Flat surface increases forge force during plunging, whereas domed one reduces the forge force. Probe outer shape may be made as cylindrical and tapered with or without threads, flutes. The design of the tool is a critical factor as a good tool can improve both the quality of the weld and the maximum possible welding speed.

It is desirable that the tool material is sufficiently strong, tough, and hard wearing at the welding temperature. Further it should have a good oxidation resistance and a low thermal conductivity to heat loss and thermal damage to the machinery further up the drive train. Hot-worked tool steel such as AISI H13 has proven perfectly acceptable for welding aluminium alloys within thickness ranges of 0.5 – 50 mm but more advanced tool materials are necessary for more demanding applications such as highly abrasive metal matrix composites or higher melting point materials such as steel or titanium. Improvements in tool design have been shown to cause substantial improvements in productivity and quality.

TWI has developed tools specifically designed to increase the penetration depth and thus increasing the plate thicknesses that can be successfully welded. An example is the “whorl” design that uses a tapered pin with re-entrant features or a variable pitch thread to improve the downwards flow of material. Additional designs include the Triflute and Trivex series. The Triflute design has a complex system of three tapering, threaded re-entrant flutes that appear to increase material movement around the tool. The Trivex tools use a simpler, non-cylindrical, pin and have been found to reduce the forces acting on the tool during welding.

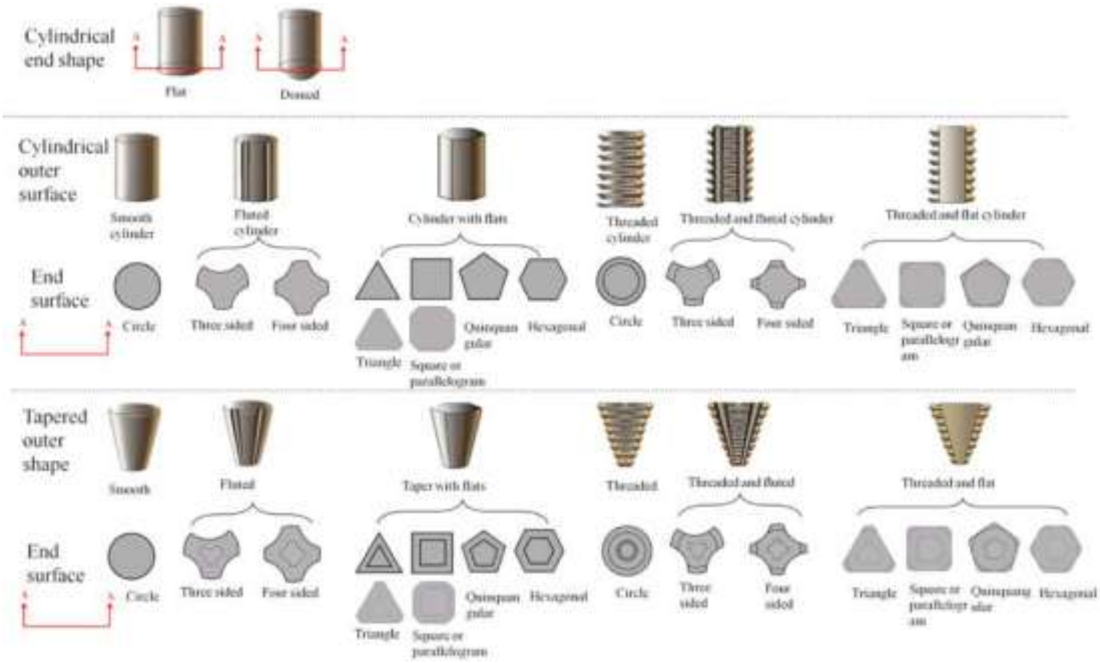


Figure 3.3 Different Shapes of Probes

The majority of tools have a concave shoulder profile which acts as an escape volume for the material displaced by the pin, prevents material from extruding out of the sides of the shoulder and maintains downwards pressure and hence good forging of the material behind the tool. The Triflute tool uses an alternative system with a series of concentric grooves machined into the surface which are intended to produce additional movement of material in the upper layers of the weld.

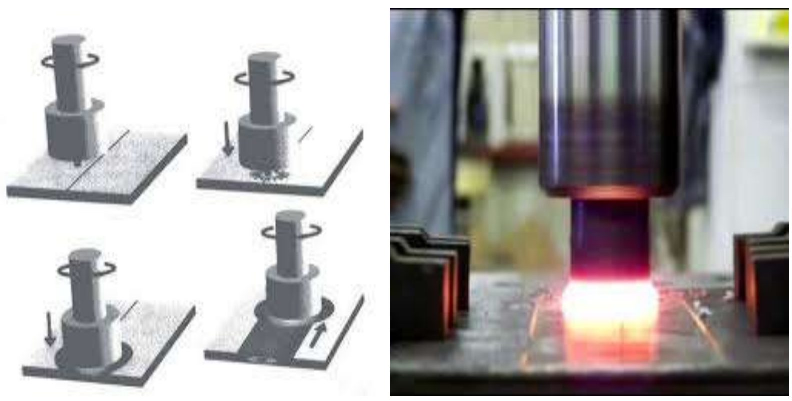


Figure 3.4 cutting tool

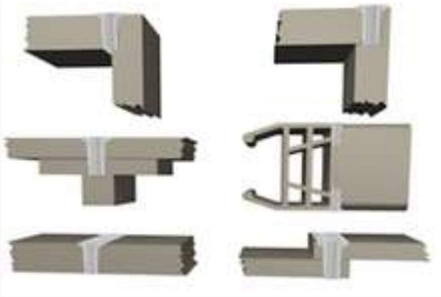


Figure 3.5 Joint designs

Widespread commercial applications of friction stir welding process for steels and other hard alloys such as titanium alloys will require the development of cost-effective and durable tools. Material selection, design and cost are important considerations in the search for commercially useful tools for the welding of hard materials. Work is continuing to better understand the effects of tool material's composition, structure, properties and geometry on their performance, durability and cost

3.1.6 FSW Fixtures

Figure 3.6 FSW Fixtures

Fixtures are used to hold the aluminium plates rigidly on the working table of vertical milling machines. A stainless steel fixture is suitable for FSW of aluminium plates.

3.1.7 ADVANTAGES OF FSW PROCESS

The solid-state nature of FSW leads to several advantages over fusion welding methods as problems associated with cooling from the liquid phase are avoided. Issues such as porosity, solute redistribution, solidification cracking and liquation cracking do not arise during FSW. In general, FSW has been found to produce a low concentration of defects and is very tolerant of variations in parameters and materials.

A number of potential advantages of FSW over conventional fusion-welding processes have been identified:

- Good mechanical properties in the as-welded condition
- Improved safety due to the absence of toxic fumes or the spatter of molten material.
- No consumables — A threaded pin made of conventional tool steel, e.g., hardened H13, can weld over 1 km (0.62 mi) of aluminium, and no filler or gas shield is required for aluminium.
- Easily automated on simple milling machines — lower setup costs and less training.
- Can operate in all positions (horizontal, vertical, etc.), as there is no weld pool.
- Generally good weld appearance and minimal thickness under/over-matching, thus reducing the need for expensive machining after welding.
- **"Green "process -** Low energy input and lack of fumes, gases, etc., resulting from the process, makes FSW friendly to our environment.

3.1.8 LIMITATIONS OF FSW PROCESS

Nevertheless, FSW is associated with a number of unique defects. Insufficient weld temperatures, due to low rotational speeds or high traverse speeds, for example, mean that the weld material is unable to accommodate the extensive deformation during welding. This may result in long, tunnel-like defects running along the weld which may occur on the surface or subsurface. Low temperatures may also limit the forging action of the tool and so reduce the continuity of the bond between the materials from each side of the weld. The light contact between the materials has given rise to the name "kissing-bond". This defect is particularly worrying since it is very difficult to detect using nondestructive methods such as X-ray or ultrasonic testing. If the pin is not long enough or the tool rises out of the plate then the interface at the bottom of the weld may not be disrupted and forged by the tool, resulting in a lack-of-penetration defect. This is essentially a notch in the material which can be a potential source of fatigue cracks.

Some disadvantages of the process have been identified:

Exit hole left when tool is withdrawn. Large down forces required with heavy-duty clamping necessary to hold the plates together. Less flexible than manual and arc processes (difficulties with thickness variations and non-linear welds). Often slower traverse rate than some fusion welding techniques, although this may be offset if fewer welding passes are required.

3.1.9 APPLICATIONS OF FSW PROCESS

Shipbuilding and Offshore

FSW used to the manufacture of fish freezer panels ,deck panels and helicopter landing platforms ,two-dimensional friction stir welds in the hydro dynamically flared bow section of the hull of the ocean viewer vessel The Boss were produced at Research Foundation Institute with the first portable FSW machine. The Super Liner Ogasawara at Mitsui Engineering and Shipbuilding is the largest friction stir welded ship so far. The Sea Fighter of Nichols Bros and the Freedom class Littoral Combat Ships contain prefabricated panels by the FSW fabricators. The Houbei class missile boat has friction stir welded rocket launch containers of China Friction Stir Centre. FSW to armor plating for amphibious assault ships

Aerospace

Boeing applies FSW to the Delta II and Delta IV expendable launch vehicles, and the first of these with a friction stir welded Interstage module was launched in 1999. The process is also used for the Space Shuttle external tank, for Ares I and for the Orion Crew Vehicle test article at NASA as well as Falcon 1 and Falcon 9 rockets at SpaceX. The toe nails for ramp of Boeing C-17 Globemaster III cargo aircraft by Advanced Joining Technologies and the cargo barrier beams for the Boeing 747 Large Cargo Freighter were the first commercially produced aircraft parts. FAA approved wings and fuselage panels of the Eclipse 500 aircraft were made at Eclipse Aviation, and this company delivered 259 friction stir welded business jets, before they were forced into Chapter 7 liquidation. Floor panels for Airbus A400M military aircraft are now made by Pfalz Flugzeugwerke and Embraer used FSW for the Legacy 450 and 500 Jets Friction stir welding also is employed for fuselage panels on the Airbus A380. BRÖTJE-Automation GmbH uses friction stir welding – through the DeltaN FS®

system – for gantry production machines developed for the aerospace sector as well as other industrial applications.

Automotive

Aluminium engine cradles and suspension struts for stretched Lincoln Town Car were the first automotive parts that were friction stir at Tower Automotive, who use the process also for the engine tunnel of the Ford GT. A spin-off of this company is called Friction Stir Link, Inc. and successfully exploits the FSW process, e.g. for the flatbed trailer "Revolution" of Fontaine Trailers. In Japan FSW is applied to suspension struts at Showa Denko and for joining of aluminium sheets to galvanized steel brackets for the boot (trunk) lid of the Mazda MX-5. Friction stir spot welding is successfully used for the bonnet (hood) and rear doors of the Mazda RX-8 and the boot lid of the Toyota Prius. Wheels are friction stir welded at Simmons Wheels, UT Alloy Works and Fundo. Rear seats for the Volvo V70 are friction stir welded at Sapa, HVAC pistons at Halla Climate Control and exhaust gas recirculation coolers at Pierburg. Tailor welded blanks are friction stir welded for the Audi R8 at Riftec. The B-column of the Audi R8 Spider is friction stir welded from two extrusions at Hammerer Aluminium Industries in Austria.

Railway Rolling Stock

Since 1997 roof panels were made from aluminium extrusions at Hydro Marine Aluminium with a bespoke 25m long FSW machine, e.g. for DSB class SA-SD trains ofAlstom LHB Curved side and roof panels for the Victoria Line trains of London Underground, side panels for Bombardier's Electrostar trains at Sapa Group and side panels for Alstom's British Rail Class 390 Pendolino trains are made at Sapa Group Japanese commuter and express A-trains, and British Rail Class 395 trains are friction stir welded by Hitachi, while Kawasaki applies friction stir spot welding to roof panels and Sumitomo Light Metal producesShinkansen floor panels. Innovative FSW floor panels are made by Hammerer Aluminium Industries in Austria for the Stadler KISS double decker rail cars, to obtain an internal height of 2 m on both floors and for the new car bodies of the Wuppertal Suspension Railway. Heat sinks for cooling high-power electronics of locomotives are made at Sykatek, EBG, Austerlitz Electronics, EuroComposite, Sapa and Rapid Technic, and are the most common application of FSW due to the excellent heat transfer.

Fabrication

Façade panels and athode sheets are friction stir welded at AMAG and Hammerer Aluminium Industries including friction stir lap welds of copper to aluminium. Bizerbameat slicers, Ökolüfter HVAC units and Siemens X-ray vacuum vessels are friction stir welded at Riftec. Vacuum valves and vessels are made by FSW at Japanese and Swiss companies. FSW is also used for the encapsulation of nuclear waste at SKB in 50-mm-thick copper canisters. Pressure vessels from ø1m semispherical forgings of 38.1mm thick aluminium alloy 2219 at Advanced Joining Technologies and Lawrence Livermore Nat Lab· Friction stir processing is applied to ship propellers at Friction Stir Link, Inc. and to hunting knives by DiamondBlade. Bosch uses it in Worcester for the production of heat exchangers.

Robotics

KUKA Robot Group has adapted its KR500-3MT heavy-duty robot for friction stir welding via the DeltaN FS® tool. The system made its first public appearance at the EuroBLECH show in November 2012.

Personal Computers

Apple applied friction stir welding on the 2012 iMac to effectively join the bottom to the back of the device.

3.2 ARTIFICIAL NEURAL NETWORK

3.2.1 INTRODUCTION

Artificial neural networks (ANN) form a part of man's constant endeavour to design and implement human like machines which can think, compute and make decisions just like the human brain. In order to achieve this ability to learn from experience, generalize from previous examples to new ones and produce correct results, ANN are biological inspired in their representation of a large number of neurons connected in a way so as to either pass information further or produce desired output with automatic adjustment of stimulus.

Human brain is a densely interconnected network of approximately 10^{11} neurons, each connected to, on average, 10^4 others. Neuron activity is *excited* or inhibited through connections to other Neurons.

Figure 3.7 neuron structure

3.2.2 Processing Element of ANN

Inputs: The number of inputs given to the summation function. Each input corresponds to a single attribute of the system that we are designing.

Weights

The weight is associated with each input. Weight expresses the relative strength of the input. Negative weight values reflect inhibitory connections, while positive values designate excitatory connections. The bias is much like a weight, except that it has a constant input of 1.

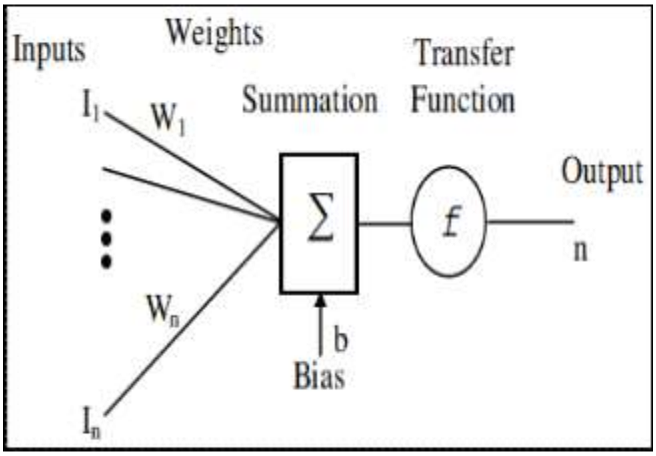


Figure 3.8 processing elements of ANN

Summation function

The summation function is used to find the weighted average of all the input elements to each neuron.

Activation /Transfer function

The activation or the transfer function is used to produce the desired output as per the value of the weights and the inputs. It can be viewed as a squashing function which brings the output of the network within certain limits.

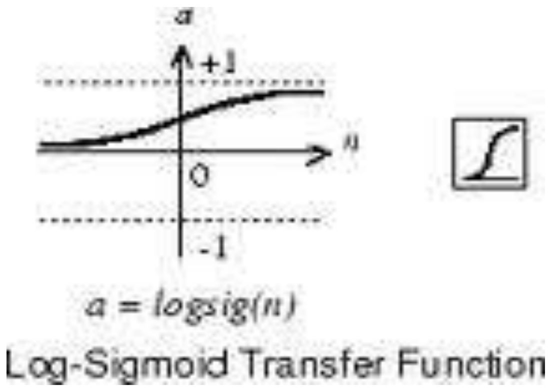


Figure 3.9 Transfer function

A log-sigmoid function, also known as a logistic function, is given by the relationship:

$$\sigma(t) = \frac{1}{1 + e^{-\beta t}}$$

Where β is a slope parameter. This is called the log-sigmoid because a sigmoid can also be constructed using the hyperbolic tangent function instead of this relation, in which case it would be called a tan-sigmoid. Here, it is refer to the log-sigmoid as simply “sigmoid”. The sigmoid has the property of being similar to the step function, but with the addition of a region of uncertainty. Sigmoid functions in this respect are very similar to the input-output relationships of biological neurons, although not exactly the same.

Output

Each processing element is allowed one output signal, which it may give to hundreds of other neurons. Normally, the output is directly equivalent to the transfer function's result. Some network topologies modify the transfer result to incorporate competition among neighbouring processing elements.

3.2.3 Learning of ANN

Learning of ANN can be categorised into two types; supervised and unsupervised learning. In the former, a pattern and target pair is made available to the network. The input is applied to the network and the output so generated is compared to the targets. The learning rule is then used to adjust the weights and biases so that the output moves as close to the target as possible. The perceptron learning rule falls in this supervised learning category. In the latter, the weights and biases are modified in response to network inputs only. There are no target outputs available.

Training can be generalised to consist of the following stages:

(1) Start with random weight allocation.

(2) Compute the difference between the target values received from these weights and the desired target value.

(3) Average the error information over the entire set of training cases.

(4) propagate the error backward through the network (Generally in the case of back propagation).

(5) Make adjustments to the weights to reduce the error.

Each cycle is called an epoch.

The training algorithm can be run in an incremental manner where the weights and biases are updated each time the input is presented to the network or as batch where the adjustment takes place after all the inputs have been presented.

3.2.4Artificial Neural Network architecture

a. Back propagation NN

The back propagation algorithm (Rumelhart and McClelland, 1986) is used in layered feed-forward ANNs. This means that the artificial neurons are organized in layers, and send their signals “forward”, and then the errors are propagated backwards. The network receives inputs by neurons in the input layer, and the output of the network is given by the neurons on an output layer. There may be one or more intermediate hidden layers. The back propagation algorithm uses supervised learning, which means that we provide the algorithm with examples of the inputs and outputs we want the network to compute, and then the error .The idea of the back propagation algorithm is to reduce this error, until the ANN learns the training data. The training begins with random weights, and the goal is to adjust them so that the error will be minimal difference between actual and expected results is calculated.

