

**Prediction, Optimization and Automatic Generation of Robotic Gas Metal
Arc Welding Process Parameters for AISI SAE 4130 Alloy Steel**



Tesfaye Negash Wordofa

**A Dissertation Submitted to the Department of Mechanical Engineering,
School of Mechanical, Chemical and Materials Engineering**

**Presented in Partial Fulfillment of the Requirement for the Degree of
Doctor of Philosophy in Mechanical Engineering (Specialization in
Manufacturing Engineering)**

**Office of Graduate Studies
Adama Science and Technology University**

June 2024
Adama, Ethiopia

**Prediction, Optimization and Automatic Generation of Robotic Gas
Metal Arc Welding Process Parameters for AISI SAE 4130 Alloy Steel**

Tesfaye Negash Wordofa

Main Supervisor: Abhay Sharma (Full Professor)

Co-Supervisor: Perumalla Janaki Ramulu (Assoc. Professor)

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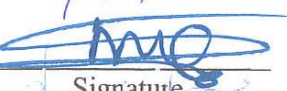
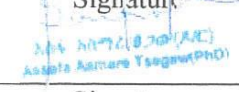
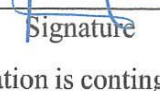
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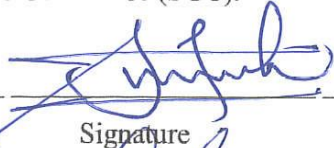
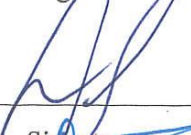
We hereby certify that the recommendations and suggestions made by the board of examiners are appropriately incorporated into the final version of the dissertation entitled **“Prediction, Optimization and Automatic Generation of Robotic Gas Metal Arc Welding Process Parameters for AISI SAE 4130 Alloy Steel”** by Mr. Tesfaye Negash Wordofa.

<u>Abhay Sharma</u>	Signature	Date
		25 July 2024
Prof. Prumalla Janaki Ramulu Major Supervisor M.Tech., PG(AI&NL), Ph.D.	Signature	Date
		30 th July 2024
Associate Professor (Manufacturing Engg.) Co-supervisor	Signature	Date

We, the undersigned, members of the board of examiners of the dissertation open defence by Mr. Tesfaye Negash have read and evaluated the dissertation entitled **“Prediction, Optimization and Automatic Generation of Robotic Gas Metal Arc Welding Process Parameters for AISI SAE 4130 Alloy Steel”** and examined the candidate during open defence. This is, therefore, to certify that the dissertation is accepted for the partial fulfillment of requirement for the Degree of Doctor of Philosophy in Mechanical Engineering (Specialization in Manufacturing Engineering).

Esmael Adem Esleman, (Ph.D) Chairperson	Signature	Date
		30/07/2024
Assistant Professor Mechanical Engineering	Signature	Date
		24/07/2024
Associate Professor Internal Examiner	Signature	Date
		24 July 2024
Assefa Asmare Tsegaw, PhD External Examiner 1	Signature	Date
		July 24, 2024
Teshome Mulatie Bogale, Ph.D. External Examiner 2	Signature	Date
		Date

Finally, approval and acceptance of the dissertation is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the candidate's Department Graduate Council (DGC) and School Graduate Committee (SGC).

Sinayehu Legesse Zeleke Mechanical Engineering Department Head	Signature	Date
		05/08/2024
Alernayehu Wakjira Huluka(PhD) School of Mechanical, Chemical & Materials Engineering Dean	Signature	Date
		05/08/2024
School Dean Legesse Lemecha Obsu (Ph.D)	Signature	Date
		06/08/24
Office of Postgraduate Studies, Dean	Signature	Date



DECLARATION

I hereby declare that this Dissertation entitled “**Prediction, Optimization and Automatic Generation of Robotic Gas Metal Arc Welding Process Parameters for AISI SAE 4130 Alloy Steel**” is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials used for this dissertation have been duly acknowledged through appropriate citations.

Tesfaye Negash Wordofa

Name of Student



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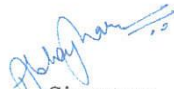
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RECOMMENDATION

We, the supervisors of this dissertation, hereby certify that we have read and revised the dissertation entitled “An Artificial Intelligence System for Prediction, Optimization and Automatic Generation of Robotic Gas Metal Arc Welding Process Parameters for *AISI SAE 4130 Alloy Steel*” prepared under our guidance by **Mr. Tesfaye Negash Wordofa** and submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy in **Mechanical Engineering** (Specialization in **Manufacturing Engineering**). Therefore, we recommend the submission of the dissertation to the department for further review and defence.

Prof. Abhay Sharma
Major Supervisor


Signature

17/04/2024

Date

Prof. Perumalla Janaki Ramulu
M.Tech., PG(AI & NL), Ph.D.
Associate Professor (Manufacturing Engg.)