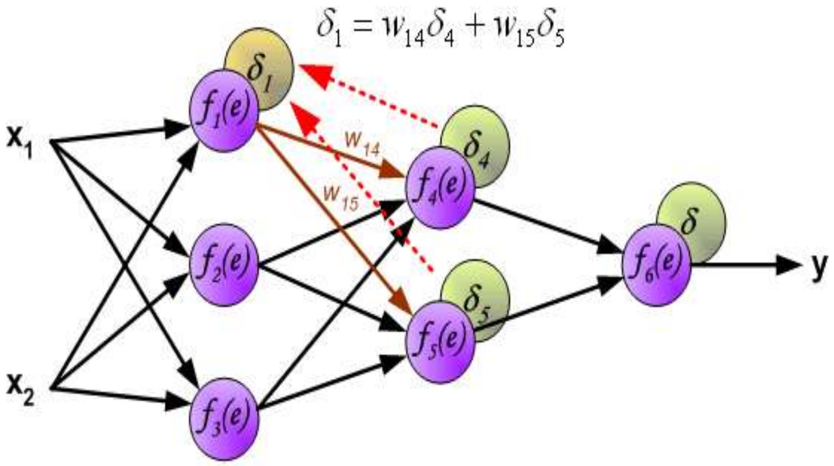


Figure 3.10 Back propagation NN architecture

b. Multi layer feed-forward NN

FFNN is a more general network architecture, where there are hidden layers between input and output layers. Hidden nodes do not directly receive inputs nor send outputs to the external environment.FFNNs overcome the limitation of single-layer NN.They can handle non-linearly separable learning tasks.

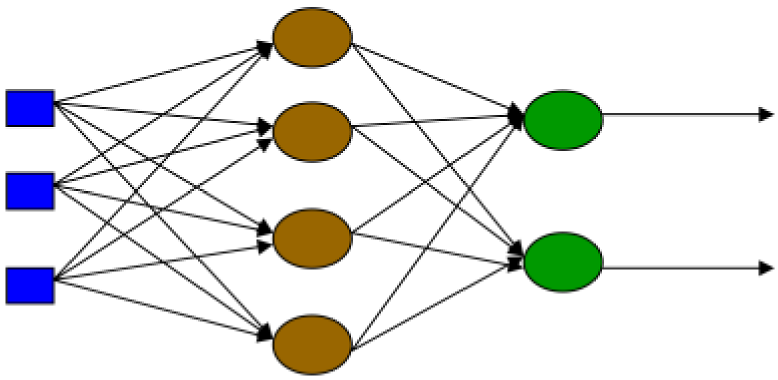


Figure 3.11 Multi layer feed-forward NN (FFNN)

c. RBF Neural Network

They are two-layer feed-forward networks. The hidden nodes implement a set of radial basis functions (e.g. Gaussian functions). The output nodes implement linear summation functions as in an MLP. The network training is divided into two stages: first the weights from the input to hidden layer are determined, and then the weights from the hidden to output layer. The training/learning is very fast. The networks are very good at interpolation.

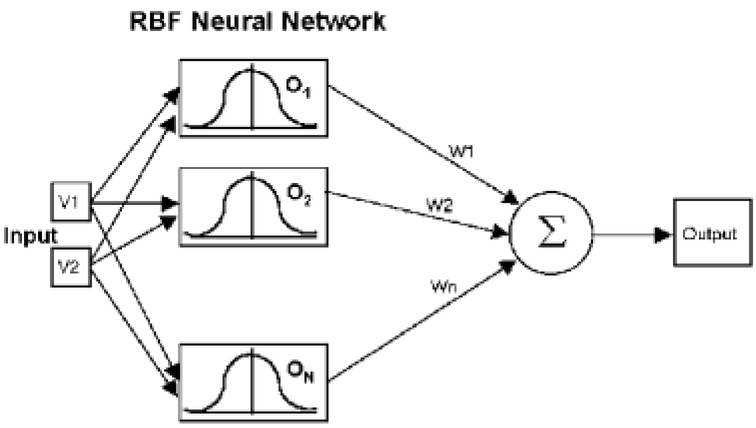


Figure 3.12 RBF Neural Network architecture

3.3 RESPONSE SURFACE METHODOLOGY

3.3.1 Introduction

Response surface methodology (RSM) is a collection of mathematical and statistical techniques for empirical model building. By careful design of experiments, the objective is to optimize a response (output variable) which is influenced by several independent variables (input variables). The response can be represented graphically, either in the three-dimensional

space or as contour plots that help visualize the shape of the response surface.
using MATLAB Surface Fitting Tool the following contour plot ,surface plot and residuals plot were drawn for tensile strength .

a. **Response : Tensile strength**

The tensile strength is maximum (105 MPA) at tool rotational speed of 1130 RPM and weld speed of 65 mm/min. When the tool speed and weld speed is reduced, the tensile strength is also reduced to 74 MPA. This is because when tool speed is increased more frictional heat is produced which causes very fine grain structure and good quality weld. Tool rotational speed has 7.5 % effect and weld speed 5% effect on tensile strength. Interaction of tool rotational speed and weld speed has 19% effect on tensile strength.

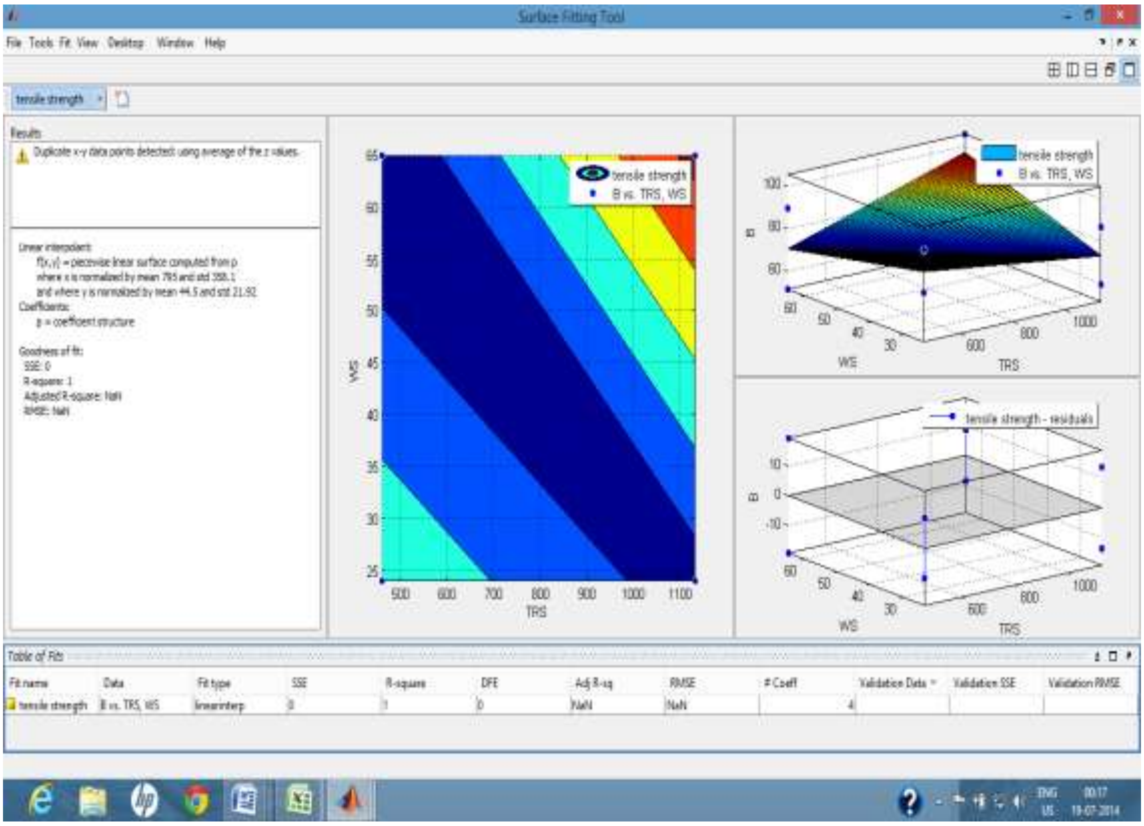


Figure 3.13 Interaction effects of TRS & WS on Tensile strength

b. Response : Hardness At Weld Nugget

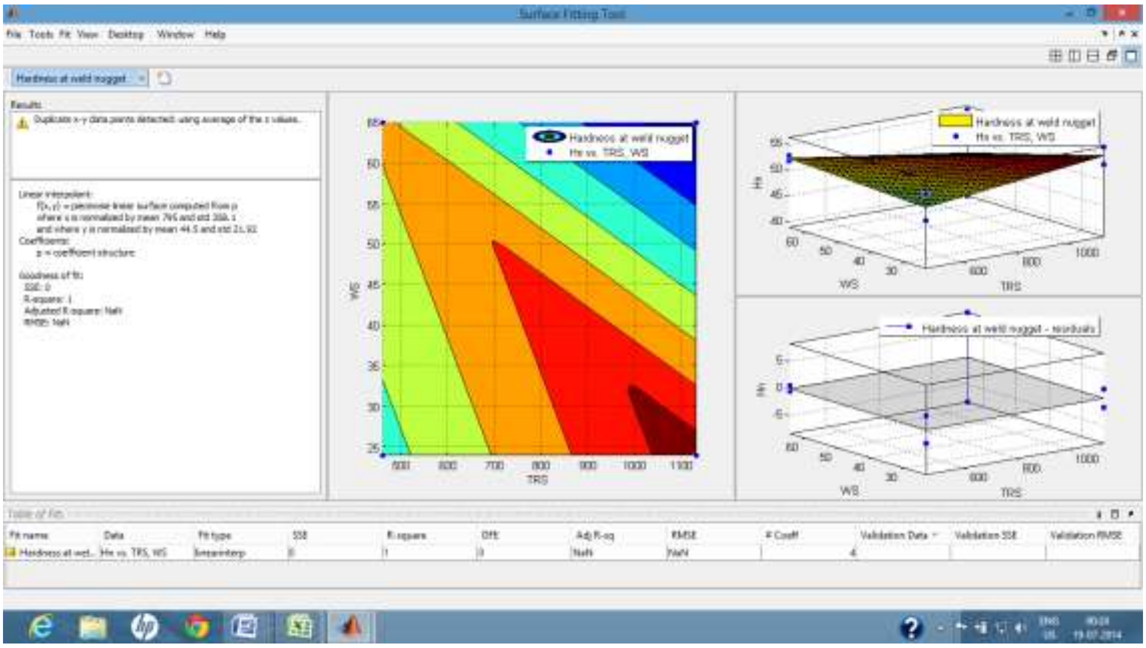


Figure 3.14 interaction effects of TRS & WS on hardness at weld nugget

The hardness at weld nugget is reduced from 56.5HV to 38.6HV due to welding .The effect of tool rotational speed (- 0.575%) and weld speed (-2.925%) has negative effect on hardness value. The interaction effect (-4.475%)of these parameters also produces negative effect on hardness value of aluminum alloy AA1100.

c. Response : Hardness At HAZ

The hardness at heat treated zone is higher (52.6 HV) when tool speed is 460 RPM and weld transverse speed is 24 mm/min. The hardness value is decreasing with increase in tool speed and weld speed. The effect of tool rotational speed and weld speed has negative effect on hardness value. The interaction effect of these parameters also produces negative effect on hardness value of aluminum alloy AA1100.

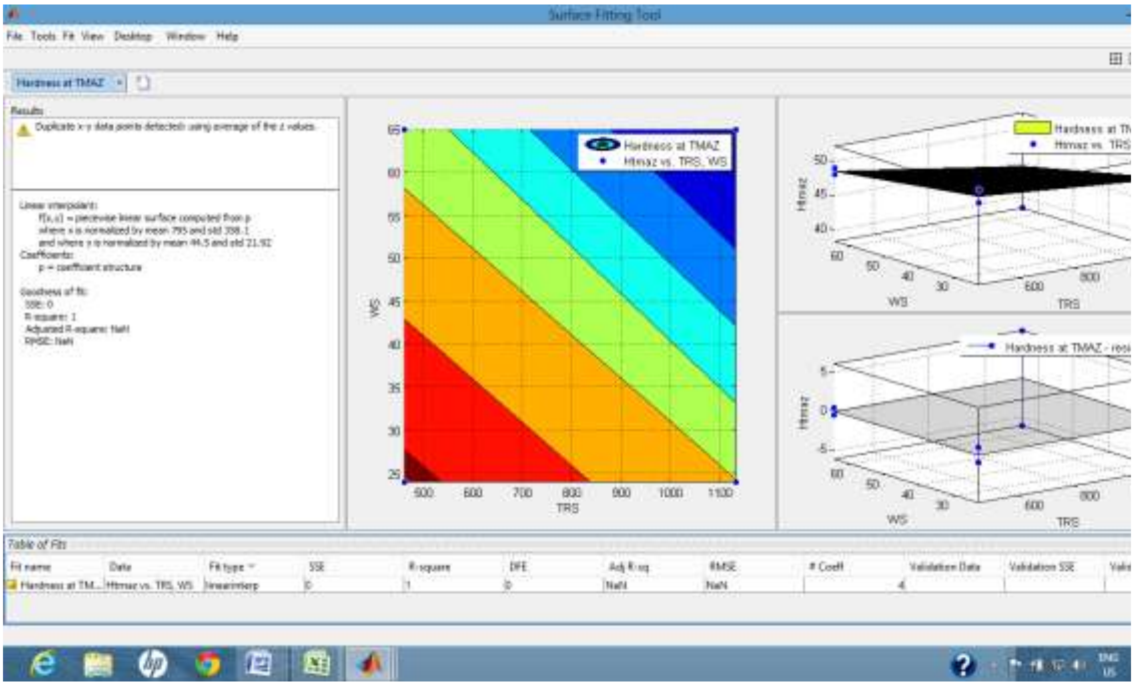


Figure 3.15 Interaction effect of TRS & WS on hardness at HAZ

d. Response : Temperature at weld nugget

The temperature at weld nugget is maximum (108^0C) at tool rotational speed of 1130 RPM and weld speed of 65 mm/min. When the tool speed and weld speed is reduced, the temperature is also reduced to 55^0C. This is because when tool speed is increased more friction is produced and hence very fine grain structure and good quality weld.

Tool rotational speed has 11.5 % effect and weld speed 24% effect on tensile strength. Interaction of tool rotational speed and weld speed has 1.5% effect on tensile strength.

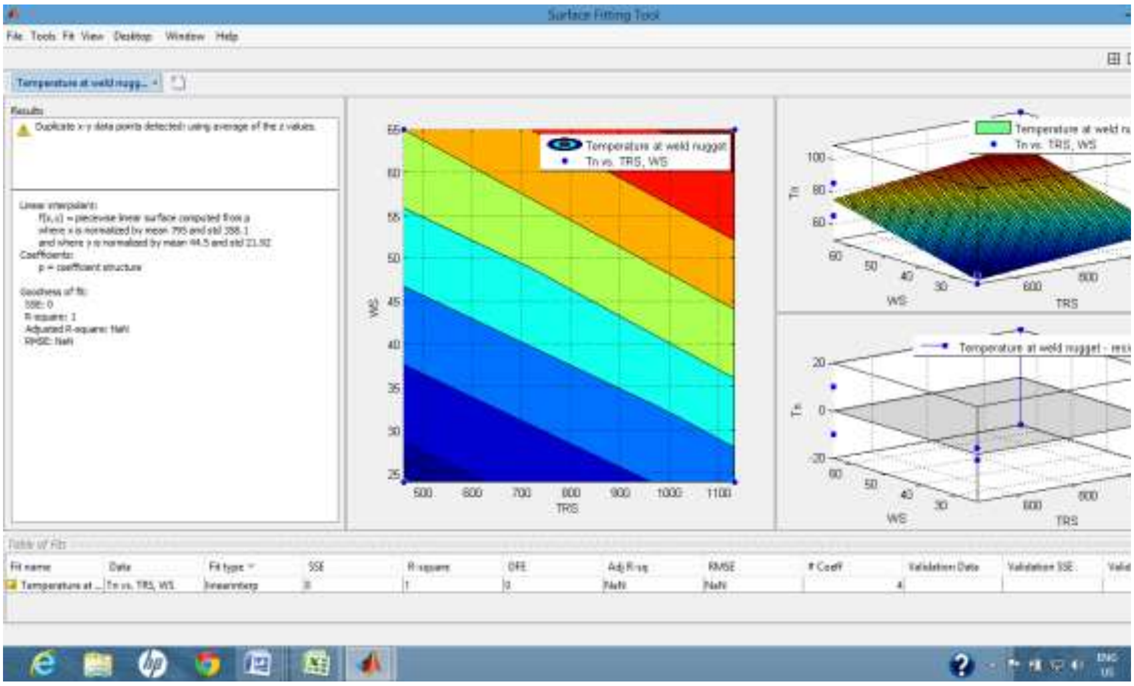


Figure3.16 Interaction effect of TRS & WS on temperature at weld nugget

e. Response : Temperature at HAZ

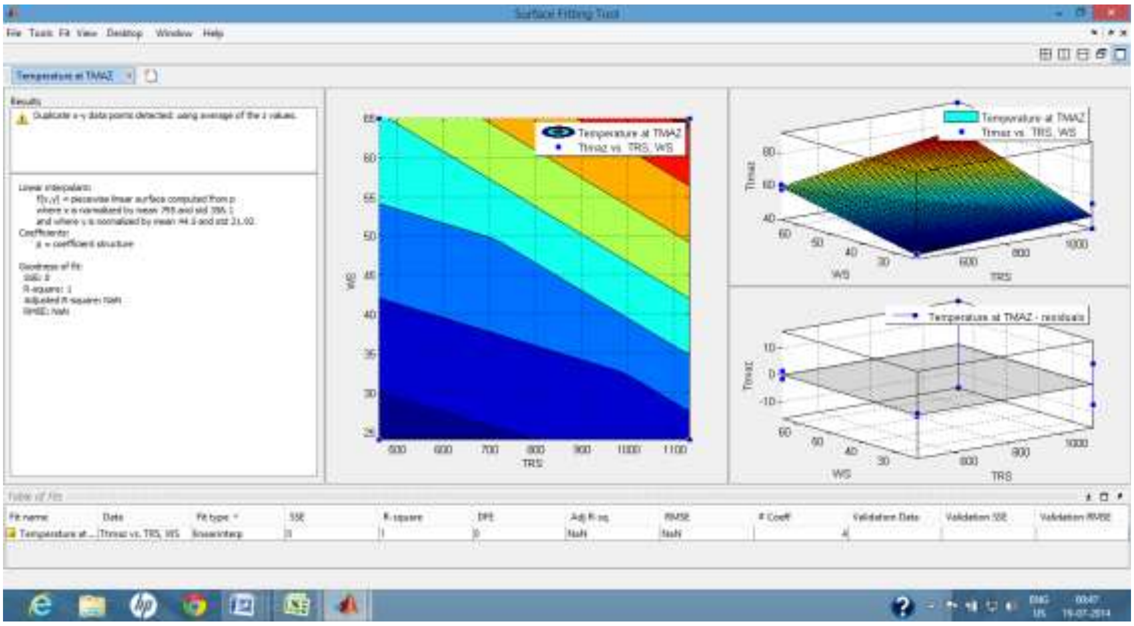


Figure3.17 Interaction effect of TRS & WS on temperature at HAZ

When tool speed and weld speed increases, the temperature at heat affected zone is increased. When tool speed is 1130 RPM and weld speed is 65mm/min the temperature is 92 ^{0} C. When these parameters decreased, the temperature also decreased to a minimum value of 42 ^{0} C. Interaction values also prove that input parameters are directly proportional to temperature at heat affected zone.

3.3.2 Full Factorial Design

To construct an approximation model that can capture interactions between N design variables, a full factorial approach (Montgomery, 1997) may be necessary to investigate all possible combinations. A factorial experiment is an experimental strategy in which design variables are varied together, instead of one at a time. The lower and upper bounds of each of N design variables in the optimization problem needs to be defined. The allowable range is then discretized at different levels. If each of the variables is defined at only the lower and upper bounds (two levels), the experimental design is called 2^N full factorial.

Design variables = 3 (The tool rotational speed, weld speed and tool pin diameter);

Levels = 2 (low and high)

Tool rotational speed = low level =460 RPM; high level = 1130 RPM;

Weld speed = low level = 24 mm/min; high level = 65 mm/min;

Tool pin diameter = low level = 6 mm; high level = 8 mm;

Full factorial design = 2^3 = 8; welding carried out at 8 different treatment combinations

Running the full complement of all possible factor combinations means that we can estimate all the main and interaction effects. There are three main effects, three two-factor interactions, and a three-factor interaction, all of which appear in the full model as follows:

$$Y=\beta_0+\beta_1N+\beta_2W+\beta_3D+\beta_{12}NW+\beta_{13}ND+\beta_{23}WD+\beta_{123}NWD+\epsilon$$

A full factorial design allows to estimate all eight `beta' coefficients {β0… β123}.

Where N, W, D is process variables. Y – Response; ϵ - error .

3.4 Design of Experiment

The main aim of this project was to find the effect of input process variables on the mechanical properties of FSW of Aluminum Alloy 1100 and to develop mathematical models to describe the relationship between the input and output variables. After that

ANN modelling of the FSW process was done and it was compared with the RSM modeling and regression modeling. Metallurgical analysis was also done to co-relate the effects of input parameters on the hardness and the tensile strength of the welded specimen. To achieve the above mentioned objectives, following are the sequence of steps which were carried out:

1. Identification of important process control variables.
2. Deciding the working range of the process control variables, viz. Tool rotational speed, weld speed, tool pin diameter,
3. Developing the design matrix.
4. Conducting the experiments as per the design matrix.
5. Recording the responses viz. Tensile strength, hardness at weld nugget, thermal flow
6. Development of mathematical models
7. Checking the adequacy of the models
8. Finding the significant of co efficient
9. Developing the final proposed model
10. Plotting of graphs and drawing conclusions
11. Development of an ANN architecture to model and to predict the mechanical properties
12. Comparison of performances of models and ANN models
13. Metallurgical analysis to co-relate the hardness and the tensile strength of the welded material with the process variables
14. Discussion of the results.

3.4.1 Identification of important process control variables

Based on literature review the important process parameters of friction stir welding are identified as tool rotational speed. Weld speed, axial force, tool shoulder diameter, tool pin diameter, tool pin shape etc.

3.4.2 Deciding the working range of the process control variables

Trial runs are conducted to find the upper and lower limits of the process parameters by varying one of the parameter and keeping the rest of parameters at constant values. Feasible limits of the parameters are chosen in such a way that the joint should be free from visible defects. Upper limit of parameter is coded as HIGH and lower limit as LOW. The selected process parameters and their upper and lower limits together with notations and units are given in Table 3.5.1.

Table 3.5.1 process control parameters and their limits

Sl.No	parameters	Units	Notation	-1	0	+1
1	Tool Rotational speed	RPM	N	460	690	1130
2	Weld speed	Mm/min	W	24	40	65
3	Tool pin diameter	mm	D	6	7	8

3.4.3 Developing the design matrix

When three factors N, W and D, each at two levels, are of interest, the design is called a 2^3 factorial design and the eight treatment combinations can be as follows.

Table 3.5.2 Design matrix

Weld no.	Trial no.	Input parameters			labels
		N	W	D	
1	4	-1	-1	-1	(1)
2	7	+1	-1	-1	a
3	1	-1	+1	-1	b
4	6	+1	+1	-1	ab
5	2	-1	-1	+1	c
6	8	+1	-1	+1	ac
7	5	-1	+1	+1	bc
8	3	+1	+1	+1	abc

There are seven degrees of freedom between the eight treatment combinations in the 2^3 design. Three degrees of freedom are associated with the main effects of N, W, and D.

Four degrees of freedom are associated with interactions; one each with NW, ND, and WD and one with NWD.

3.4.4 Conducting the experiments as per the design matrix

The experiments were conducted at the central workshop of Delhi Technological University. A conventional vertical milling machine was used for FSW of aluminium alloy 1100. The feed speed and tool rotation (rpm) value of the milling machine play major roles in ensuring sound FSW joints. During the investigation, basic limitations of the milling machine also became apparent, for example rpm and feed speed setting were as per the machining operations. Furthermore, the load value is also unknown. The experience gained with the milling machine for FSW of aluminium is that it is the tool that is capable of demonstrating the FSW process for aluminium at a low feed speed.

Figure 3.18 vertical milling machine

3.4.5 The Base Metal Used

For carrying out the research work, test specimens were prepared from 5 mm thickness Aluminium Alloy 1100 plate. Dimension of each plate was 100x50x5 mm. Composition of the base material is identified by spectro analysis using Hilger Polyvac 2000 Optical Emission Spectrometer. Optical emission spectrometry involves applying electrical energy in the form of spark generated between an electrode and a metal sample, whereby the vaporized atoms are brought to a high energy state within a so-called “discharge plasma”. These excited atoms and ions in the discharge plasma create a unique emission spectrum specific to each element.

a. Spectro Analysis of AA1100

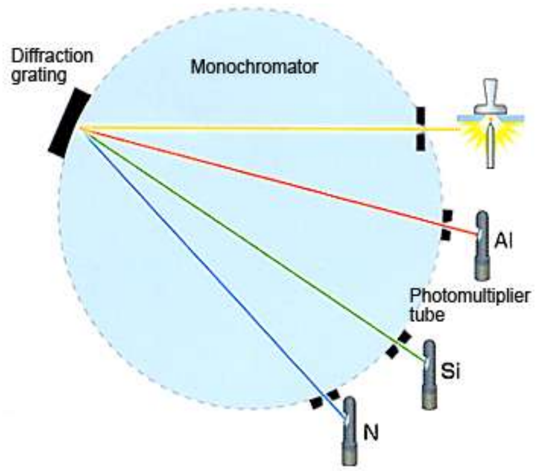


Figure 3.19 Principle of Optical Emission Spectrometry

In the Optical Emission Spectroscopy technique, atoms in a sample are excited by energy that comes from a spark formed between sample and electrode. The energy of the spark causes the electrons in the sample to emit light which is converted into a spectral pattern. By measuring the intensity of the peaks in this spectrum, OES analysers can produce qualitative and quantitative metal analysis of the material composition with uncompromising accuracy.

b. Microscopic Examination of AA1100

The primary objective of metallographic examinations is to reveal the constituents and structure of metals and their alloys by means of a light optical or scanning electron microscope. In special cases, the objective of the examination may require the development of less detail than in other cases but, under nearly all conditions, the proper selection and preparation of the specimen is of major importance. Radical 40 xs-800x Metallurgical Microscope with 5mp Camera is used for examination. The metal is tested as per ASTM E-3 standard. 25% nitric acid solution is used for etching the metal. The magnification factor of 250 X is used. The microstructure consists of Mg_2Al_2 deposited along the grain boundaries.

After these two tests the chemical composition of AA1100 is tabulated as follows.

Table 3.5.3 chemical composition of AA 1100

Al	Cu	Mg	Si	Fe	Mn	Ni	Zn	Pb	Sn	Ti	Cr
99.16 %	0.123%	0.036	0.185	0.322	0.023	0.025	0.052	0.023	0.020	0.010	0.005

AA 1100 is categorized as strain – hardened Wrought Aluminium Alloy Conforms to IS: 737 Gr.19002.

3.4.6 Tool Material Used

EN 8: It is a very popular grade of through-hardening medium carbon steel, which is readily machinable in any condition. EN8 is suitable for the manufacture of parts such as general-purpose axles and shafts, gears, bolts and studs. It can be further surface-hardened typically to 50-55 HRC by induction processes, producing components with enhanced wear resistance. EN8 in its heat treated forms possesses good homogenous metallurgical structures, giving consistent machining properties. Good heat treatment results on sections larger than 63mm may still be achievable, but it should be noted that a fall-off in mechanical properties would be apparent approaching the centre of the bar. It is therefore recommended that larger sizes of EN8 are supplied in the untreated condition, and that any heat treatment is carried out after initial stock removal. This should achieve better mechanical properties towards the core.

Eight sets of plates were welded as per the design matrix by selecting trials at random and welding was carried out. Figure 3.20 shows few samples in welded condition.

Figure 3.20 welded samples

3.4.7 Recording the Responses

a. Hardness Test

Hardness Testing is a collection of different methods for measuring a definite characteristic of metallic materials, namely:

- The resistance to penetration of a specific Indenter defined by fixed form and properties,
- Under the application of a certain static force for a definite time,
- Using precise measuring procedures.

The result, usually expressed by a number or by a range of numbers, must be qualified by an accepted convention indicating exactly by which one of the possible methods such result was obtained. Hardness so defined is not an intrinsic property of any material, like density or melting point; it is rather a characteristic deriving from the composition, the thermal and mechanical history of the material, and essentially from the structure or more properly the microstructure of the specimen involved.

It is commonly believed that, there is an approximate correspondence between hardness data and a range of tensile strength results. ASTM E 92, Standard Hardness Conversion Tables for Metals, is the best known and authoritative compilation. it is a very useful tool for process control and for materials acceptance, if performed correctly. The hardness readings will NOT represent true through hardness when:

- Plating by a different element (e.g. Chromium) is present a plasma or thermal-sprayed layer was deposited the specimen is decarburised (having lost Carbon) on the surface case hardening was performed (carburising, induction or flame hardening, nitriding etc.)
- welding or flame cutting was done nearby a recast layer, produced by electro discharge machining,
- is present local strain (deformation) hardening like disc cutting took place on the tested surface or nearby surface improvement process like shot peening is present
- The part has widely varying (thick and thin) sections where response to heat treatment may be different

- The surface was abusively treated (e.g. by uncontrolled grinding) producing local overheating
- There is reason to suspect that hardness is not constant through the thickness of part.

Vickers Hardness Test

Vickers Hardness is a very popular test, which is characterized by a square based diamond pyramid indenter, exactly ground to a standard form with 136 degrees between opposite faces and used to leave a mark in metal under a precisely applied force by taking care to avoid impact: the diagonals of the impression have to be measured using a suitable microscope and the results are either calculated using a given formula (see at the end of this section) or looked up in Tables arranged for each of the forces (loads) used. The theory and practice of the test is most authoritatively exposed in: ASTM E 92 – Standard test method for Vickers Hardness of Metallic Materials An International standard, issued by ISO – International Standards Organisation, available on this subject .

The values found are designated by HV for Hardness Vickers, followed by the force (load) in kg, or by DPH which means Diamond Pyramid Hardness and sometimes with the number of seconds when the load was applied. Commonly used loads are 5, 10, 30 and 50 kg, but the range can be enlarged if necessary. In theory the hardness number should be independent of the force used, but in practice, as differences can be found, one must always report the load used. Vickers should not be used for cast iron which has a non uniform structure, because the impression tends to be small, and unable to give a true average. The smaller impression requires a smoother surface, to be read accurately. Vickers hardness is applicable to soft and hard materials, to thick and thin specimens. There is no danger to deform the indenter during normal operation, but sharp blows must be avoided because the diamond tip could break and then give erroneous results. Minimum thickness of at least ten times the depth of the indentation is to be observed, but it is easier to reduce it, simply by selecting a lighter load. As usual no marks should be seen on the opposite surface. Many different types of Vickers hardness testers exist from different manufacturers. As with any precision instrument, the equipment should be regularly maintained following the instructions, and the tip of the pyramid should be examined under a microscope at regular time intervals. For completeness we shall note that for testing very thin specimens or layers, (or even single crystals or phases in a microstructure) a similar method has been standardized which employs very light forces (loads) (from 1 g to 1 kg).

The formula used for calculating the Vickers Hardness Number (or Diamond Pyramid Hardness)

$HV = 1.8544 * P/ d^2$

where P = force (load) in kilograms; d = diagonal length of the impression in mm (milli meters)(or, better, average of two readings, mutually perpendicular).

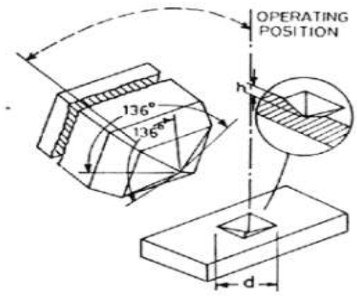


Figure 3.21 Vickers hardness measurement

Preparation of Test Specimens:- The test specimens should be conditioned at 23 ±2°C and 50 ± 5% relative humidity for not less than 24 hours prior to testing.

- The free films are placed between two cover sheets of clear film (MylarT* or equivalent) to facilitate handling of the specimens.
- The utmost care must be exercised in cutting specimens to prevent nicks and tears along the edges of the specimen that are likely to cause premature failure.
- The specimens of 60 x 20 x 5 mm were cut from the welded plate along transverse direction for hardness test and micro structure test as per ASTM E-92 STANDARD

Figure 3.22 samples for hardness test

TENSILE TEST

Tensile testing, also known as **tension testing**, is a fundamental materials science test in which a sample is subjected to a controlled tension until failure. The results from the test are commonly used to select a material for an application, for quality control, and to predict how a material will react under other types of forces. Properties that are directly measured via a tensile test are ultimate tensile strength, maximum elongation and reduction in area. From these measurements the following properties can also be determined: Young's modulus, Poisson's ratio, yield strength, and strain-hardening characteristics.

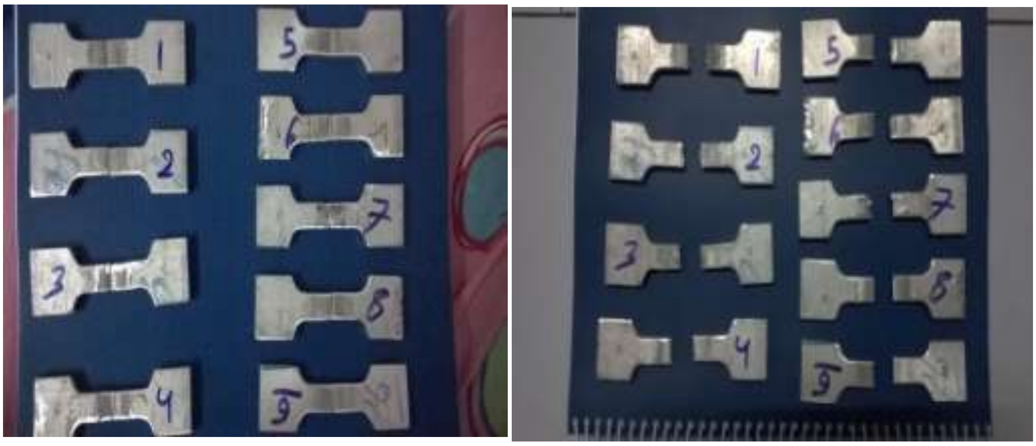


Figure 3.23 specimens for tensile test

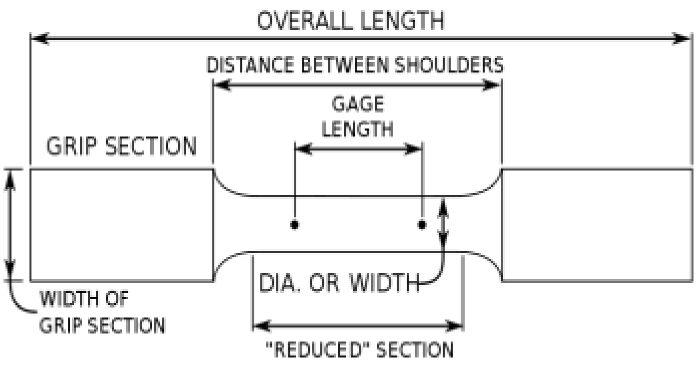


Figure 3.24 Tensile specimen nomenclature

Overall length = 100 mm; reduced section = 32 mm; grip section = 30 mm;

Width of grip section = 5mm; Radius = 6 mm;

<u>Table 3.5.4 Recording of responses</u>

Weld no.	Trial no.	Input parameters			label	Responses				
		N rpm	W mm/min	D mm		Tensile Strength(MPA)	Hardness (HV) At weld	Hardness (HV) At HAZ	Temperature At weld °C	Temperature At HAZ ^{0}C
1	4	-1	-1	-1	1	74	47.9, 48.3	52.6 51.8	55	43
2	7	+1	-1	-1	a	59	52.6 53.1	51.8 52.1	70	55
3	1	-1	+1	-1	b	51	51.6 51.8	47.9 48.3	85	61
4	6	+1	+1	-1	ab	88	55.2 55.7	50.6 50.4	68	60
5	2	-1	-1	+1	c	94	53.6 52.8	50.2 50.4	50	42
6	8	+1	-1	+1	ac	86	56.5 56.0	46.0 46.2	55	40
7	5	-1	+1	+1	bc	89	52.6 52.8	49.2 48.8	65	58
8	3	+1	+1	+1	abc	105	38.6 39.1	38.6 38.2	108	92

CHAPTER 4

DEVELOPMENT OF MATHEMATICAL MODEL

Mathematical models can be proposed as the basis for a control system for the FSW process to predict particular mechanical property and to establish the inter relationship between weld process parameters to weld mechanical property . These mathematical models can be fed into computer to predict the mechanical property for a particular combination of input parameters. The experimental data were used to develop multilinear regression models, and analysis of the models was carried out through ANOVA and surface plots. Minitab 17.0 was used for this purpose.