Co-supervisor

Signature

12/04/2024

Date

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TABLE OF CONTENTS

CONTENTS	PAGE
ACKNOWLEDGEMENT	vi
LIST OF TABLES.....	xi
LIST OF FIGURES.....	xii
LIST OF ACRONYMS AND ABBREVIATIONS.....	xiv
ABSTRACT	xvi
1. CHAPTER ONE: INTRODUCTION.....	1
1.1 Background of the dissertation	1
1.2 Motivation for the dissertation.....	5
1.3 Problem statement.....	6
1.4 Objective of the dissertation	8
1.4.1 General objective:.....	9
1.4.2 Specific objectives:.....	9
1.5 Scope of the dissertation	9
1.6 Significance of dissertation	10
1.7 Structure of the dissertation	11
2. CHAPTER TWO: LITERATURE REVIEW	12
2.1 Introduction	12
2.2 Prediction of robotic GMAW input parameters	15
2.3 Programming and controlling of robotic GMAW process	18
2.4 Optimization of robotic GMAW input process parameters.....	21
2.5 Effect welding parameters on weld quality characteristics of steel materials ...	23
2.5.1 Effect of arc voltage	29
2.5.2 Effect of welding current.....	30
2.5.3 Effect of wire feed rate	31
2.5.4 Effect of travel speed.....	33
2.5.5 Effect of contact tip-to-work distance	35
2.5.6 Effect of shielding gas flow rate.....	36
2.5.7 Effect of electrode work angle.....	37
2.5.8 Effect of heat input	39
2.6 Summary of welding parameters impacts on weld quality characteristics.....	40
2.7 Research gap analysis.....	41
2.7.1 Prediction of optimum welding parameters	42
2.7.2 Welding robot programming and controlling.....	42
2.7.3 Input process parameter optimization.....	42
CHAPTER THREE: MATERIALS AND METHODOLOGIES.....	44

3.1 Base material and its properties.....	44
3.2 Electrode for robotic GMAW process.....	46
3.3 Input process parameters of robotic GMAW process	46
3.3.1 Identification and selection of processes parameters	46
3.3.2 Constants of welding parameters and variables	50
3.4 JMP and design of experiments	50
3.4.1 JMP	50
3.4.2 Design of experiments for robotic GMAW parameters optimization	51
3.5 Robotic GMAW process setup	54
3.5.1 Transpuls synergic 2700 CMT power sources	54
3.5.2 Welding robot system (KUKA KR 5)	55
3.6 Specimens preparation and welding test specimens.....	58
3.6.1 Test specimens preparation	58
3.6.2 Welding test specimens	59
3.7 Quality characteristics and limits for imperfection.....	60
3.8 Weld inspections, tests and examination	62
3.8.1 Joint strength tests	62
3.8.2 Throat thickness measurement	64
3.8.3 Joint penetration measurement	66
3.8.4 Microstructural analysis of welded joints.....	67
3.8.5 Extent of HAZ Measurement	70
3.8.6 Micro hardness testing.....	71
3.9 MATLAB programming.....	72
3.9.1 Fuzzy logic	72
3.9.2 Cubic spline interpolation.....	72
3.10 Optimization models and techniques.....	73
3.10.1 Constraints for bounded robotic GMAW parameter optimization	73
3.10.2 Statistical analyses.....	74
3.10.3 Mathematical model: Regression analysis	74
3.10.4 Optimization and desirability analysis	75
3.10.5 Response surface methodology	76
3.10.6 Prediction and validation of the model.....	76
CHAPTER FOUR: RESULTS AND DISCUSSION.....	77
4.1 Base material and its properties.....	77
4.2 Robotic GMAW process setup and consumables	77
4.3 Quality level-based prediction of welding parameters.....	78
4.3.1 Modeling and prediction of weld quality characteristics using fuzzy logic	78
4.3.2 Membership function and fuzzy set	79
4.3.3 Triangular-shaped membership function.....	79

4.3.4 Defining the linguistic variables and terms	80
4.3.5 Create membership function.....	81
4.3.6 Construct the rule base expert systems.....	83
4.3.7 Throat thickness.....	90
4.3.8 Joint penetration	93
4.4 Process parameter optimization for joint strength and joint penetration	97
4.4.1 Performance of the joints.....	97
4.4.2 Statistical analyses	99
4.4.3 Desirability profiling and optimization	104
4.4.4 Prediction and validation of the model.....	105
4.4.5 Response for break strength	106
4.4.6 Response for joint penetration.....	108
4.5 Optimization of welding parameters for a set of EWA.....	111
4.5.1 Joint strength	114
4.5.2 Joint penetration	115
4.5.3 Prediction formula	120
4.5.4 Efficiency checking of developed model	122
4.5.5 Validation of model	122
4.6 Automatic generation of optimal combination of welding parameters	123
4.6.1 Algorithm for optimal parameters	123
4.6.2 The interpolated optimum combination of welding parameters.....	124
4.6.3 Optimal welding parameters for different EWA	127
4.7. Mechanical and microstructural characterization influence of EWAs	132
4.7.1 Microstructure analysis	132
4.7.2 SEM fracture surface analysis	134
4.7.3. X-ray diffraction (XRD) analysis	137
4.7.4 Extent of HAZ	138
4.7.5 Micro-hardness	142
CONCLUSIONS AND RECOMMENDATIONS	146
5.1 Conclusion	146
5.1.1 Quality level-based prediction of welding parameters	146
5.1.2 Process parameter optimization on AISI SAE 4130 alloy steel	147
5.1.3 Optimization of welding parameters for a set of electrode work angles	147
5.1.4 Automatic generation of optimal combination of welding parameters	148
5.1.5 Mechanical and microstructural characterization of 4130 alloy steel	148
5.2 Recommendations.....	150
REFERENCES	151
LIST OF PUBLICATIONS	164
APPENDICES.....	165