4.1 Formulation of mathematical model :

The Response function can be expressed as: $Y = f\,(N, W, D)$

Where, Y = response; N = tool rotational speed; W = weld speed; D= tool pin diameter

A linear regression model with three predictor variables can be expressed with the following equation: $Y = b_0+b_1N+b_2W+b_3D+b_{12}NW+b_{13}ND+b_{23}WD+b_{123}NW\,D$

Where b_0 is constant and b_1 ,b_2, b_3, b_{12}, b_{13}, b_{23} , b_{123} are co- efficients of model

b_0, the Y-intercept, can be interpreted as the value to predict for Y if N=W=D = 0

Since N is a continuous variable, b_1 represents the difference in the predicted value of Y for each one-unit difference in N, if other independent variables remains constant. This means that if N is differed by one unit, and W and D did not differ, Y will differ by b_1 units, on average.

4.2 Evaluation of the co-efficient of model

The values of the co efficient of the response function were calculated using regression analysis. The calculations were carried out using MINITAB17 and values listed in Table 4.1

Table 4.1 estimated value of the co-efficient of the model

Sl.no	Co-efficient	Tensile Strength(MPA)	Hardness (HV)		Temperature(^{0}C)	
			At weld	At HAZ	At weld	At HAZ
1	b_0	138.4	27.07	61.04	-102.1	-69.43
2	b_1	-0.1726	- 0.01864	- 0.001471	+ 0.2786	+ 0.2204
3	b_2	-4.155	- 0.2749	- 0.2938	+ 5.882	+ 3.265
4	b_3	-3.298	+ 2.560	- 1.475	+ 19.39	+ 14.74
5	b_{12}	0.004951	+ 0.001594	+ 0.000633	- 0.008810	- 0.005825
6	b_{13}	0.01746	+ 0.004419	+ 0.000336	- 0.03804	- 0.03185
7	b_{23}	0.4539	+ 0.06256	+ 0.05027	- 0.7690	- 0.4347
8	b_{123}	-0.000510	- 0.000271	- 0.000112	+ 0.001274	+ 0.000892

The responses (mechanical properties) were expressed as a linear function of the input process parameters as follows:

Regression Equations

Tensile strength (TS) = $b_0+b_1N+b_2W+b_3D+b_{12}NW+b_{13}ND+b_{23}WD+b_{123}NWD$

Tensile Strength (TS) = 138.4 – 0.1726 N – 4.155 W – 3.298 D + 0.004951 NW + 0.01746 ND + 0.4539 WD - 0.000510 NWD

Hardness at weld nugget = $b_0+b_1N+b_2W+b_3D+b_{12}NW+b_{13}ND+b_{23}WD+b_{123}NWD$

H_N = 27.07 – 0.01864 N – 0.2749 W + 2.560 D + 0.001594 NW + 0.004419 ND + 0.06256 WD - 0.000271 NWD

Hardness at HAZ = $b_0+b_1N+b_2W+b_3D+b_{12}NW+b_{13}ND+b_{23}WD+b_{123}NWD$

H_{HAZ} = 61.04 – 0.001471 N – 0.2938 W – 1.475 D + 0.000633 NW + 0.000336 ND + 0.05027 WD - 0.000112 NWD

Temperature at weld nugget (T_N) = $b_0+b_1N+b_2W+b_3D+b_{12}NW+b_{13}ND+b_{23}WD+b_{123}NWD$

T_N = -102.1 + 0.2786 N + 5.882 W + 19.39 D – 0.008810 NW – 0.03804 ND – 0.7690 WD + 0.001274 NWD

Temperature at HAZ(T_{HAZ}) = $b_0+b_1N+b_2W+b_3D+b_{12}NW+b_{13}ND+b_{23}WD$+b123NWD

T_{HAZ} = -69.43 + 0.2204 N + 3.265 W + 14.74 D – 0.005825 NW – 0.03185 ND – 0.4347 WD + 0.000892 NWD

4.3 Checking adequacy of the model

Analysis of variance (ANOVA) is a procedure for assigning sample variance to different sources and deciding whether the variation arises within or among different population groups. Samples are described in terms of variation around group means and variation of group means around an overall mean. If variations within groups are small relative to variations between groups, a difference in group means may be inferred. Hypothesis Tests are used to quantify decisions.

The analysis of variance (ANOVA) was used to check the adequacy of the developed models. As per this technique:

(a) The F-ratio of the developed model is calculated and is compared with the standard tabulated value of F- ratio for a specific level of confidence.

(b) If calculated value of F- ratio does not exceed the tabulated value, then with the corresponding confidence probability the model may be considered adequate. For analysis , a confidence interval of 95% is taken.[31]

4.3.1 ANOVA : Tensile Strength

Effect of tool rotational speed on tensile strength is calculated as follows

N = 1/4n[a-(1)+ab-b+ac-c+abc-bc] ;n-no.of.replicates =1; a,b,c are lables and value for these lables are taken from Table3.5.4

N=1/4[59-74+88-51+86-94+105-89]; ¼[30]=7.5 ;

Sum of squares SS_N =[contrast]^2/8n = 30^3/8=112.5

Effect of weld speed = W= 1/4n[b+ab+bc+abc-1-a-c-ac];

=¼[51+88+89+105-74-59-94-86]; = ¼[20]=5 ; sum of squares SS_W = 20^2/8=50

Effect of tool pin diameter (D) = 1/4n[c+ac+bc+abc-1-a-b-ab]

= ¼[94+86+89+105-74-59-51-88] = ¼[102] = 25.5; Sum of squares SS_D = 1300.5

Interaction effect of tool speed and weld speed (NW)

= 1/4n[ab-a-b+1+abc-bc-ac+c] ; = ¼[88-59-51+74+105-89-86+94] = 1/4[76]=19 ; sum of squares SS_{NW} = 722

Interaction effect of tool speed and pin diameter (ND) = 1/4n[1-a+b-ab-c+ac-bc+abc] ; = ¼[74-59+51-88-94+86-89+105] = ¼[-14]= -3.5

Sum of squares SS_{ND} = [-14]^2/8 = 24.5

Interaction effect of weld speed and pin diameter = WD=1/4n[1+a-b-ab-c-ac+bc+abc] ; = ¼[74+59-51-88-94-86+89+105] = ¼[8]=2 ;

sum of squares SS_{WD} = 8;

Interaction effect of tool speed, weld speed and pin diameter

=1/4n[abc-bc-ac+c-ab+b+a-1] ; =¼[105-89-86+94-88+51+59-74] =1/4[-28]= -7 ; sum of squares SS_{NWD} = [-28]^2/8 = 98

Total sum of squares = $SS_T = SS_N+SS_W+SS_D+SS_{NW}+SS_{ND}+SS_{WD}+SS_{NWD}$

= 112.5+50+1300.5+722+24.5+8+98 = 2315.5

Pure Error = $Y^2_{ijk} – Y^2_{...}$/8n = 646 – (646/8) = 565.25

The tool pin diameter has maximum effect (25.5) % on tensile strength .Tool rotational speed has 7.5 % effect and weld speed 5% effect on tensile strength. Interaction of tool rotational speed and weld speed has 19% effect on tensile strength. Interaction of tool rotational speed and tool pin diameter has negative effect

(-3.5%) on tensile strength. Interaction of weld speed and tool pin diameter has 2% effect on tensile strength. Interaction of tool rotational speed , weld speed and tool pin diameter has negative effect (-7%) on tensile strength.

Calculated value of F-ratio for the selected model is **1.51195.** Tabulated value corresponding to the probability confidence (95%) is 5.59 for degrees of freedom 1,7 numerator and denominator. As calculated value of F –ratio does not exceed tabulated value the model can be considered adequate.

Table 4.2 ANOVA for tensile strength

source	Sum of squares	DF	Mean square	F value	P value
model	2315.5	7	330.7857	1.51195	0.2995
N	112.5	1	112.5	0.51577	0.6035
W	50	1	50	0.22854	0.7161
D	1300.5	1	1300.5	5.94430	0.2478
NW	722	1	722	3.30012	0.3204
ND	24.5	1	24.5	0.11232	0.7941
WD	8	1	8	0.03657	0.8797
NWD	98	1	98	0.44794	0.6245
Pure error	1750.25	8	218.7812		
Total	4065.75	15			

4.3.2 ANOVA : HARDNESS AT WELD NUGGET

Effect of tool rotational speed on hardness wt weld nugget is calculated as follows.

N = 1/4n[a-(1)+ab-b+ac-c+abc-bc]

n-no.of.replicates =1; a,b,c are lables and value for these lables are taken from table 3.5.4

Effect of tool rotational speed

N=1/4(1)[52.85-48.1+55.45-51.7+56.25-53.2+38.85-52.7]

N= ¼[-2.3]= - 0.575

-Sign indicates negative effect of tool rotational speed on hardness value at weld nugget.

Sum of squares (SS_N)= contrast^2 /8n = $[-2.3]^2$ /8 = 0.66125 ; SS_N = 0.66125

Effect of weld speed = W= 1/4n[b+ab+bc+abc-1-a-c-ac]

W=1/4[51.7+ 55.45+52.7+38.85-48.1-52.85-53.2-56.25]

=1/4[-11.7] = -2.925; Sum of squares SS_W = $[-11.7]^2$ /8=17.11125

Effect of tool pin diameter (D) = 1/4n[c+ac+bc+abc-1-a-b-ab]

D=1/4[53.2 +56.25 + 52.7 + 38.85 - 48.1 - 52.85 - 51.7 - 55.45]

D=¼[-7.1]= -1.775; Sum of squares = SS_D = $[-7.1]^2$ /8 = 6.30125

Interaction effect of tool speed and weld speed (NW)= 1/4n[ab-a-b+1+abc-bc-ac+c]

NW=1/4[55.45 - 52.85 -51.7 + 48.1 + 38.85 -52.7 - 56.25 + 53.2]

= ¼[-17.9]= -4.475; SS_{NW} = $[-17.9]^2$ /8 = 40.05125

Interaction effect of tool speed and pin diameter (ND) = 1/4n[1-a+b-ab-c+ac-bc+abc]

=¼[48.1 - 52.85 + 51.7 - 55.45 - 53.2 + 56.25 - 52.7 + 38.85]

=¼[-19.3]= -4.825; Sum of squares SS_{ND} = $[-19.3]^2$/8=46.56125

Interaction effect of weld speed and pin diameter = WD=1/4n[1+a-b-ab-c-ac+bc+abc]

=1/4[48.1+ 52.85 - 51.7 -55.45 - 53.2 - 56.25 + 52.7+ 38.85]

=¼[-24.1]= -6.025; SS_{WD} = $[-24.1]^2$/8= 72.60125

Interaction effect of tool speed, weld speed and pin diameter

=1/4n[abc-bc-ac+c-ab+b+a-1]

=¼[38.85 - 52.7 -56.25 + 53.2 - 55.45 + 51.7 + 52.85 -48.1] = ¼[-15.9]= - 3.975

SS_{NWD} = $[-15.9]^2/8$= 31.60125

Sum of squares of total = $SS_N+SS_W+SS_D+SS_{NW}+SS_{ND}+SS_{WD}+SS_{NWD}$ = 214.8888

Pure Error = $Y^2_{ijk} – Y^2_{...}/8n$ = 409.1-409.1/8 = 409.1-51.1375= 357.9625

The hardness at weld nugget is reduced due to welding .The effect of tool rotational speed, weld speed and tool pin diameter has negative effect on hardness value. The interaction effect of these parameters also produces negative effect on hardness value of aluminum alloy AA1100. The hardness is inversely proportional to tool speed, weld speed and tool pin diameter.

Table 4.1.3 ANOVA for hardness at weld nugget

source	Sum of squares	DF	Mean square	F value	P value
model	**214.8888**	**7**	**30.6984**	**0.6860697**	**0.6843**
N	**0.66125**	**1**	**0.661250**	**0.0147781**	**0.9230**
W	**17.11125**	**1**	**17.11125**	**0.3824144**	**0.6474**
D	**6.30125**	**1**	**6.30125**	**0.1408248**	**0.7715**
NW	**40.05125**	**1**	**40.05125**	**0.8950938**	**0.5176**
ND	**46.56125**	**1**	**46.56125**	**1.0405840**	**0.4937**
WD	**72.60125**	**1**	**72.60125**	**1.6225440**	**0.4237**
NWD	**31.60125**	**1**	**31.60125**	**0.7062472**	**0.5551**
Pure error	357.9625	**8**	**44.74531**		
Total	**572.8513**				

4.3.3 ANOVA : HARDNESS AT HEAT AFFECTED ZONE

Effect of tool rotational speed on hardness at heat affected zone is calculated as follows.

N = 1/4n[a-(1)+ab-b+ac-c+abc-bc] ; label values are taken from table 3.5.4

N=1/4[51.95-52.2+50.5-48.1+46.1-50.3+38.4-49]

N=1/4[-12.65] ; N = -3.1625 ;

SS_N=[-12.65]^2 /8 = 20.00281

Effect of weld speed= W= 1/4n[b+ab+bc+abc-1-a-c-ac]

= 1/4[48.1+50.5+49+38.4-52.2-51.95-50.3-46.1]

= 1/4[-14.55] ; W = -3.6375; SSw = [-14.55]^2 /8 = 26.46281

Effect of tool pin diameter

D = 1/4n[c+ac+bc+abc-1-a-b-ab]

= 1/4[50.3+46.1+49+38.4-52.2-51.95-48.1-50.5]

D = 1/4[-18.95]= -4.7375; SS_D = 44.88781

Interaction effect of tool speed and weld speed (NW)= 1/4n[ab-a-b+1+abc-bc-ac+c]

NW = 1/4[50.5-51.95-48.1+52.2+38.4-49-46.1+50.3]

NW = 1/4[-3.75]=-0.9375

SS_{NW} = [-3.75]^2/8=1.757812

Interaction effect of tool speed and pin diameter (ND) = 1/4n[1-a+b-ab-c+ac-bc+abc]

ND=1/4n[52.2-51.95+48.1-50.5-50.3+46.1-49+38.4]

= 1/4[-16.95] = - 4.2375; SS_{ND} = 35.91281

Interaction effect of weld speed and pin diameter

WD=1/4n[1+a-b-ab-c- ac+bc+abc]

1/4[52.2+51.95-48.1-50.5-50.3-46.1+49+38.4]

WD=1/4[-3.45]=-0.8625 ; Sum of squares SS_{WD}=1.487812

Interaction effect of tool speed ,weld speed and pin diameter

NWD=   1/4n[abc-bc-ac+c-ab+b+a-1]

=1/4[38.4-49-46.1+50.3-50.5+48.1+51.95-52.2]

NWD=1/4[-9.05]; SS_{NWD}=163.805

Yijk^2-Y^2…/8 = 386.55-386.55/8 = 386.55-48.31875=338.2312

Pure error = 338.2312-294.3169=43.9143

The hardness at heat treated zone is reduced due to welding .The effect of tool rotational speed, weld speed and tool pin diameter has negative effect on hardness value. The interaction effect of these parameters also produces negative effect on hardness value of aluminum alloy AA1100.

Table 4.1.4 Anova For Hardness At Heat Affected Zone

source	Sum of squares	DF	Mean square	F value	P value	
model	294.3169	7	42.04527	7.6595	0.0278	statistically significant.
N	20.00281	1	20.00281	3.643972	0.3072	
W	26.46281	1	26.46281	4.820809	0.2721	
D	44.88781	1	44.88781	8.177346	0.2142	
NW	1.757812	1	1.757812	0.3202259	0.6722	
ND	35.91281	1	35.91281	6.542344	0.2373	
WD	1.487812	1	1.487812	0.2710392	0.6944	
NWD	163.805	1	163.805	29.84085	0.1153	
Pure error	43.9143	8	5.489288			
Total	632.5481					

4.3.4 ANOVA: Temperature at weld nugget

Effect of tool rotational speed on Temperature at weld nugget (N)=

N = 1/4n[a-(1)+ab-b+ac-c+abc-bc] ; label values are taken from table 3.5.4

= ¼[70-55+68-85+55-50+108-65] = ¼[46] = 11.5

Sum of squares = [46]^2/8 =264.5

Effect of weld speed = W= 1/4n[b+ab+bc+abc-1-a-c-ac]

¼[85+68+65+108-55-70-50-55]=1/4[96] = 24 ; SS_W = 1152;

Effect of tool pin diameter (D) = 1/4n[c+ac+bc+abc-1-a-b-ab]

¼[50+55+65+108-55-70-85-68]=0 ; SS_D=0

Interaction effect of tool speed and weld speed (NW)= 1/4n[ab-a-b+1+abc-bc-ac+c]

= ¼[68-70-85+55+108-65-55+50]=1/4[6]=1.5 ; SS_{NW} = 4.5

Interaction effect of tool speed and pin diameter (ND) = 1/4n[1-a+b-ab-c+ac-bc+abc]

=1/4[55-70+85-68-50+55-65+108] = ¼[50] = 12.5 ; SS_{ND}= 312.5

Interaction effect of weld speed and pin diameter = WD=1/4n[1+a-b-ab-c-ac+bc+abc]

=1/4[55+70-85-68-50-55+65+108] = ¼[40] = 10 ; SS_{WD} = 200

Interaction effect of tool speed, weld speed and pin diameter

=1/4n[abc-bc-ac+c-ab+b+a-1]

= ¼[108-65-55+50-68+85+70-55] = ¼[70] = 17.5 ; SS_{NWD} = 612.5

Yijk^2-Y^2/8 = (556-556/8) = 556-69.5 = 486.5

Pure error = 2546-486.5 = 2059.5

Total sum of squares = 2546;

The tool rotational speed has positive effect(11.5%) on temperature at weld nugget. The weld speed has 24% positive effect on temperature. When weld speed is increased temperature at weld nugget is also increased. Tool pin diameter has no effect on temperature at weld nugget. Interaction effect of tool speed and weld speed is less(1.5%). Interaction effect of tool speed and pin diameter has 12.5 % positive effect on temperature. Interaction of weld speed and pin diameter has 10% positive effect on temperature. Interaction of tool speed,weld speed and pin diameter increases weld nugget temperature.

Table 4.1.5 ANOVA for temperature at weld nugget

source	Sum of squares	DF	Mean square	F value	P value
model	2546	**7**	363.7143	5.980913	0.04439346
N	264.5	**1**	264.5	4.349435	0.28463858
W	1152	**1**	1152	18.94347	0.14377340
D	0	**1**	0	0	0
NW	4.5	**1**	4.5	0.073997	0.83092317
ND	312.5	**1**	312.5	5.138726	0.26448893
WD	200	**1**	200	3.288798	0.32081320
NWD	612.5	**1**	612.5	10.07194	0.19432760
Pure error	486.5	**8**	60.8125		
Total	3032.5				

4.3.5 ANOVA : TEMPERATURE AT HEAT AFFECTED ZONE

Effect of tool rotational speed on Temperature at HAZ

N=1/4n[a-(1)+ab-b+ac-c+abc-bc]

=1/4[55-43+60-61+40-42+92-58]=1/4[43]=10.75 ; SS_N = 231.125

Effect of weld speed = W= 1/4n[b+ab+bc+abc-1-a-c-ac]

=1/4[61+60+58+92-43-55-42-40]= ¼[91]=22.75 ; SS_W = 1035.125

Effect of tool pin diameter (D) = 1/4n[c+ac+bc+abc-1-a-b-ab]

=1/4[42+40+58+92-43-55-61-60]=1/4(13)= 3.25 ; SS_D = 21.125

Interaction effect of tool speed and weld speed (NW)= 1/4n[ab-a-b+1+abc-bc-ac+c]

=1/4[60-55-61+43+92-58-40+42]= ¼[23]=5.75 ; SS_{NW} = 66.125

Interaction effect of tool speed and pin diameter (ND) = 1/4n[1-a+b-ab-c+ac-bc+abc]

=1/4[43-55+61-60-42+40-58+92]=1/4[21]=5.25 ; SS_{ND} = 55.125

Interaction effect of weld speed and pin diameter = WD=1/4n[1+a-b-ab-c-ac+bc+abc]

=1/4[43+55-61-60-42-40+58+92]= ¼[45] = 11.25 ; SS_{WD} = 253.125

Interaction effect of tool speed, weld speed and pin diameter

=1/4n[abc-bc-ac+c-ab+b+a-1]

= ¼[92-58-40+42-60+61+55-43]=1/4[49]=12.25 ; S_{NWD}=300.125

Pure error = 1961.875-394.625 = 1567.25

Above calculations shows that when tool speed ,weld speed and pin diameter increase the temperature at heat affected zone is increased. When these parameters decreased the temperature also decreased. Interaction values also prove that input parameters were directly proportional to temperature at heat affected zone.

Table 4.1.6 ANOVA for temp 'at HAZ

source	Sum of squares	DF	Mean square	F value	P value
model	**1961.875**	**7**	**280.2679**	**1.430623**	**0.44330748**
N	**231.125**	**1**	**231.125**	**1.179774**	**0.47371849**
W	**1035.125**	**1**	**1035.125**	**5.283779**	**0.26123236**
D	**21.125**	**1**	**21.125**	**0.1078322**	**0.79801249**
NW	**66.125**	**1**	**66.125**	**0.337534**	**0.66493950**
ND	**55.125**	**1**	**55.125**	**0.2813847**	**0.68951297**
WD	**253.125**	**1**	**253.125**	**1.297245**	**0.45869807**
NWD	**300.125**	**1**	**300.125**	**1.531983**	**0.43261963**
Pure error	**1567.25**	**8**	**195.9062**		
Total	**3529.125**				

4.3.6 Development of the final proposed models :

The models developed to predict the mechanical properties are as follows :

Regression Equations

Tensile strength (TS) = $b_0 + b_1 N + b_2 W + b_3 D + b_{12} NW + b_{13} ND + b_{23} WD + b_{123} NWD$

Tensile Strength (TS) = 138.4 – 0.1726 N – 4.155 W – 3.298 D + 0.004951 NW + 0.01746 ND + 0.4539 WD - 0.000510 NWD

Hardness at weld nugget = $b_0 + b_1 N + b_2 W + b_3 D + b_{12} NW + b_{13} ND + b_{23} WD + b_{123} NWD$

H_N = 27.07 – 0.01864 N – 0.2749 W + 2.560 D + 0.001594 NW + 0.004419 ND + 0.06256 WD - 0.000271 NWD

Hardness at HAZ = $b_0 + b_1 N + b_2 W + b_3 D + b_{12} NW + b_{13} ND + b_{23} WD + b_{123} NWD$

H_{HAZ} = 61.04 – 0.001471 N – 0.2938 W – 1.475 D + 0.000633 NW + 0.000336 ND + 0.05027 WD - 0.000112 NWD

Temperature at weld nugget

$[T_N]= b_0+b_1N+b_2W+b_3D+b_{12}NW+b_{13}ND+b_{23}WD+b_{123}NWD$

T_N = -102.1 + 0.2786 N + 5.882 W + 19.39 D – 0.008810 NW – 0.03804 ND – 0.7690 WD + 0.001274 NWD

Temperature at HAZ

$T_{HAZ} = b_0+b_1N+b_2W+b_3D+b_{12}NW+b_{13}ND+b_{23}WD+b123NWD$

T2 = -69.43 + 0.2204 N + 3.265 W + 14.74 D – 0.005825 NW – 0.03185 ND – 0.4347 WD + 0.000892 NWD

4.3.7 PREDICTION OF RESPONSES BY REGRESSION MODEL

By substituting the input parameters in the final proposed models , the tensile strength, hardness at weld nugget ,hardness at heat affected zone, temperature at weld nugget ,temperature at heat affected zone were predicted and tabulated as follows.

Table 4.1.7 Predicted responses by regression model

Weld no	Tool speed rpm	Weld speed Mm/m	Pin dia mm	Tensile Streng	Hardness H_N	Hardness $_{HAZ}$	Temp T_N	Temp T_{HAZ} ^0C
1	460	24	6	61.75	53.7750	54.0875	51.75	38.00
2	1130	24	6	69.25	53.2125	50.9250	63.25	48.75
3	460	65	6	66.75	50.8625	50.4500	75.75	60.75
4	1130	65	6	74.25	50.3000	47.2875	87.25	71.50
5	460	24	8	87.25	51.9875	49.3500	51.75	41.25
6	1130	24	8	94.75	51.4250	46.1875	63.25	52.00
7	460	65	8	92.25	49.0750	45.7125	75.75	64.00
8	1130	65	8	99.75	48.5125	42.5500	87.25	74.75

4.3.8 TESTING THE MODELS

The developed models were tested for the accuracy of their predictive ability. 5 test cases were selected at random from the design matrix and the experimental mechanical properties were compared to the parameters obtained from the mathematical models. The results are summarized in table 4.1.8 below

Table 4.1.8 Testing of mathematical model

Weld no	Tool speed(rp	Weld speed Mm/min	Pin dia mm		Tensile Strength	Hardness (H_N)	Hardness H_{TMAZ}	Temp T_N	Temp T_{TMAZ}
1	460	24	6	Actual Predicted % error	74.00 61.75 17.22	52.2 53.7750 -3.02	52.2 54.0875 -3.61	55 51.75 5.91	43 38 11.63
3	460	65	6	Actual Predicted % error	51 66.75 30.88	48.1 50.8625 -5.74	48.1 50.45 -4.83	85 75.75 10.88	61 60.75 0.409
4	1130	65	6	Actual Predicted % error	88 74.25 15.62	50.5 50.3 0.396	50.5 47.2875 6.35	68 87.25 -28.3	60 71.5 -19.16
5	460	24	8	Actual Predicted % error	94.00 87.25 7.11	50.3 51.9875 -3.35	50.3 49.35 1.83	50 51.75 -3.5	42 41.25 1.785
7	460	65	8	Actual Predicted % error	89.00 92.25 -3.65	49 49.075 0.153	49 45.7125 6.71	65 75.750 -16.53	58 64.010 -10.34

From the table it is observed that the performance of the mathematical model is good and it can be used for predicting the mechanical properties in Friction stir welding.

CHAPTER 5

RESULTS AND DISCUSSIONS

The mathematical models developed above can be employed to predict the mechanical properties of weld for the range of parameters used in the investigation by substituting their respective values in coded form . Based on these models, the main and the interaction effects of the process parameters on the mechanical properties were computed and plotted as depicted in figures. The results show the general trends between cause and effect.

5.1 Direct effect of process variables on Tensile strength

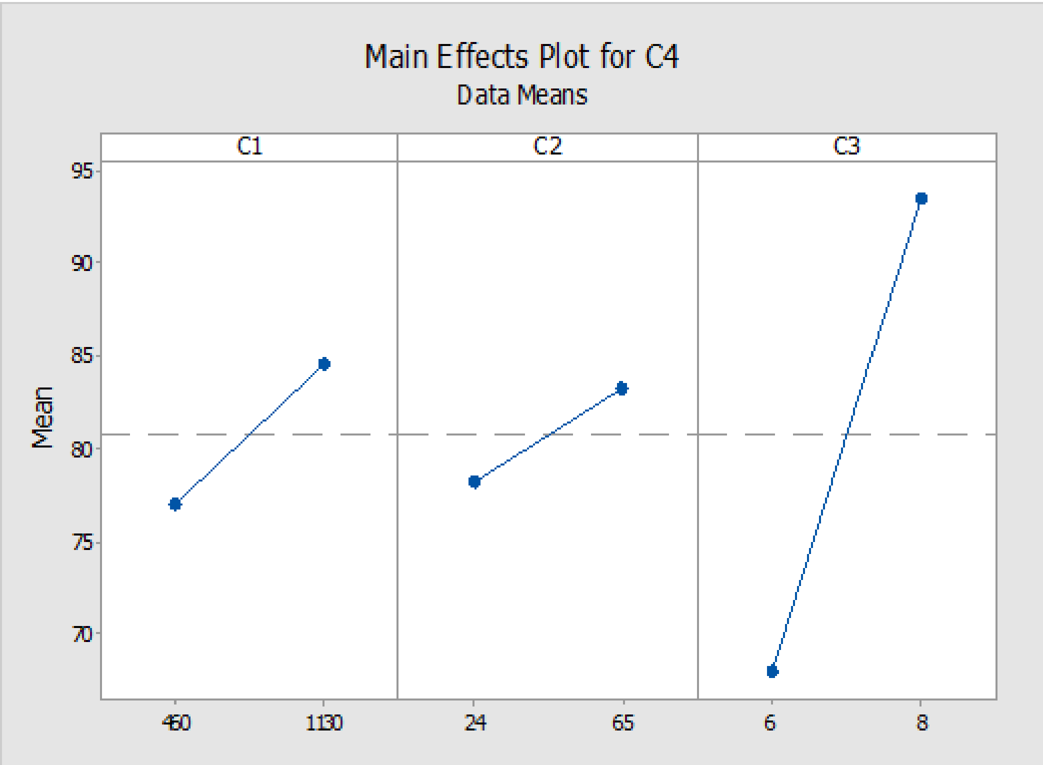


Figure5.1Direct effect of TRS(C1) ,WS(C2) and D(C3) on Tensile strength (C4)

The Figure shows that the tensile strength C4 of Friction stir welded Aluminium Alloy 1100 increases with increase in tool rotational speed C1, weld speed C2 and shoulder pin diameter C3. By reducing the rpm value, the tensile strength of the joint is reduced. The reason for this may be that the amount of heat generated was not sufficient for proper stirring, which in turn may be the reason for the reduced tensile strength.

5.2 Direct effect of process variables on Hardness at weld nugget

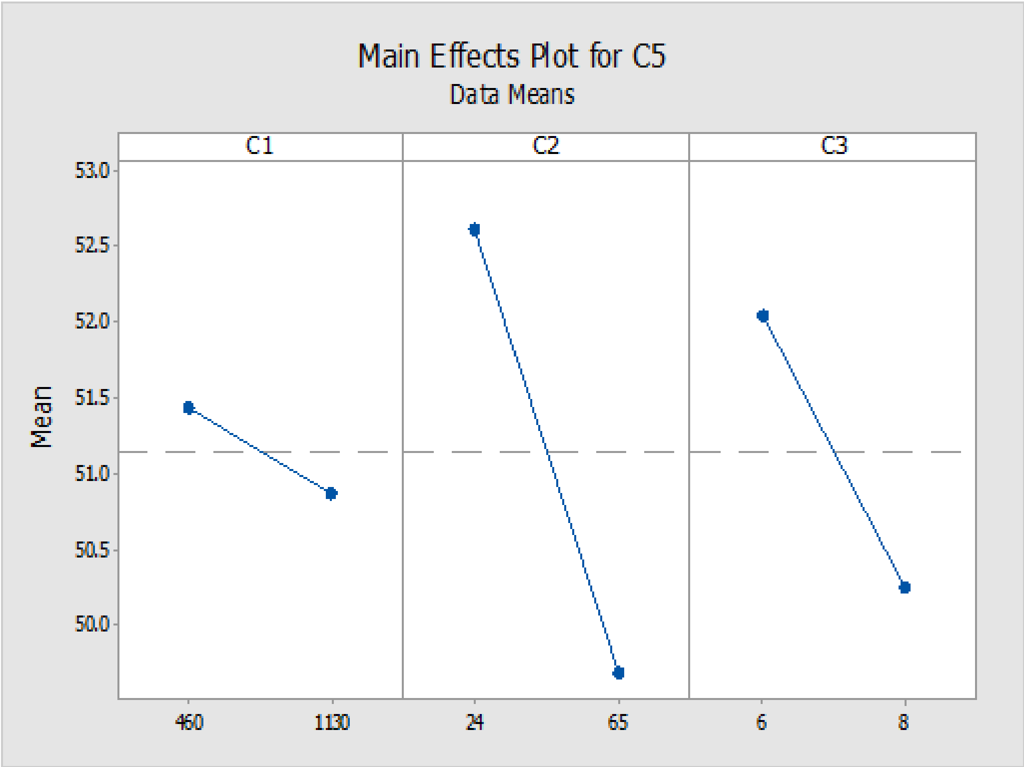


Figure5.2 Direct effect of TRS(C1) ,WS(C2) and D(C3) on Hardness at weld nugget

The Hardness at weld nugget is decreasing with increase in tool rotational speed, weld speed and shoulder pin diameter. The hardness is drastically decreased from 52.5 HV to 42 HV due to increase in weld speed. The effect of tool rotational speed, weld speed and tool pin diameter has negative effect on hardness value.

5.3 Direct effect of process variables on Hardness at HAZ

The Hardness at heat affected zone is higher at low tool rotational speed ,weld speed and shoulder pin diameter. The hardness at heat treated zone is reduced due to welding . The effect of tool rotational speed, weld speed and tool pin diameter has negative effect on hardness value. The interaction effect of these parameters also produces negative effect on hardness value of aluminum alloy AA1100.

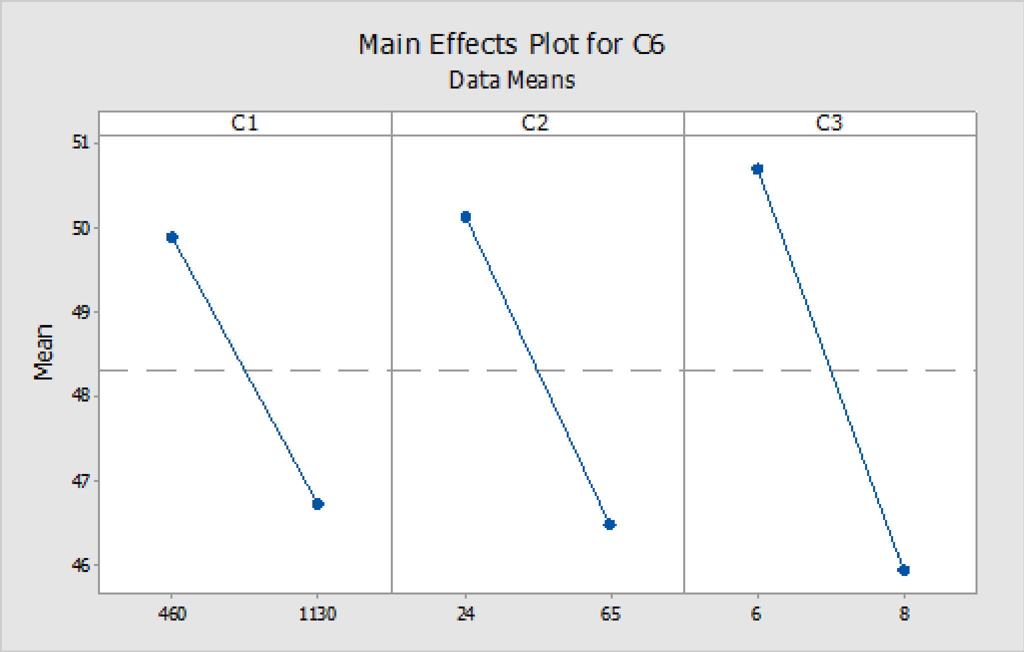


Figure 5.3 Direct effect of TRS(C1) ,WS(C2) and D(C3) on Hardness at HAZ

5.4 Direct effect of process variables on temperature at weld nugget

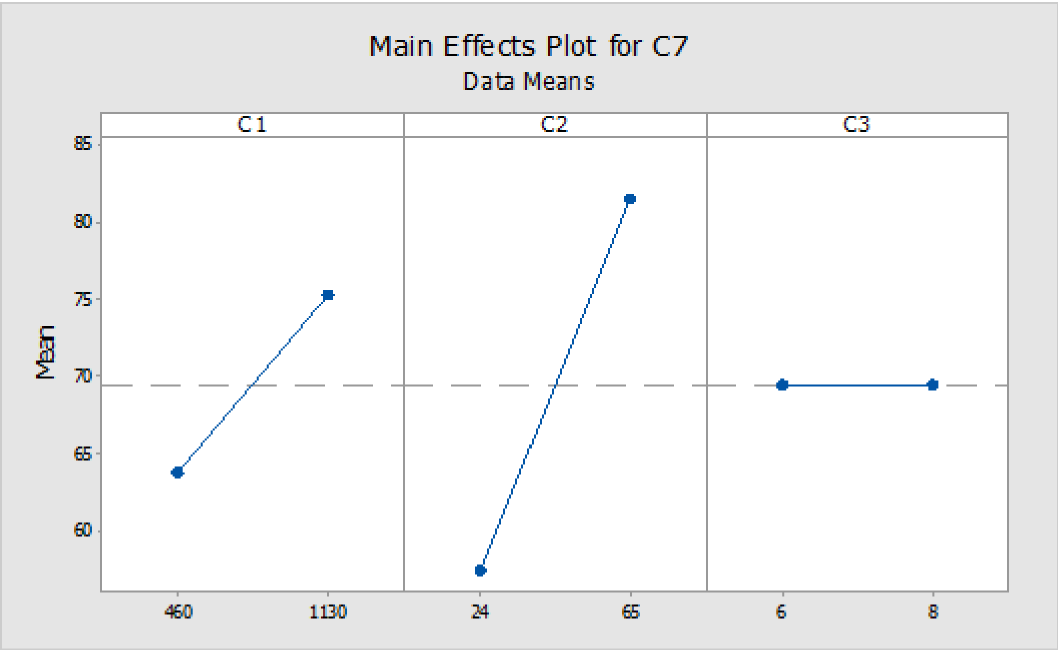


Figure 5.4 Direct effect of TRS(C1) ,WS(C2) & D(C3)on temperature at weld nugget (C7)

The tool rotational speed has positive effect(11.5%) on temperature at weld nugget. The weld speed has 24% positive effect on temperature. When weld speed is increased temperature at weld nugget is also increased. Tool pin diameter has no effect on temperature at weld nugget. Interaction effect of tool speed and weld speed is less (1.5%). Interaction effect of tool speed and pin diameter has 12.5 % positive effect on temperature. Interaction of weld speed and pin diameter has 10% positive effect on temperature. Interaction of tool speed, weld speed and pin diameter increases weld nugget temperature.