LIST OF TABLES

TABLE	PAGE
Table 1.1 Robotic GMAW parameters, responses and optimization methods.....	14
Table 2.1 Welding process type, materials, and parameters	23
Table 3.1 Chemical composition of <i>AISI SAE</i> 4130 alloy steel wt. in (%)	44
Table 3.2 Properties of <i>AISI SAE</i> 4130 alloy steel	45
Table 3.3 Chemical composition of copper coated solid wire in wt. (%)	46
Table 3.4 Process parameters with their levels considered for Robotic GMAW.....	47
Table 3.5 Welding set parameters and description for Robotic GMAW	50
Table 3.6 Experimental design for prediction of welding parameters	52
Table 3.7 Experimental design for process parameter optimization	53
Table 3.8 Experimental design for input parameter optimization for a set of EWA.....	53
Table 3.9 Experimental design for mechanical and microstructural characterization	54
Table 3.10 Transpuls synergic 2700 CMT power source technical data.....	55
Table 3.11 KUKA KR 5 welding robot technical specification.....	57
Table 3.12 Limits for imperfections, EN ISO 5817:2014 imperfection designation	61
Table 3.13 Range of imperfections for 'D', 'C', and 'B' quality levels	61
Table 3.14 Nominal throat thickness and joint penetration for fillet welds	66
Table 3.15 Factor constraints robotic GMAW parameter optimization.....	73
Table 4.1 Rule base weight factors for fuzzy rule.....	83
Table 4.2 Fuzzy input membership functions and sets.....	85
Table 4.3 Fuzzy output membership functions and sets for quality level 'D'.....	85
Table 4.4 Fuzzy output membership functions and sets for quality level 'C'	86
Table 4.5 Fuzzy output membership functions and sets for quality level 'B'	86
Table 4.6 Predicted and experimental values for quality level D, C and B.....	89
Table 4.7 Responses of break strength and joint penetration	99
Table 4.8 Break strength parameter estimate full model.....	99
Table 4.9 New fitted model or simplified model for break strength	100
Table 4.10 Joint penetration parametric estimate	100
Table 4.11 Estimation Efficiency Summaries, Actual design and intended design	101
Table 4.12 Summary, Lack of fit.....	102
Table 4.13 Analysis of variance	103
Table 4.14 Canonical curvature.....	103
Table 4.15 Predicted optimum combinations of input parameters.....	105
Table 4.16 Responses of break strength and joint penetration	118
Table 4.17 Predicted optimum combinations of input parameters for different EWA	120
Table 4.18 Summary of fit for 35° EWA.....	122
Table 4.19 Predicted and experimental values with percentage error	123
Table 4.20 Optimized welding parameters for range of EWA.....	123
Table 4.21 Extent of HAZ measurements and micro-hardness tests results	141

LIST OF FIGURES

FIGURE	PAGE
Figure 1.1: Schematic diagram of gas metal arc welding process	2
Figure 1.2: Weld defects and imperfections	7
Figure 1.3: Welding with different torch angles.....	8
Figure 2.1: Schematic diagram of the experimental apparatus	13
Figure 3.1: Spectrometer setup for material composition test.....	44
Figure 3.2: Thickness of base metal (a) 2mm, (b) 4mm, (c) 6mm	46
Figure 3.3: Schematic representation of t-joint fillet weld.....	49
Figure 3.4: Robot welding system.....	56
Figure 3.5: 'T' joint 3D model with dimensions (mm).....	58
Figure 3.6: 'T'-joint test specimens	59
Figure 3.7: 'T'-joint welded samples	60
Figure 3.8: Weld proportions in relation to throat thickness and joint penetration.....	62
Figure 3.9: Universal testing machine for fillet weld break strength (.....	63
Figure 3.10: Fillet weld method of testing	64
Figure 3.11: Break strength testing (CVRGU, India).....	64
Figure 3.12: Schematic diagram of throat thickness	65
Figure 3.13: Fillet weld guage (ASTU, Ethiopia)	65
Figure 3.14: Schematic diagram of joint penetration.....	66
Figure 3.15: Abrasive cutting machine (ASTU, Ethiopia).....	67
Figure 3.16: Polishing machine (ASTU, Ethiopia)	67
Figure 3.17: Welded specimens for mechanical test and microstructural examination	68
Figure 3.18: Metallurgical microscope (ASTU, Ethiopia)	68
Figure 3.19: Scanning electron microscopy (ASTU, Ethiopia).....	69
Figure 3.20: X-ray diffractometer (ASTU, Ethiopia).....	69
Figure 3.21: Extent of HAZ measurement (ASTU, Ethiopia).....	70
Figure 3.22: HAZ measurement locations on VP and HP.....	70
Figure 3.23: Vickers micro-hardness tester (ASTU, Ethiopia)	71
Figure 3.24: Hardness test locations on fillet weld specimen	71
Figure 4.1: Architecture of fuzzy logic model and robotic GMAW process	78
Figure 4.2: Fuzzy logic control model for travel speed input parameters	81
Figure 4.3: Membership function for throat thickness of 4mm plate.....	82
Figure 4.4: Membership function for joint penetration of 4mm plate.....	82
Figure 4.5: Acceptable process conditions for achieving quality level 'b' for 2mm plate...	87
Figure 4.6: Welded samples for throat thickness measurement for a 4mm plate.....	90
Figure 4.7: Surface plots of process parameters' effects on TT	91
Figure 4.8: Surface plots of process parameters' effects on TT	92
Figure 4.9: Surface plot of process parameters' effects on TT	93
Figure 4.10: Welded samples for joint penetration measurement for 4mm plate	94
Figure 4.11: Surface plot of process parameters' effects on JP	95
Figure 4.12: Surface plot of process parameters' effects on JP	96

Figure 4.13: Surface plot of process parameters' effects on JP	97
Figure 4.14: Infringement phenomenon of break strength	98
Figure 4.15: Joint penetration.....	98
Figure 4.16: Effect summaries, actual by predicted plot	102
Figure 4.17: Prediction variance profile.....	102
Figure 4.18: Prediction profiler plot with max. Desirability and optimum factor settings	104
Figure 4.19: Response surface plots of process parameters' effects on break strength	107
Figure 4.20: Response surface plots of process parameters' effects on break strength	108
Figure 4.21: Response surface plots of process' parameters effects on break strength	108
Figure 4.22: Response surface plots of process parameters' effects on break strength	109
Figure 4.23: Response surface plots of process parameters' effects on break strength	110
Figure 4.24: response surface plots of process parameters effects on break strength	110
Figure 4.25: Schematic diagram of JP at different EWA with CTWD is 15mm	111
Figure 4.26: Infringement phenomenon of break strength OSTJ1	115
Figure 4.27: Joint penetration measurement of OSTJ1	116
Figure 4.28: Prediction profiler with desirability maximized at 35° EWA	119
Figure 4.29: Optimal setting of WFR at different EWA	128
Figure 4.30: The heat map of WFR and TS at different EWA.....	128
Figure 4.31: Optimal setting of TS at different EWA	129
Figure 4.32: The heat map of TS and CTWD at different EWA.....	130
Figure 4.33: Optimal setting of CTWD at different EWA	131
Figure 4.34: The heat map of WFR and CTWD at different EWA.....	131
Figure 4.35: BM optical microstructure evaluation of 4130 alloy steel at 50X	133
Figure 4.36: HAZ optical microstructure of AISI SAE 4130 alloy steel at 50X.....	133
Figure 4.37: FZ optical microstructure of AISI SAE 4130 alloy steel at 50X	134
Figure 4.38: SEM micrographs of the welded surface of AISI SAE 4130 alloy steel	136
Figure 4.39: XRD pattern of AISI SAE alloy steel	138
Figure 4.40: Maximum extents of HAZ on the vertical plate, 5X	139
Figure 4.41: The extent of HAZ on the horizontal plate, 5X	140
Figure 4.42: MTJ2: Equal extent of HAZ on vertical and horizontal plate, 5×	140
Figure 4.43: Weld macrographs in different weld zones; 20X.....	142
Figure 4.44: Micro-hardness on HAZ	143
Figure 4.45: Micro-hardness on FZ	144

LIST OF ACRONYMS AND ABBREVIATIONS

a	Nominal throat thickness of the fillet weld
AHW	Atomic hydrogen (arc) welding
AISI	American iron and steel institute
ANOVA	Analysis of variance
BS	British standard
C. Total	Corrected total
CAW	Carbon arc welding
CMT	Cold metal transfer
CTWD	Contact tip to work distance
DoF	Degree of freedom
DoE	Design of experiment
EGW	Electro gas welding
EN	European standard
ESW	Electroslag welding
EVJP	Experimental value joint penetration
EVT	Experimental value throat thickness
EWA	Electrode work angle
FCAW	Flux-cored arc welding
GMAW	Gas metal arc welding
GTAW	Gas tungsten arc welding
H	Excessive throat thickness
h	Excessive penetration
H'	Insufficient throat thickness
h'	Lack of penetration
HAZ	Heat-affected zone
HVN	Hardness Vickers number
ID	Imperfection designation
ISO	International organization for standardization
JP	Joint penetration
MIAB	Magnetically impelled arc butt welding
MTJ	Mechanical and microstructural 'T' joint
OSTJ	Optimization for a set of electrode work angle 'T' joint

OTJ	Optimization for 'T' joint
PAW	Plasma arc welding
PTJ	Prediction 'T' joint
PVJP	Predicted value joint penetration
PVTT	Predicted value throat thickness
QLJP	Quality level for joint penetration
QLTT	Quality level for throat thickness
RMSE	Square root of the mean square error
RSM	Response surface methodology
SAE	Society of automotive engineers
SAW	Submerged arc welding
SGFR	Shielding gas flow rate
SMAW	Shielded metal arc welding
SW	Stud arc welding
TJ	'T'- joint
trim	Triangular membership function
TT	Throat thickness
TV	Targeted value
UN-EXC (UE)	Unacceptable excessive
UN-INS (UI)	Unacceptable insufficient
WFR	Wire feed rate
Z	Leg length of fillet weld

LIST OF NOMENCLATURES

μ_o	Magnetic permeability of metals
f_2	Conduction zone angle (electromagnetic force)
γ	Surface tension of the liquid metals
η	GMAW process efficiency
β_0	Average response in the fractional experiment
$\beta_1, \beta_2 \dots$	Regression coefficients
E	Random error
P	Density of the drop
σ^2	Constant variance