5.5 Direct effect of process variables on temperature at HAZ

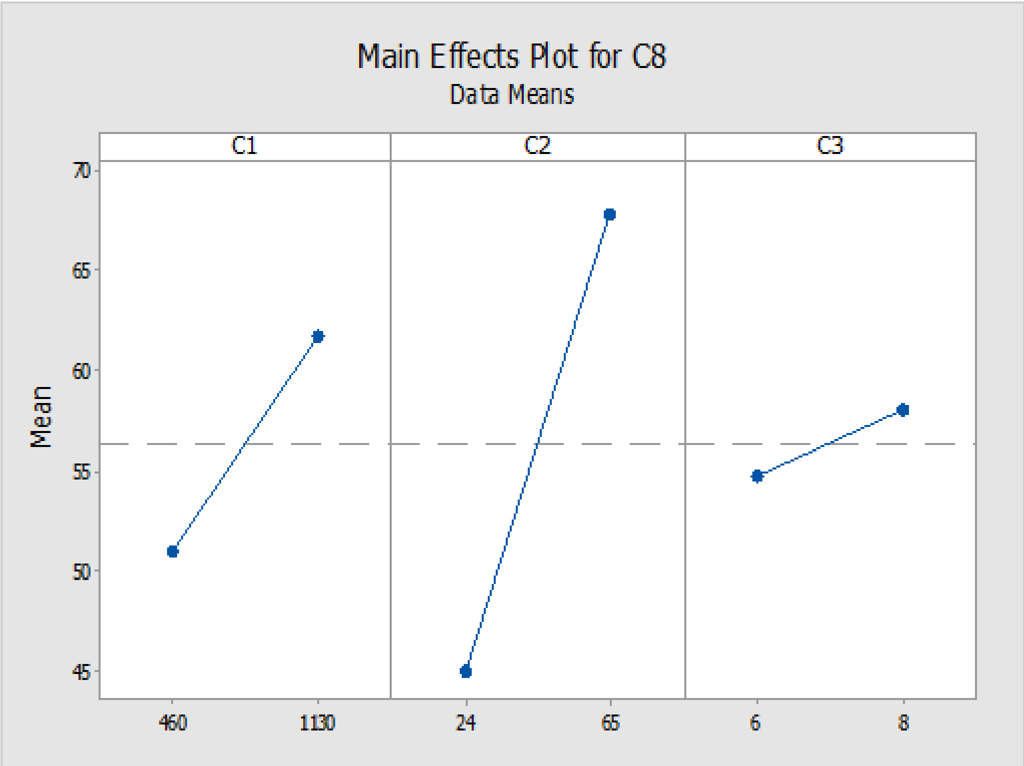


Figure 5.5 Direct effect of TRS(C1) ,WS(C2) and D(C3) on temperature at HAZ (C8)

From the figure it is shown that the temperature at heat affected zone is higher at greater tool speed ,weld speed and shoulder pin diameter. Higher weld speed is preferred for good mechanical properties. Tool pin diameter has less effect on temperature.

5.2 Interaction effect of process variables on the mechanical properties

5.2.1 Interaction effect of TRS,WS and D on Tensile strength

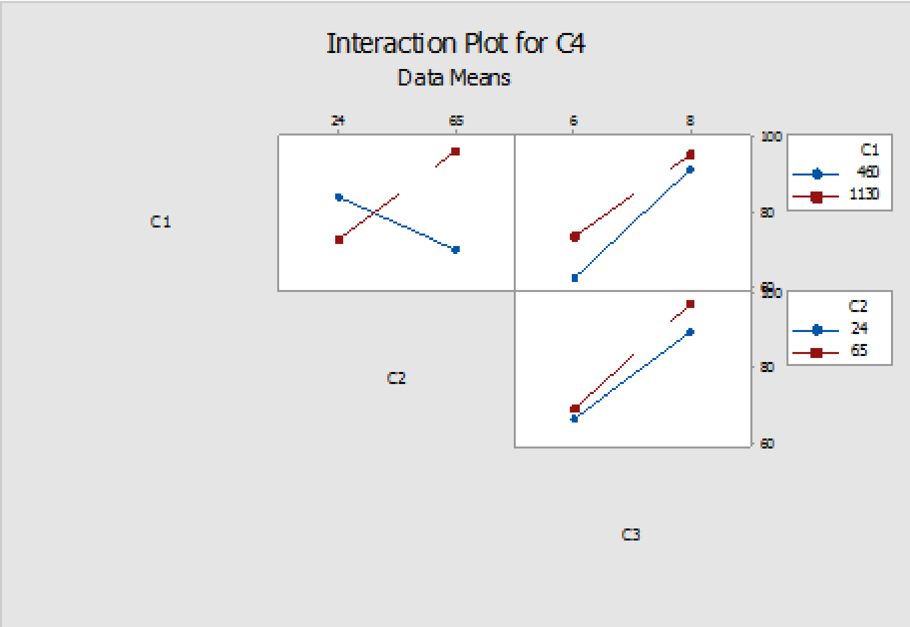


Figure 5.6 Interaction effect of TRS,WS and D on Tensile strength

Interaction of tool rotational speed and weld speed has 19% effect on tensile strength. Interaction of tool rotational speed and tool pin diameter has negative effect (-3.5%) on tensile strength. Interaction of weld speed and tool pin diameter has 2% effect on tensile strength Interaction of tool rotational speed , weld speed and tool pin diameter has negative effect (-7%) on tensile strength. By increasing the feed speed and reducing the rpm value, the tensile strength of the joint is reduced. The reason for this may be that the amount of heat generated was not sufficient for proper stirring, which in turn may be the reason for the reduced tensile strength.

5.2.2 Interaction effect of TRS,WS and D on hardenss at weld nugget

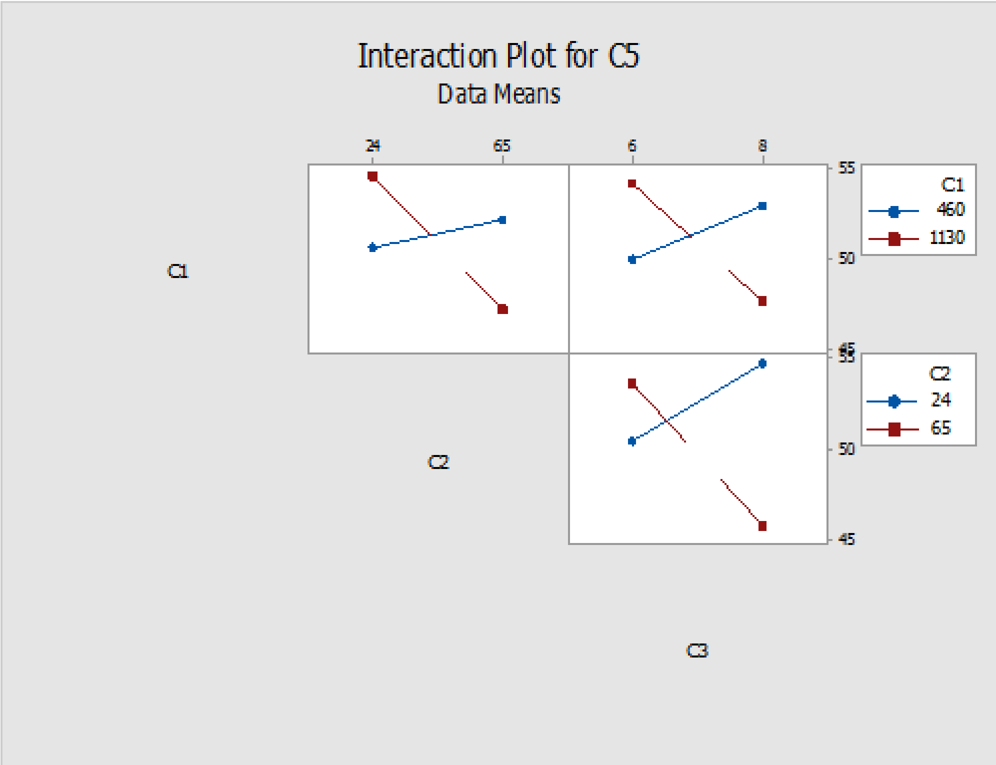


Figure 5.7 Interaction effect of TRS,WS and D on Hardness at weld nugget

The interaction effect of input parameters produces negative effect on hardness value of aluminum alloy AA1100. The hardness is inversely proportional to tool speed ,weld speed and tool pin diameter. Interaction of tool speed and weld speed produce the negative effect of-4.475 % on hardness value. Interaction of tool speed and tool pin diameter has negative effect of -4.825% on hardness values. Interaction of weld speed and tool pin diameter has negative effect of -6.025% on hardness values Interaction of tool speed ,weld speed and pin diameter has -3.975 % on hardness values.

5.2.3 Interaction effect of TRS,WS and D on Hardness at HAZ

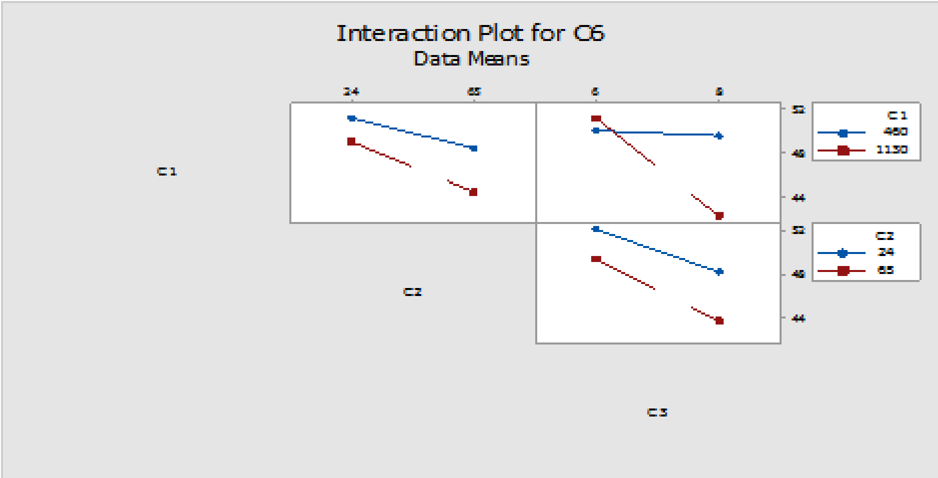


Figure 5.2.3 Interaction effect of TRS,WS and D on Hardness at HAZ

The interaction effect of input parameters produces negative effect on hardness value of aluminum alloy AA1100. The hardness is inversely proportional to tool speed ,weld speed and tool pin diameter. Interaction of tool speed and weld speed produce the negative effect of-4.475 % on hardness value. Interaction of tool speed and tool pin diameter has negative effect of -4.825% on hardness values. Interaction of weld speed and tool pin diameter has negative effect of -6.025% on hardness values. Interaction of tool speed ,weld speed and pin diameter has -3.975 % on hardness values.

5.2.4 Interaction effect of TRS,WS and D on temperature at weld nugget

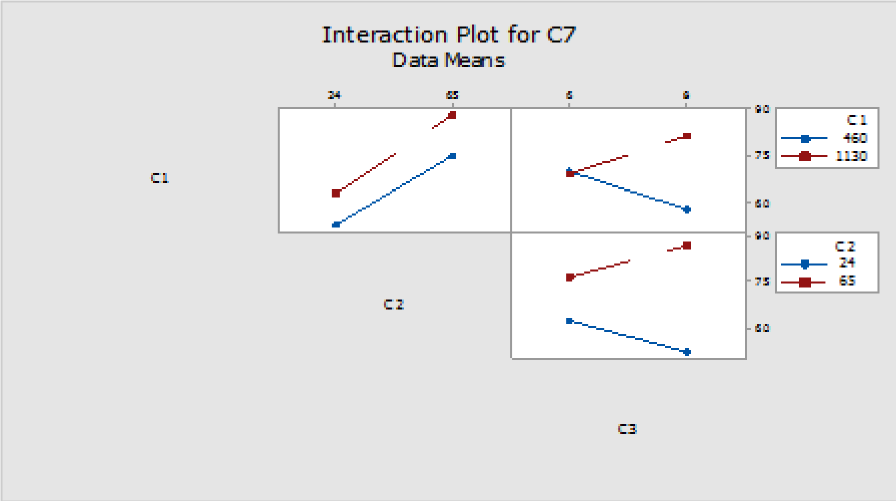


Figure 5.9 Interaction effect of TRS,WS and D on temperature at weld nugget

Interaction effect of tool speed and weld speed is less(1.5%). Interaction effect of tool speed and pin diameter has 12.5 % positive effect on temperature. Interaction of weld speed and pin diameter has 10% positive effect on temperature. Interaction of tool speed, weld speed and pin diameter increases weld nugget temperature.

5.2.5 Interaction effect of TRS,WS and D on Temperature at HAZ

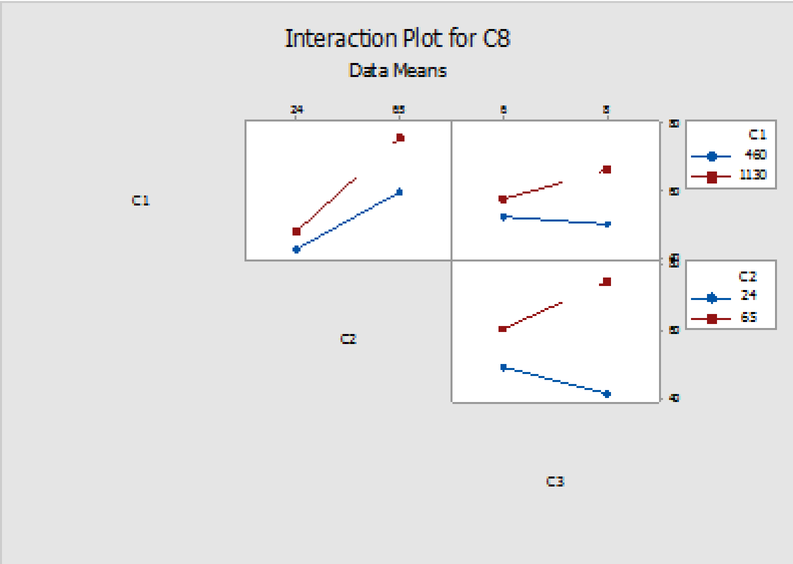


Figure No 5.2.5 Interaction effect of TRS,WS and D on Temperature at HAZ

Analytical calculations shows that when tool speed , weld speed and pin diameter increase the temperature at heat affected zone is increased. When these parameters decreased the temperature also decreased. Interaction values also prove that input parameters were directly proportional to temperature at heat affected zone.

CHAPTER 6

MODELLING USING ARTIFICIAL NEURAL NETWORK

6.1 Basic approach to mathematical modeling using Artificial Neural Network in friction stir welding scenario

A neural network is an adaptable system that can learn relationships through repeated presentation of data and is capable of generalizing to new , previously unseen data.

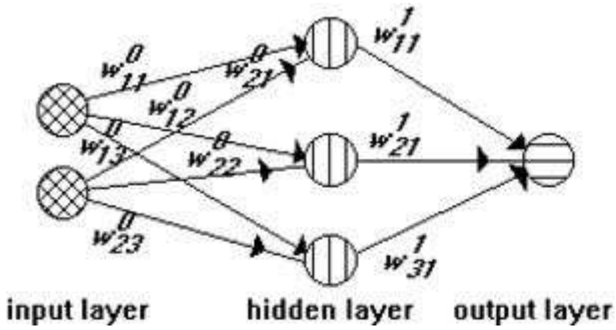


Figure 6.1 basic scheme of an Artificial Neural Network

If a network is to be of any use , there must be inputs (which carry the values of variables of interest in the outside world) and outputs (which form predictions , or control signals). There may be hidden neurons , which playan internal role in the network . the input,hidden and output neurons need to be connected together .the artificial neurone as shown in figure 6.1 receives a number of inputs (either from original data , or from the output of other neurons in the neural network) and processes the input to generate the output for that particular neurone. The steps are schematically shown in figure 6.2 for our application ,this function is a sigmoid function which is the same for all neurons.