ABSTRACT

Robot-based gas metal arc welding (GMAW) process has increased the welding process efficiency and empowered the fabrication industries with complex weld paths. The selection of process parameters and their combinations affect the weld bead geometry and mechanical properties of the materials to be welded. The selection of input parameters should be based on the weld path the robot has followed, weld quality level requirement, material type and thickness. In this dissertation work, wire feed rate (WFR), travel speed (TS), contact tip to work distance (CTWD), and electrode work angle (EWA), were considered as input parameters for a specific range to weld 'T'-joints of AISI SAE 4130 alloy steel of 2, 4 and 6mm thicknesses. A set of experiments were performed by using DoE methods. An artificial intelligence system was used for quality-level-based (B, C, and D) prediction of welding parameters and response surface methodology of the central composite design technique and mathematical models were developed. Analysis of variance and lack of fit test were verified to determine any statistically significant welding parameters. Break strength, throat thickness, joint penetration, micro-hardness test and microstructure examination were investigated and evaluated under significant welding parameters. A prediction profiler with a desirability function was used and predicted the optimal combination of welding parameters for a set of (35°, 40°, 45°, 50°, and 55°) EWA. For the remaining accessible range of EWA from 35° to 55°, the data has been auto-generated using cubic spline interpolations methods. The microstructural changes in the weld zone, the extent of HAZ in both (horizontal and vertical) plates and the variation in hardness across joints have been investigated. The optimal break strength of 67.45kN and joint penetration of 3.71mm were predicted at WFR of 8.29m/min, TS is 243mm/min, EWA is 40° and CTWD is 10mm parameters. In case of 35° EWA: WFR=9m/min, TS=358.78mm/min, and CTWD=16.22mm; 45° EWA: WFR=7m/min, TS=418.98mm/min, and CTWD=10mm; 50° EWA: WFR=7.40m/min, TS=159.26mm/min and CTWD=16.63mm; and 55° EWA: WFR=7.26m/min, TS=281.31mm/min and CTWD=14.38mm were noted as optimal welding parameters. Microstructural examination revealed that at lower WFR (3m/min) and higher TS (450 mm/min), lower heat input and a faster cooling rate were observed, resulting in a fine-grain structure in the weldments. Conversely, higher WFR (9m/min) and lower TS (150mm/min) produced more heat input and a slower cooling rate, resulting in a coarse grain structure in the weldments. The recorded average crystallite size of the base metal and fusion zone is 25.75nm and 24.5nm respectively. The greatest extent of the HAZ (956.08µm) was observed at 3m/min WFR, 150mm/min TS, 55° EWA, and 20mm CTWD on the vertical plate. Whereas, the lowest extent of HAZ on the horizontal plate was 298.99µm, at 7m/min WFR, 350mm/min TS, 35° EWA, and 15mm CTWD. The optimized and automatically generated welding parameters facilitate the automatic control system of a robotic GMAW process which will raise the programmable efficiency of the welding robot.

Keywords: Artificial intelligence system; robotic GMAW; welding parameters; AISI SAE 4130 alloy steel; quality levels; mechanical and microstructural characterization.

CHAPTER ONE: INTRODUCTION

1.1 Background of the dissertation

Welding is a multifaceted process involving diverse physical and chemical phenomena, encompassing heat flow, plasma physics, and modes of metal transfer. Welding significantly differs from other manufacturing processes due to its complicated, multi-variable, multi-outcome nature. Robotic GMAW is one of the most popular welding methods and is crucial for industrial welding for large-volume production with the paramount quality joints and complicated weld paths (Kah, P. *et al.*, 2015). In all the manufacturing sectors, more than 85% of products required welding operations for joining various materials with similar and dissimilar thicknesses (Thamilarasi, *et al.*, 2015). The fusion welding process characteristics which influence major weld joints are the heat source intensity, the heat input rate, the methods used, and the effectiveness of shielding gas to protect the weld from atmospheric contaminations (Kim, *et al.*, 2003; Amit Kumar, *et al.*, 2016; Srivastava and Garg, 2017). There are several types of fusion arc welding processes includes Laser welding, Arc welding, Induction welding, Solid reactant welding, and Oxy-fuel gas welding. Among these, the most commonly used process is arc welding which join metals with intense heat generation (Anzehaee, *et al.*, 2010; Srivastava and Garg, 2017). Under this phenomenon, there are many processes, including Stud arc welding (SW), Electroslag welding (ESW), Gas metal arc welding (GMAW), Carbon arc welding (CAW), Electro gas welding (EGW), Atomic hydrogen welding (AHW), Flux-cored arc welding (FCAW), Gas tungsten arc welding (GTAW), Magnetically impelled arc butt welding (MIAB), Plasma arc welding (PAW), Shielded metal arc welding (SMAW), and Submerged arc welding (SAW) (Messler, N.D. 2004). Many experimental research findings revealed that GMAW is the preferred joining process due to its versatility, reliability, high productivity, high efficiency, good weld quality, easy-to-realize automation, and low production cost (Kamble and Rao, 2013; Ley, *et al.*, 2015; Ghosh, *et al.*, 2017; Srivastava and Garg, 2017). Due to the versatility and advantages of this process, this has been applied to many real-time industrial applications (Pires, *et al.*, 2003; Badheka, 2013; Gupta, *et al.*, 2019; Thompson, *et al.*, 2021). Low alloy steels, high alloy steels, stainless steel, carbon steel, titanium, copper, nickel alloy, and aluminium are among the major essential metals welded by the GMAW (Kamble and Rao, 2013; Jia, *et al.*, 2014;

Chaudhari, *et al.*, 2018). The basic concept of GAMW is the melting and joining of metals by an established arc between base metals and wire electrodes as demonstrated in Fig. 1.1 (Messler, N.D. 2004; Ramos-Jaime, *et al.*, 2013; Srivastava and Garg, 2017). In this process, the continuous filler wire is drawn automatically by a wire feeder from a reel. Heat is largely focused on the welding arc from the tip of the melting electrode to liquefied weld pools (Kim, *et al.*, 2003). Molten weld puddles and filler wire were sheltered by the shielding gas (Sathiya, *et al.*, 2011).