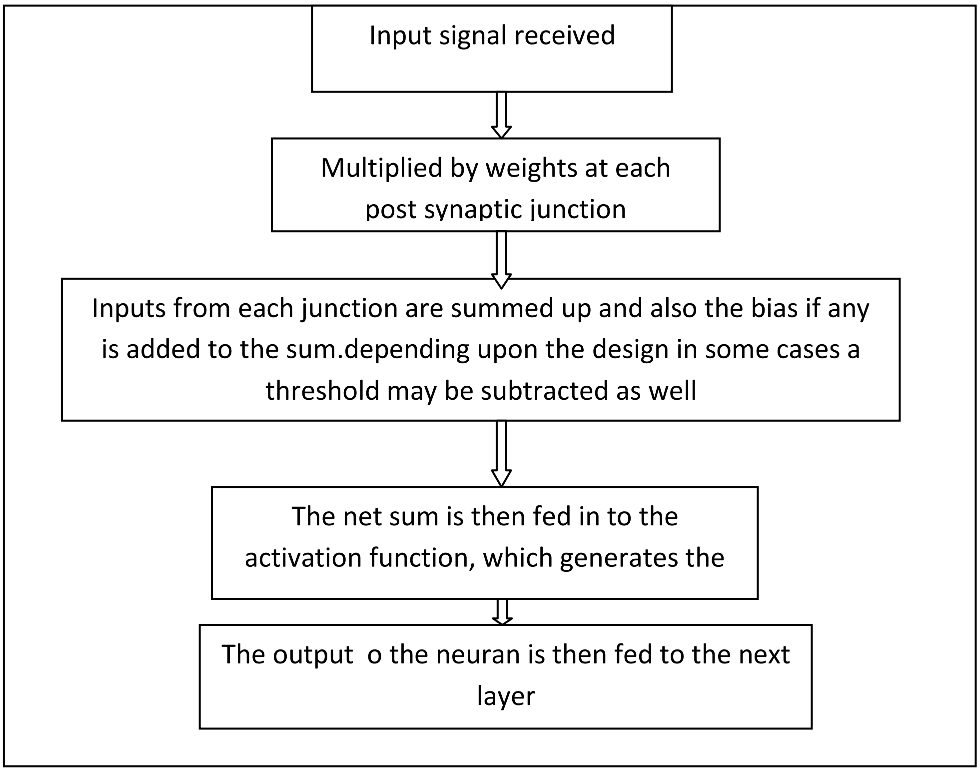


Figure 6.2 sequence of steps in the processing of signal by neuron

The back propagation algorithm is used in layered feed – forward ANNs. This means that the artificial neurons are organized in layers , and their signals are fed " forward " , and then the errors are propagated backwards. The back propagation algorithm uses supervised learning ,which means that we provide the algorithm with examples of the inputs and outputs we want the network to compute ,and then the error (difference between actual and expected results) is calculated. The idea of the back propagation algorithm is to reduce this error, until the ANN learns the training data. The training begins with random weights, and the goal is to adjust them so that the error will be minimal. The sequence of steps of for the training of a simple 2 layer network using back propagation training algorithm is shown in figure 6.2

E is the error function , i and j are the number of layers and number of neurons in each layer respectively , o is the network output , D is the desired output , w is the weights , A is the activation function for the "j" th neurons . For training the network with one more layer we need to make some considerations .If it is to adjust the weights of a previous layer , it is necessary first to calculate how the error depends not on the weight , but in the input from the previous layer. Thus by generating the above approach we can model any number of layers in the network.The algorithm progresses iteratively through a number of epochs. At each epoch the training cases are each submitted to the network and the output and the error is calculated This

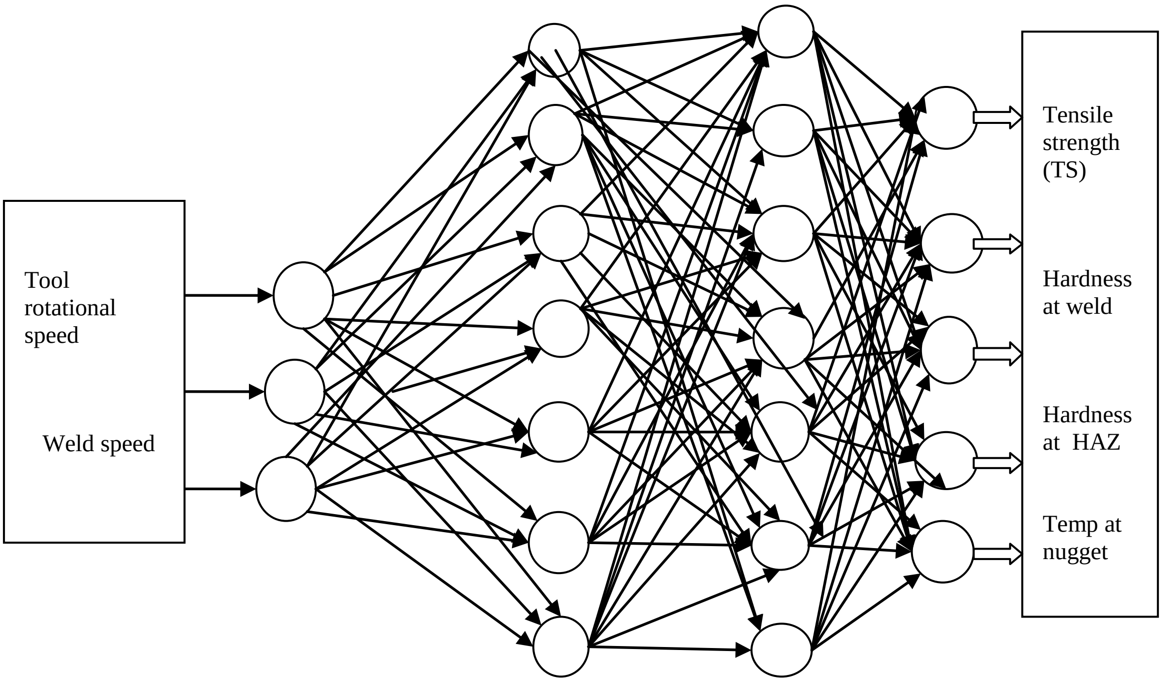


Figure 6.3 FFNN to predict mechanical properties

error is used together with the error surface gradient to adjust the weights and then the process is repeated till the outputs are within a desired level of accuracy.

A typical feed forward network is shown in fig 6.3. This network is used in the present research for the modelling of the process. To model the process 3 input parameters viz , tool rotational speed , weld speed , tool pin diameter were considered and their effect on 5 mechanical properties namely tensile strength ,hardness at weld nugget, hardness at heat affected zone were studied , so for our modelling the input and the output layer of net work had 3,and 5 neurons respectively. The input layer is not a neural layer in the true sense of the word ;it is just used to introduce the input variables in the network. The performance of a neural is dependent on the number of hidden layers and the number of hidden neurons in the hidden layers. Therefore sufficiently large number of trials must be carried out before deciding the optimum number of hidden layers and the number of neurons in the hidden layers .The goal was kept as 0.01 .

6.2 computational work

Computational work for the training of the network was carried out in MATLAB R2009a software. Few examples are given below .

6.2.1 computational experimental work

Network name : ex -1

No.of hidden layers : 2

Network type : feed forward back propagation

Training function : gradient descent with momentum back propagation

No.of neurons in first hidden layer : 7

Adaptation learning function : gradient descent with momentum weight and bias learning function

No .of neurons in input layer : 3

Performance function : MSE

Transfer function : log sigmoid transfer function

Epochs : 1000

Goal : 0.01

Learning rate : 0.01

Epochs made : 5844

6.2.2 computational experimental work

Network name : ex -2

No.of hidden layers : 2

Network type : feed forward back propagation

Training function : gradient descent with momentum back propagation

No.of neurons in first hidden layer : 20

Adaptation learning function : gradient descent with momentum weight and bias learning function

No .of neurons in input layer : 3

Performance function : MSE

Transfer function : log sigmoid transfer function

Epochs : 1000

Goal : 0.01

Learning rate : 0.01

Epochs made : 4457

6.3 Matlab functions used to train, test and validate

```
tr =    trainFcn: 'trainlm'

      trainParam: [1x1 struct]

      performFcn: 'mse'

    performParam: [1x1 struct]

        derivFcn: 'defaultderiv'

       divideFcn: 'dividerand'

      divideMode: 'sample'

     divideParam: [1x1 struct]

        trainInd: [1x4 double]
```

```
    valInd: [1x2 double]
   testInd: [1x2 double]
      stop: 'Validation stop.'
num_epochs: 12
 trainMask: {[1x4 double]}
   valMask: {[1x2 double]}
  testMask: {[1x2 double]}
best_epoch: 6
      goal: 0
    states: {1x8 cell}
     epoch: [0 1 2 3 4 5 6 7 8 9 10 11 12]
      time: [1x13 double]
      perf: [1x13 double]
     vperf: [1x13 double]
     tperf: [1x13 double]
        mu: [1x13 double]
  gradient: [1x13 double]
  val_fail: [0 0 0 0 0 1 0 1 2 3 4 5 6]
 best_perf: 7.0111
best_vperf: 26.3333
best_tperf: 500
```

This structure contains all of the information concerning the training of the network. For example, tr.trainInd,tr.valInd and tr.testInd contain the indices of the data points that were used in the training, validation and test sets, respectively. To retrain the network using the same division of data, you can setnet.divideFcn to 'divideInd', net.divideParam.trainInd to tr.trainInd,net.divideParam. valInd to tr.valInd, net.divideParam.testInd to tr.testInd.The tr structure also keeps track of several variables during the course of training, such as the value of the performance function, the magnitude of the gradient, etc. You can use the training record to plot the performance progress by using the plotperf command:

```
plotperf(tr)
```

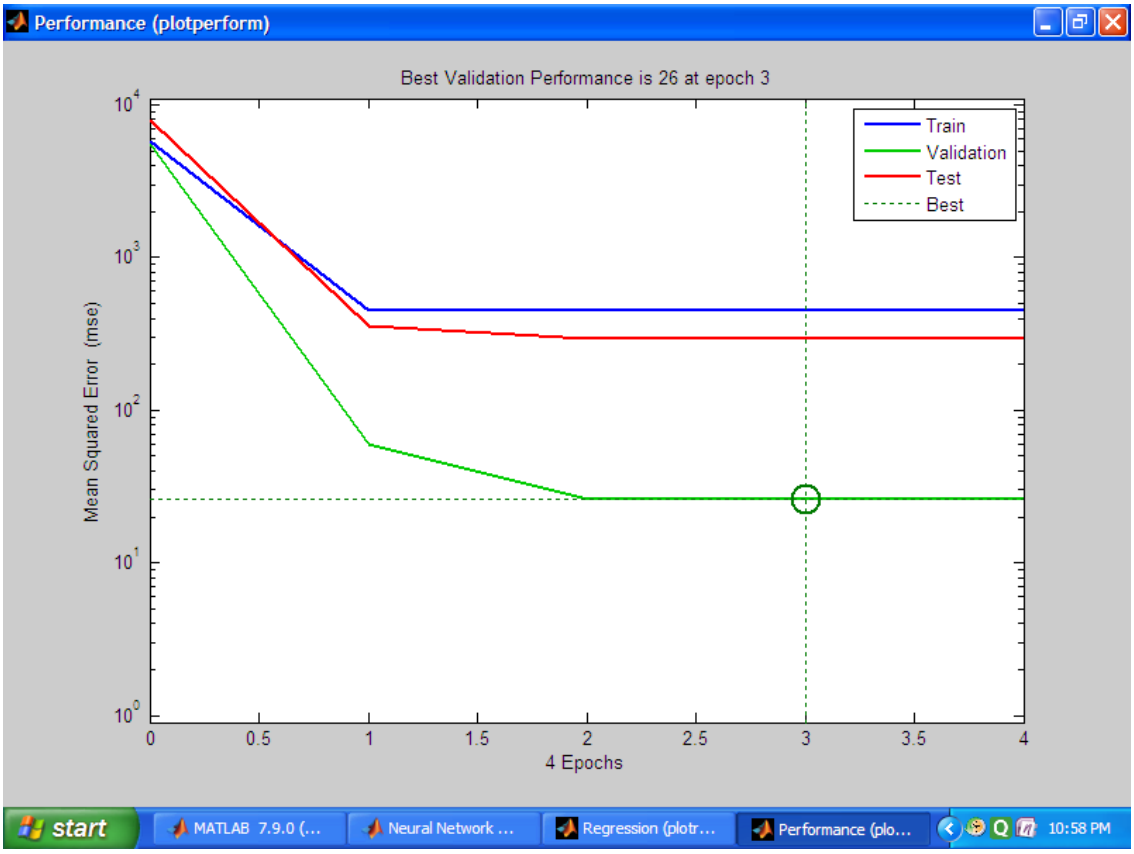


Figure 6.4 epochs vs MSE for 3-7-7-5

The figure 6.4 indicates the iteration at which the validation performance reached a minimum. The training continued for 6 more iteration before the training stopped. This figure does not indicate any major problems with the training. The validation and test curves are very similar. If the test curve had increased significantly before the validation curve increased, then it is possible that some over fitting might have occurred. The property tr.best_epoch indicates the iteration at which the validation performance reached a minimum. The next step in validating the network is to create a regression plot, which shows the relationship between the outputs of the network and the targets. If the training were perfect, the network outputs and the targets would be exactly equal.

6.4 Verification and Validation of Neural Networks

The evaluation and validation of an artificial neural network prediction model are based upon one or more selected error metrics. Generally, neural network models which perform a function approximation task will use a continuous error metric such as mean absolute error (MAE), mean squared error (MSE) or root mean squared error (RMSE). The errors will be summed over the validation set of inputs and outputs, and then normalized by the size of the validation set. the objective of a neural network model is to generalize successfully (i.e., work well on data not used in training the neural network), the True Error is statistically defined on "an asymptotically large number of new data points that converge in the limit to the actual population distribution" (Weiss and Kulikowski 1991). True Error should be distinguished from the Apparent Error, the error of the neural network when validating on the data set used to construct the model, i.e. the training set. True Error is also different from Testing Error, the error of the neural network when validating on a data set not used to construct the model, i.e. the

testing set. Since any real application can never determine True Error, it must be estimated from Apparent Error and / or Testing Error. To summarize, when facing neural network validation, the error metric(s) must be selected and the validation data set must be selected. These decisions should ideally be made prior to even training the neural network as validation issues have direct impact on the data available for the training, the number of neural networks required to be trained, and even on the training method.

6.5 Validation With Sparse Data

The two most common methods of neural network validation, are briefly described.

a. Re-substitution – It re-substitutes the data used to construct the model for estimating model error, i.e. this is the training set error. Therefore the estimate of True Error equals the Apparent Error, and Bias is assumed to equal zero. Re substitution is sometimes used in neural network validation, however it is usually noted to be biased downward (sometimes severely). It does use all of the data for both model construction and model validation, and requires only one model to be constructed.

b. Train-and-test - divide the data set into two sets. Use one set to construct the model (train the neural network) and use the other set to validate the model (test the neural network). This is the most common method of neural network validation. True Error is estimated directly as the testing set error, and Bias could be calculated by subtracting off the Apparent Error (training set error) from the testing set error. The proportion set aside for training of the available data has ranged, in practice, from 25% to 90%. The training set error (and therefore the estimate of True Error) is highly dependent on the exact sample chosen for training and the exact sample chosen for testing (which are completely dependent on each other since they are mutually exclusive). This creates a highly variable estimate of True Error, especially for small sample sizes. modification of this method is to divide the data into three sets - a training set, a first testing set used during training and a second testing set used for validating the trained network. The first testing set is used during training to decide when training should cease, that is, before over fitting take place. The second testing set is used to estimate the True Error of the trained network. This method may result in a better generalizing final network, but the available data sample is divided three ways instead of two ways, decreasing the number of data points used for model construction. For both versions of train-and-test, only one model is constructed, but both training and testing are done on a subset of the available data.

6.6 Analysis of Residuals

The residual, or error, for pattern p is simply the target minus the network output:

$$r_p = - o_p - t_p$$

There are three primary discoveries to be made from residual plots. These are discussed in turn. The first phenomenon to look for on a residual plot is bias. Bias is a systematic distribution of the residuals. In neural networks, bias often takes the form of undershoot or overshoot. Undershoot is where the network model does not reach the upper and lower extremes of the target data. Overshoot is the opposite phenomenon. Undershoot is a more frequently11found bias, especially for networks using the popular sigmoid transfer function, and can often be remedied by retraining the network on an expanded normalization range.

The second phenomenon which can be easily recognized using residual plots is relative magnitude of individual errors. This was discussed in the earlier section where the squared error term (RMSE or MSE) was more favorable to many small errors than to a few large errors. The application will dictate which kinds of errors are permissible, but the modeler will want to check on distribution of the errors. Sometimes, a well performing network will produce a few large errors (clear misses) for outlying data points. These outliers can be further investigated for correctness and appropriateness to the model.

The third aspect of residual analysis is related to the second. Residual plots of the testing and training sets must be compared. While it is expected that the overall magnitude of the error for the training set will be as low or somewhat lower than that of the testing set, both distributions should behave similarly. Significantly different residual distributions of training and testing errors can indicate bias in either or both of the data sets (i.e., the sets are inherently different from each other), or too small of a sample in one or both sets. Also, a large increase of magnitude of error from the training set to the testing set can be indicative of overtraining, i.e. memorization of the training set with poor generalization ability. Many remedies have been published addressing overtraining (also called over fitting). These include reducing the network size, pruning trained connections with small weights, and ceasing training before the test set error significantly degrades.