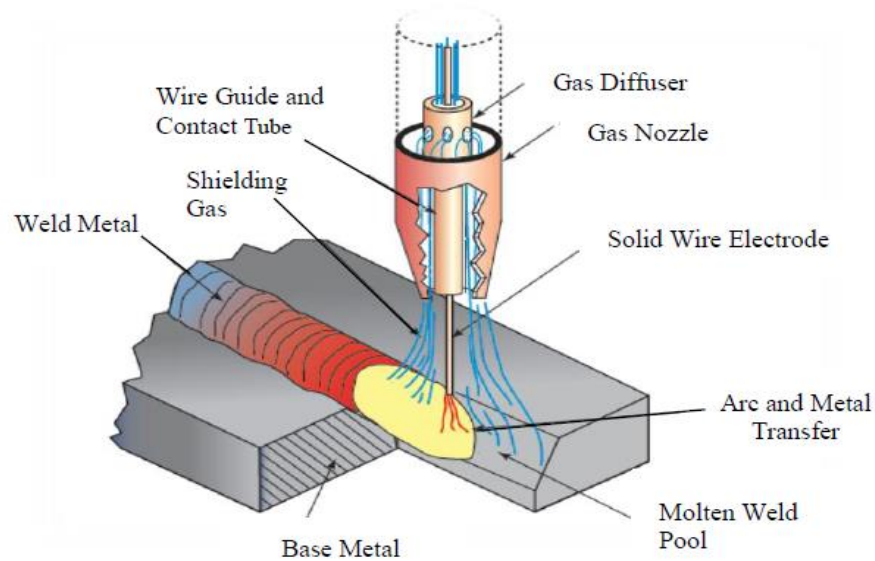


Figure 1.1: Schematic diagram of gas metal arc welding process (Messler, N.D. 2004)

The weldment quality characteristics are mainly portrayed by the heat-affected zone (HAZ), of weld bead geometry, penetration, microstructure, and mechanical properties (Kim, *et al.*, 2003; Kamble and Rao 2013; Cruz, *et al.*, 2015; Amit Kumar, *et al.*, 2016; Srivastava and Garg, 2017). In line with this, the quality level of the weld joint can be determined by surface imperfections and internal imperfections. Surface imperfections include lack of fusion, incomplete penetration, excessive convexity, excessive penetration, excessive asymmetry, excessive throat thickness, insufficient throat thickness, spatter, etc. Likewise, internal imperfections include cracks, porosity, inclusions, lack of fusions, lack of penetrations, etc. (SS-EN ISO 5817:2014 1977).

To characterize different welding input parameters and their impact on weld quality researchers have implemented several methods. These include the design of experiment methods, Taguchi

method, factorial design, regression analysis, response surface methods, mathematical equations, artificial intelligence systems, etc. (Benyounis and Olabi, 2008; Tham, *et al.*, 2012; Rahman, 2014; Srivastava and Garg, 2017). Welding input parameters and their level (the process parameters' working capabilities) are selected based on different conditions and procedures including types of material, the function of the welded part, the strength requirement, etc. (Kamble and Rao, 2013). GMAW input process parameters are the most significant factors that influence the methods by which the electrode is transferred to a parental metal, weld bead geometry, cost of welding, and quality of weld (Ghosh, *et al.*, 2017; Gothi and Ramavat, 2017; Lermen, *et al.*, 2018). GMAW is a comprehensive and multi-parameter mechanism wherein quality is paramount of welds affected by which input parameters are not known (Drosos and Kotsakis, 2014; Adak, *et al.*, 2015). The most significant task in this process are the selection of proper welding input parameters (Kamble and Rao, 2013). So, Srivastava and Garg, (2017) advised that intensive investigation of several GMAW input process parameters is required to characterize the weld quality and their interdependence.

This robotic GMAW process has versatility and flexibility in the choice of process variables based on the type of joint, and materials (Srinivasulu, *et al.*, 2022). By adopting this process, the improvement in productivity, weld quality, programmability, flexibility, workspace utilization, operational safety, and labor cost reductions (Kah, P. *et al.*, 2015). The weld quality is represented in terms of joint strength, penetration, weld bead geometry, heat-affected zone (HAZ), microstructures, mechanical properties, distortion of the welded joint, and deposition efficiency (Cruz, *et al.*, 2015). Welded joint quality is decided based on the characterization phenomenon irrespective of the welding process. The depth of penetration, heat-affected zone, bead height, and bead width were incorporated as performance evaluation attributes along with input process parameters (Cheng, *et al.*, 2021). Thus, weld quality refers to the level of acceptability or reliability of a welded joint in terms of its structural integrity, performance, and ability to meet the requirements of its intended application. Several factors contribute to weld quality, including strength and durability, absence of defects, proper fusion, correct weld size and shape, good penetration, uniformity, minimal distortion, residual stresses, and surface finish. Among these factors, weld geometry, i.e., correct weld size and shape, and good penetration matter the most as they can't be altered. Proper weld bead geometry ensures strength and

durability, while minimal distortion and residual stresses, along with surface finish, can be addressed by post-processing or heat treatment. For instance, EN ISO 5817:2014 is an international standard that specifies quality levels for imperfections in fusion-welded joints in all types of steel. This standard provides criteria for assessing the quality of welds based on the amount and size of imperfections. It defines different quality levels (referred to as "categories") ranging from "A" to "D", with "A" being the highest quality level and "D" representing the lowest. Each category has specific acceptance criteria for imperfections like cracks, porosity, incomplete fusion, etc. Category A has very stringent requirements, typically used for critical applications where weld quality is paramount, such as in pressure vessels for nuclear applications. Category B has stringent requirements for applications where a high level of weld quality is necessary, such as in aerospace or certain types of structural steelwork. Category C has standard requirements typically used for general applications in industries like construction, where welds need to meet established quality standards. Category D represents basic requirements. This category allows for higher imperfections and is often used for non-critical applications where appearance and cosmetic imperfections are less important.

GMAW input process parameters affect the mode of metal transfer, weld bead geometry, overall weld quality, and cost of welding (Kamble and Rao, 2013; Ghosh, *et al.*, 2017; Lermen, *et al.*, 2018). There are controllable and uncontrollable parameters that affect the welding quality characteristics. Ghazvinloo and Shadfar, (2010) concluded that with a 99% confidence level, good tensile values and strong welds were achieved using optimum welding parameters. Hammersberg, (2013) indicated that determining the weld geometry, the torch angle, and plate position was the most influential parameter than the productivity parameters (voltage, current, and welding speed). Among all the welding factors, an electrode-to-work angle (welding torch angle) is the main factor that has to be controlled for quality weldment (Hammersberg, 2013). Srivastava and Garg, (2017) conclude that optimization of process parameters is very costly and time-consuming due to several constraints and complexity of process parameters. These parameters should be selected judiciously to reach the desired quality dictated by the area of applications of the weldment (Joshi, *et al.*, 2014; Gyasi, *et al.*, 2017).

Prediction of the optimum combination of welding parameters is important to reduce the cost of welding. Currently, there are various artificial intelligence (AI) systems and data modelling tools accessible for estimating the optimum combination of process parameters to achieve the desired level of quality outcomes in different manufacturing processes. These AI systems are based on fuzzy logic, neural-fuzzy networks, genetic algorithms, artificial neural networks (ANN), swarm particle optimization (SPO), etc. To improve weld quality and productivity with high precision, many industries integrate automated welding processes. Automation of a welding process is essential to establish the relationship between process parameters and weld quality characteristics.

1.2 Motivation for the dissertation

The joining process is one of the pillar methods of the manufacturing process among all joining methods robotic GMAW is the key processes for joining ferrous and non-ferrous materials with multiple parameters and variables. Optimization process parameters, process control, and producing the product as its requirement in different quality levels are the aspiration of the industries to produce their products. Especially, A steel materials which achieving a wide range of applications with their superior properties. In focus their strength-to-weight ratio, claims and challenges noted in welding of such steels are the grounds for selecting *AISI SAE 4130* alloy steel.

Further motivation for the dissertation is provided by:

- The motivation here is to add scientific literature by providing the impact of input parameters on weld quality characteristics, insights into input parameters prediction and optimization of the robotic GMAW Process.
- The research gap in the scientific literature on the effects of torch orientation on weld quality characteristics and difficulties to established the optimum combination of welding parameters for a set of electrode work angles.
- The current time essentiality of application of artificial intelligence methods for welding process monitoring, controlling, and enhancing the desired weld quality levels is the research area that significantly contributes to quality and productivity in the robotic GMAW process.

- The quality characteristics of weld such as joint strength, weld bead geometry, throat thickness, joint penetration, the extent of HAZ, microstructure and mechanical properties of the weldment for a set of electrode work angles, etc. need to be more exploration in research work.
- Investigating the optimal process conditions and the optimum combination of welding parameters to get the desired quality characteristics of the robotic GMAW process has been essential.
- Automatic generation of optimum combination of welding order and parameters sets from experimental results and extract relevant geometric, material, and production information for robotic GMAW process still needs more research work and investigation.
- The influences of EWA on mechanical and microstructural behavior of ‘T’ welded joints do not investigated and documented extensively.

1.3 Problem statement

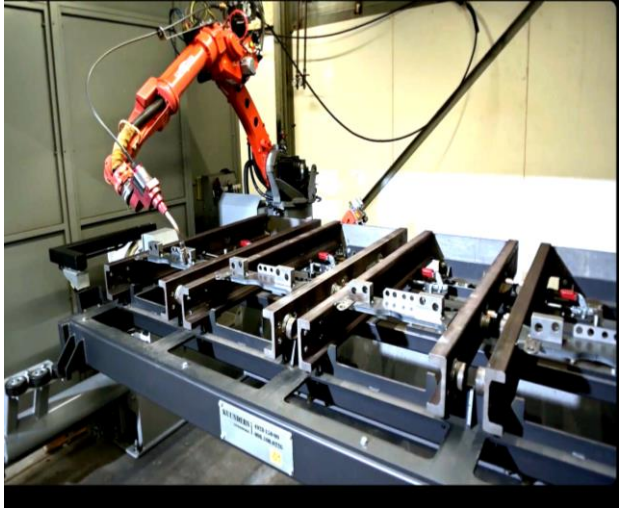
Robotic GMAW used to join similar and dissimilar metals in the industry; including automotive industries, aerospace and aircraft construction, fabrication of pressure vessels and steel structures, shipbuilding, manufacturing plants, mechanical industries, construction industries, railroads, etc. The quality and productivity of this process are significantly affecting the profitability of the industry. To increase the quality and productivity of the fabrication of metal parts and assembly of different metallic structures, the robotic welding process is paramount. In this process input process parameters optimization, robot programming, and prediction of welding parameters are challenges in industry. During the internship and fieldwork had visited different industries including; Mesfin Industrial Engineering, the Bishoftu automotive industry, the Addis machine building industry, the armament manufacturing industry, the steel and metal fabrication factory in Ethiopia and the Van Hool vehicle industry in Belgium. In Mesfin Industrial Engineering, Ethiopia, had been observed and identified as a lack of weld quality including; lack of fusion, insufficient weld bead, excessive weld bead, improper weld geometry, and excessive spatters are some of the weld imperfections that have been observed (Fig. 1.2). In addition to this, the large-size vehicle structure has been welded by semi-automatic GMAW process that is difficult to control some welding parameters which contribute to produce

defective weld components. In the Van Hool automotive industry, Belgium, the welding is performed with fully automatic process; in this automatic process automatic generation of input parameters and realization of optimum combination of welding parameters for a set of torch angles (other than 45°) are challenging tasks; taking into account in practical aspects, the possibility of using the same welding torch angle can be prohibited in the process, and a change of angle will be inevitable due to irregularities and extended parts in terms of part size, shape, and geometry Fig. 1.3 (a) and (b).