Plot Fitting

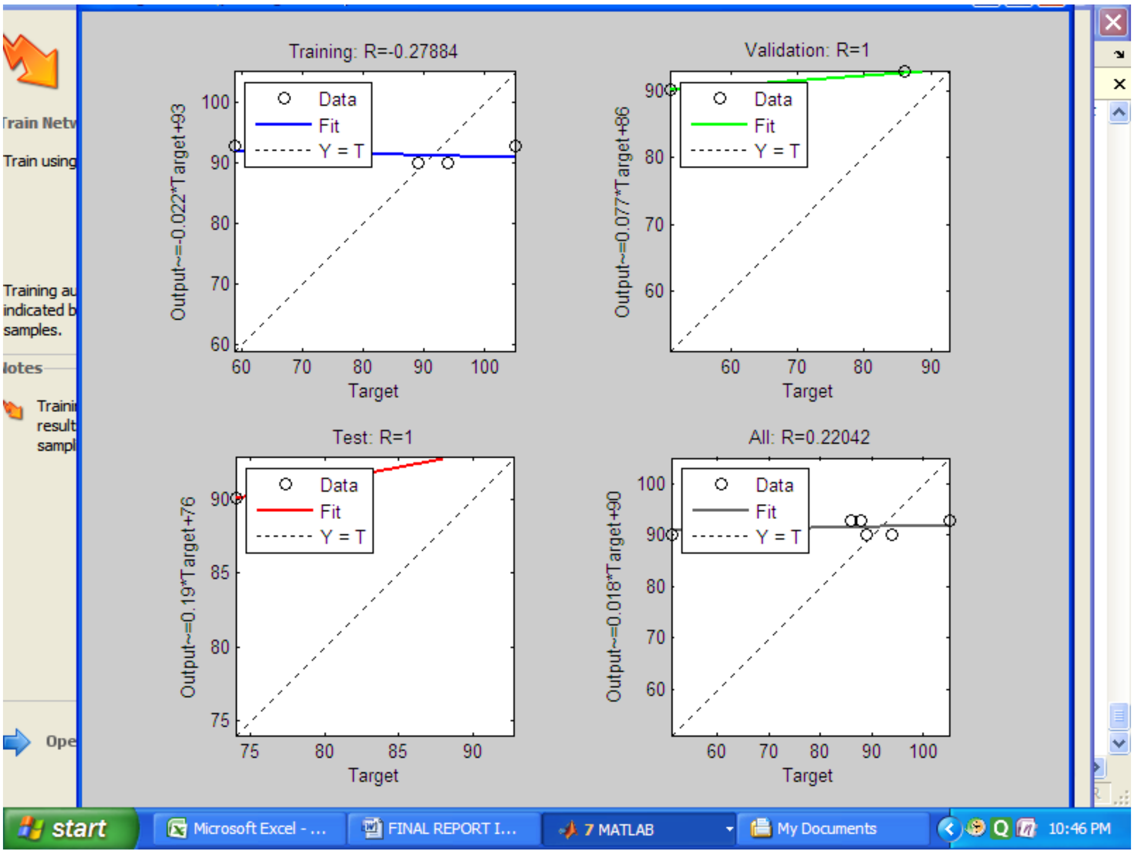


Figure 6.5 fit plot

The three plots represent the training, validation, and testing data. The dashed line in each plot represents the perfect result – outputs = targets. The solid line represents the best fit linear regression line between outputs and targets. The R value is an indication of the relationship between the outputs and targets. If R = 1, this indicates that there is an exact linear relationship between outputs and targets. If R is close to zero, then there is no linear relationship between outputs and targets. For this example, the training data indicates a good fit. The validation and test results also show R values that greater than 0.9. The scatter plot is helpful in showing that certain data points have poor fits. For example, there is a data point in the test set whose network output is close to 35, while the corresponding target value is about 12. The next step would be to investigate this data point to determine if it represents extrapolation (i.e., is it outside of the training data set). If so, then it should be included in the training set, and additional data should be collected to be used in the test set.

6.7. Conclusions

Because neural networks are purely empirical models, validation is critical to operational success. Most real world engineering applications require getting maximal use of a limited data set. Careful selection of an error metric(s) will ensure that the error being minimized is in fact the one most applicable to classification or approximation problem at hand. The trained network must be examined for signs of bias, even if error tolerances are met. Identification of bias will alert the user so that the network can be modified, or its outputs altered to reflect the known bias. Residuals of the training and testing sets can warn the user of the phenomena of overtraining and over fitting. When using an interpretive schedule because of discrete target outputs, care must be taken to ensure the proper balance of Type I and Type II errors.

CHAPTER 7

METALLURGY OF FSW

7.1 Weld Metallurgy

7.1.1 Introduction

The welding metallurgy may be defined as the changes that occur in metals as a result of being joined by the welding process. These changes are manifested by changes in mechanical properties. Physical properties generally result in distortion and the heat transfer rates of the base material. The time and temperature are the two main factors that affect the metallurgical changes. The time the material is at an elevated temperature and the rate at which the heat energy is applied to the base material are important considerations in welding metallurgy.

7.1.2 Microstructure Of Aluminium Alloy 1100

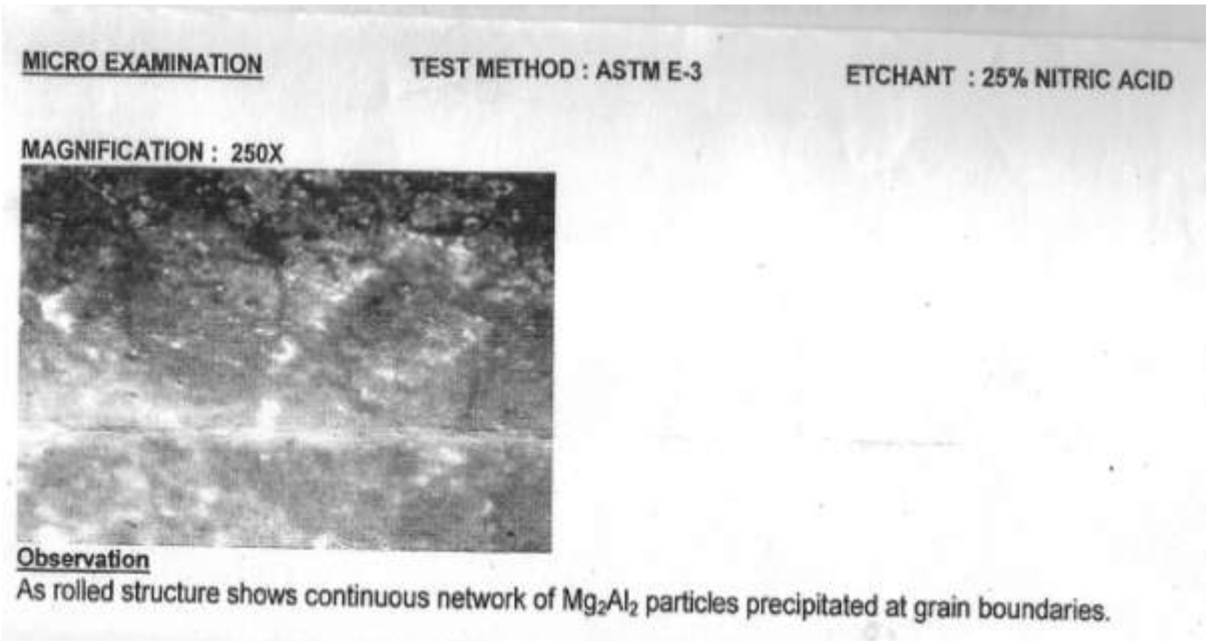


Figure 7.1 microstructure of AA1100

Evolution of fine equiaxed grains from an initial coarser grain structure was observed in the volume of Al alloy .

7.1.3 ZONES IN A FS WELD

Unaffected Material or Parent Metal

This is material remote from the weld, which has been deformed, and which although it may have experienced a thermal cycle form the weld is not affected by the heat in terms of microstructure or mechanical properties

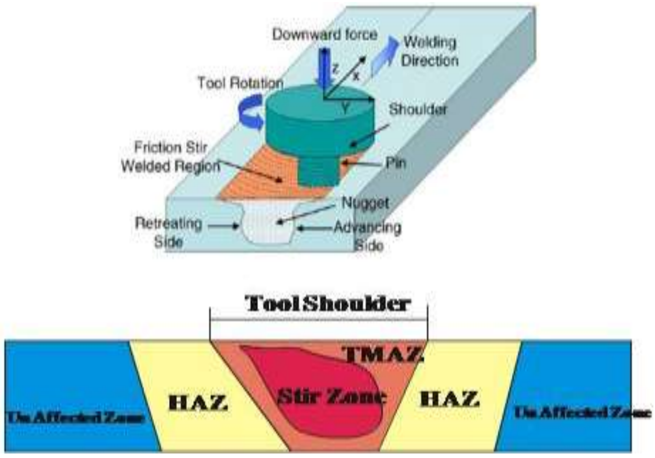


Figure 7.2 Zones in FS Weld (Courtesy of www.google.co.in)

Heat Affected Zone (HAZ)

In this region, which clearly will lie closer to the weld centre, the material has experienced a thermal cycle which has modified the microstructure and the mechanical properties. However, there is no plastic deformation occurring in this area. In the previous system, this was referred to as the "thermally affected zone". The term heat affected zone is now preferred, as this is a direct parallel with the heat affected zone in other thermal processes, and there is little justification for a separate name.

Thermo Mechanically Affected Zone (TMAZ)

In this region, the material has been plastically deformed by the friction stir welding tool, and the heat form the process will also have exerted some influence on the material. In the case of aluminium, it is people to get significant plastic strain without recrystallization in this region, and there is generally a distinct boundary between the recrystallized zone and the deformed zones of the TMAZ

Weld Nugget

The recrystallized area in the TMAZ in aluminium alloys has traditionally been called the nugget. Although this term is descriptive, it is not very scientific. However, is use has become widespread, and as there is no word which is equally simple with greater scientific merit, this term has been adopted. A schematic diagram is shown in the above Figure 3.3.2 which clearly identifies the various regions. It has been suggested that the area immediately below the cool shoulder (which is clearly part of the TMAZ) should be given a separate category, as the grain structure is often different here. The microstructure here is determined by rubbing by the rear face of the shoulder, and the material may have cooled below its maximum. It is suggested that this area is treated as a separate sub-zone of the TMAZ.

7.2 HEAT INPUT TO THE WELD

In the friction stir welding (FSW) process, heat is generated by friction between the tool and the workpiece. This heat flows into the workpiece as well as the tool. The amount of heat conducted into the workpiece determines the quality of the weld, residual stress and distortion of the workpiece. The amount of the heat that flows to the tool dictates the life of the tool and the capability of the tool for the joining process. The majority of the heat generated from the friction, i.e., about 95%, is transferred into the workpiece and only 5% flows into the tool and the fraction of the rate of plastic work dissipated as heat is about 80%.

Heat flow during welding, can strongly affect phase transformations during welding and thus the resultant microstructure and properties of the weld. It is also responsible for weld residual stresses and distortion[35] . The analytical solution derived by Rosenthal.D for three-dimensional heat flow in a semi infinite work piece during welding is as follows.

$$2\pi(T - T_0)kR / Q = \exp\left[-\frac{V(R - x)}{2\alpha}\right]$$

Where T – measured temperature in ^{0} C; T_0 - initial temperature in ^{0} C ; k- thermal conductivity of aluminium alloy in J/ms K = 229 for aluminium ;R - radial distance from the origin, namely, (x^2 + y^2 + z^2)^1/2 ; x – desired distance from origin ; Q

– heat input (W)V – travel speed (mm/s); α - workpiece thermal diffusivity = 8.5 X 10^{-5} m^2 / s for aluminium

As the heat input Q and welding speed V both increase, the weld pool becomes more elongated, shifting from elliptical to teardrop shaped. Due to frictional contact with the shoulder, the surface material is hotter than the in situ material, so that the final weld microstructure is composed of bands of material with different temperature histories.

Thermal flow is determined by solving D.Rosanthal ‘s 3D equation and is tabulated as follows.

Table 7.1 heat flow calculations

Run number	Tool speed (RPM)	Weld speed (mm/min)	Toolpin Diameter (mm)	Temp At nugget (^{0}C)	Heat flow [Q] in w/cm/^{0}c In weld nugget	Temp At HAZ (^{0}C)	Heat flow [Q] in w/cm/^{0}c In HAZ of weld
1	460	24	6	55	297.48	43	178.48
2	1130	24	6	70	446.22	55	297.48
3	460	65	6	85	594.96	61	356.97
4	1130	65	6	68	426.39	60	347.06
5	460	24	8	50	247.90	42	168.57
6	1130	24	8	55	297.48	40	148.74
7	460	65	8	65	396.64	58	327.23
8	1130	65	8	108	823.03	92	664.38

7.3 MIRO STRUCTURAL ANALYSIS

As the heat input Q and welding speed V both increase, the weld pool becomes more elongated, shifting from elliptical to teardrop shaped. Due to frictional contact with the shoulder, the surface material is hotter than the in situ material, so that the final weld microstructure is composed of bands of material with different temperature histories.

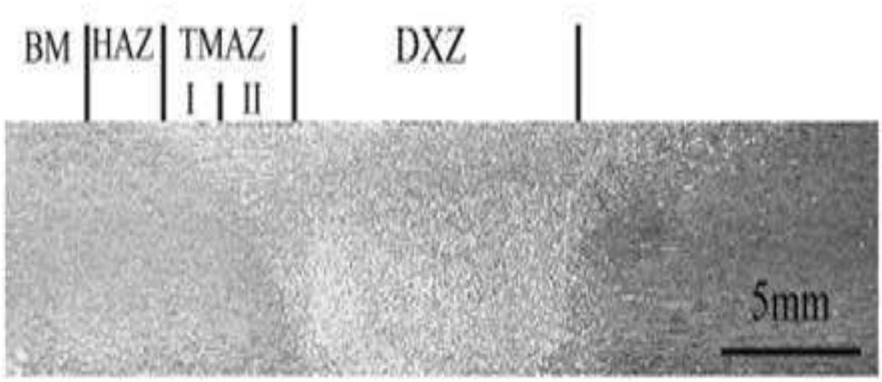


Figure 7.3 microstructure after FS welding

The micro structural study shows that the weld region is composed of unaffected base metal

And the weld nugget is characterized by a fine equiaxed grain structure. Both thermal and mechanical effect from heat generation and stirring effect engender welding characteristic in term of stresses, tensile and hardness properties. For which, the rotating tool rotational and traverse speed interchangeably influenced the temperature profile and affectively manipulate the material flow behaviour, weld material chemical composition, microstructure orientation, strain, residual stress, thermal stress, material hardness and strength of the weld ment

7.4 FLOW OF MATERIAL

Early work on the mode of material flow around the tool used inserts of a different alloy, which had a different contrast to the normal material when viewed through a microscope, in an effort to determine where material was moved as the tool passed. The data was interpreted as representing a form of in-situ extrusion where the tool, backing plate and cold base material form the “extrusion chamber” through which the hot. In this model the rotation of the tool draws little or no material around the front of the pin instead the material parts in front of the pin and passes down either side. After the material has passed the pin the side pressure exerted by the “die” forces the material back together and consolidation of the join occurs as the rear of the tool shoulder passes overhead and the large down force forges the material. More recently, an alternative theory has been advanced that advocates considerable material movement in certain locations. This theory holds that some material does rotate around the pin, for at least one rotation, and it is this material movement that produces the “onion-ring” structure in the stir zone. The researchers used a combination of thin copper strip inserts and a "frozen pin" technique, where the tool is rapidly stopped in place. They suggested that material motion occurs by two processes:

Material on the advancing front side of a weld enters into a zone that rotates and advances with the pin. This material was very highly deformed and sloughs off behind the pin to form arc-shaped features when viewed from above (i.e. down the tool axis). It was noted that the copper entered the rotational zone around the pin, where it was broken up into fragments. These fragments were only found in the arc shaped features of material behind the tool. The lighter material came from the retreating front side of the pin and was dragged around to the rear of the tool and filled in the gaps between the arcs of advancing side material. This material did not rotate around the pin and the lower level of deformation resulted in a larger grain size. The primary advantage of this explanation is that it provides a plausible explanation for the production of the onion-ring structure. The marker technique for friction stir welding provides data on the initial and final positions of the marker in the welded material. The flow of material is then reconstructed from these positions. Detailed material flow field during friction stir welding can also be calculated from theoretical considerations based on fundamental scientific principles. Material flow calculations are routinely used in numerous engineering applications. Calculation of material flow fields in friction stir welding can be undertaken both using comprehensive numerical simulations and simple but insightful analytical equations. The comprehensive models for the calculation of material flow fields also provide important information such as geometry of the stir zone and the torque on the tool.

CHAPTER 8

CONCLUSIONS AND FUTURE SCOPE

8.1 CONCLUSIONS

The following conclusions and observations were drawn from the experiment performed and the analytical model predicted.

1. Theoretical methods and empirical approach were developed based on regression analysis method and the response surface methodology(RSM).

2. The tool pin diameter has maximum effect(25.5) % on tensile strength .Tool rotational speed has 7.5 % effect and weld speed 5% effect on tensile strength . Interaction of tool rotational speed and weld speed has 19% effect on tensile strength. Interaction of tool rotational speed and tool pin diameter has negative effect (-3.5%) on tensile strength

Interaction of weld speed and tool pin diameter has 2% effect on tensile strength. Interaction of tool rotational speed ,weld speed and tool pin diameter has negative effect (-7%) on tensile strength.

3. The hardness at weld nugget is reduced due to welding .The effect of tool rotational speed, weld speed and tool pin diameter has negative effect on hardness value. The interaction effect of these parameters also produces negative effect on hardness value of aluminum alloy AA1100.

4. The tool rotational speed has positive effect(11.5%) on temperature at weld nugget. The weld speed has 24% positive effect on temperature. When weld speed is increased temperature at weld nugget is also increased. Tool pin diameter has no effect on temperature at weld nugget. Interaction effect of tool speed and weld speed is less(1.5%). Interaction effect of tool speed and pin diameter has 12.5 % positive effect on temperature. Interaction of weld speed and pin diameter has 10% positive effect on temperature. Interaction of tool speed,weld speed and pin diameter increases weld nugget temperature.

5.when tool speed ,weld speed and pin diameter increase the temperature at heat affected zone is increased. When these parameters decreased the temperature also decreased. Interaction values also prove that input parameters were directly proportional to temperature at heat affected zone.

6. Increase in tool rotation speed causes more heat input which, in turn, enlarges the TMAZ and HAZ consequently, results in low tensile strength. However, increasing the weld speed reduces the heat input resulting in smaller TMAZ and HAZ which leads to greater tensile strength.

7. The microhardness profiles (Hv) appear uniform for the plates joined using the lower rotating speed and the lower welding speed .

8.2 FUTURE SCOPE OF WORK

1. Welding of materials like Copper, Titanium, and magnesium by using friction stir welding is an area of interest.

2. Higher thickness aluminium plates can be welded by employing double sided FSW. One can try to use tools made of different materials to improve the quality of the joints.

3. Mathematical model can be developed to predict shear strength of welding.

4. Finite element analysis of friction stir welding process can be done to optimize the welding parameters.

5. Further investigations on the forces generated during single and multiple passes for different alloys at different conditions and for different process parameters might be very beneficial strength.

6. FSW process has demonstrated its capabilities and been approved as a novel method for joining aluminium and other metals. The welding process improves existing structural properties and leaves the weld “cold”. In some cases, if proper care is taken, weld properties equal those of the base material. Anyone currently working with aluminium could be using FSW. It is within everyone’s reach. It is just a question of daring to use it, eliminating the smoke and spatter typical of arc-welding

7. FSW IS the best process to weld aluminium for long lengths with an excellent quality.

8. Considerable effort is being made to weld higher temperature materials such as titanium and steels by using FSW.

9. Take the process beyond its current use of mainly simple butt and lap joint configurations and make it a much more flexible fabrication process.

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