Figure 1.2: Weld defects and imperfections (Mesfine Industrial Engineering, Ethiopia)

The most significant challenges for producing the welded product with the desired weld quality characteristics are incorrect input parameters setting, usage of the same parameters setting for a set of torch angles, and lack of application of artificial intelligence in robotic welding systems. The goal of this research work; prediction optimum combination of welding parameters for different quality levels, input process parameters optimization and automatic generation of the optimum combination of welding parameters for all accessible torch angles to reduce the defective part to be produced and enhancing the programmability of robot welding systems.



(a). Welding of intricate structures (<https://vimeo.com/valkwelding>)



(b). Welding of trailer chassis (www.valkwelding.com)

Figure 1.3: Welding with different torch angles

1.4 Objective of the dissertation

This dissertation focuses on providing a detailed analysis input parameters optimization, prediction and programming of the robotic GMAW process and the impact of input parameters on weld quality characteristics. Further, to explore and predict quality level-based prediction of the optimum combination of welding parameters by an artificial intelligence system. Additionally, investigation and optimization of input parameters for a set of torch angles for

aspects of *AISI SAE 4130* alloy steel through experimental study, and investigate the impact of input parameters on mechanical and microstructural characterization of 'T' welded joints at a set of electrode work angles.

1.4.1 General objective:

The main objective of this dissertation is to investigate and predict the optimal process parameters of robotic GMAW process on *AISI SAE 4130* alloy steel and optimize the input parameters for different quality levels.

1.4.2 Specific objectives:

Based on the general objective, the specific objective are articulated to;-

1. Examine major problems and prospects of optimization, prediction, and programming of input parameters for the robotic GMAW process.
2. Explore the impacts of GMAW input process parameters on weld quality characteristics.
3. Develop an artificial intelligent system to predict welding parameters for the range of different quality levels, such as quality levels 'D', 'C', and 'B'.
4. Analyze the optimum combination of welding input process parameters for joining of *AISI SAE 4130* alloy steel materials using response surface methodology (RSM).
5. Identify the optimal level of welding parameters such as wire feed rate, travel speed, and contact tip to work distance for a set of torch angles (35°, 40°, 45°, 50° and 55°) concerning the weld path the robot has been followed.
6. Generate an optimum combination of welding parameters for all reachable (35° to 55°) electrode work angles.
7. Investigate the impact of input parameters on mechanical and microstructural characteristics in the weldment such as microstructural changes, extent of HAZ, and hardness variation across the welded structures.

1.5 Scope of the dissertation

The findings and conclusions of this work are limited to study and investigation of welding *AISI SAE 4130* alloy steel material welded by robotic GMAW process. An artificial intelligence

system for quality level-based prediction of welding parameters, investigation of optimum combination of welding parameters, automatic generation of optimal input parameters for a set of torch angles, and examination of the influence of electrode work angle on mechanical and microstructural properties on the weldment have been accomplished. However, the conclusions presented in this work provide a basis for the investigation of different welding processes, and types/sizes of materials and indicate the possibility.

1.6 Significance of dissertation

The research identified a novel method for improving the efficiency of robotic GMAW by incorporating varying quality levels (B, C, and D). The finding creates a wide range of opportunities for the manufacturing industry to produce their products at different quality levels. This contribution propagates the field of robotic GMAW process by providing a new approach to enhancing the quality and productivity of the manufacturing industry with potential applications in automotive industries, shipbuilding, railroads, manufacturing plants, mechanical industries, construction industries, aerospace and aircraft construction, fabrication of pressure vessels and steel structures. Those industries stand to benefit from welded products of high integrity and provide explicit information to support companies to produce products on the desired quality levels aspects, since to generate and predict the optimum combination of welding parameters by cubic spline interpolation methods and outlay artificial intelligence capabilities. Meeting these demands would bring greater value to welded products. Moreover, companies having fully integrated automated intelligent systems, optimized production and improved productivity with shorter lead time would maintain a high level of competitiveness. In general, this research work provides research outputs on optimization, prediction, programming and generation of input process parameters for the robotic GMAW process. These will yield reductions in parameter setting time, welding time, defect rates, and improvements in welding quality and productivity. In addition to this, it shows the existing challenges and future research areas in the robotic GMAW process.

1.7 Structure of the dissertation

The dissertation consists of a total of five chapters, the explanation of all chapters has been considered in the following sections.

Chapter one, Provides the background of the dissertation, research contributions and the dissertation layout and subchapters including motivation for the dissertation, problem statement, objectives of the dissertation, scope of the dissertation and significance of the dissertation have been presented.

Chapter two, Describes the state-of-the-art, theoretical and conceptual framework of the robotic GMAW process including brief reviews of scientific facts of optimization, prediction and programming of input parameters for the robotic GMAW process. The research gap and challenges have been identified and the review of previous work in the publications is included as part of this dissertation.

Chapter three, Covers the details of the materials, methodologies, research tools and equipment used in the dissertation. The mechanical and chemical properties of the base metal and consumables. As well as welding input parameters and quality level of the ‘T’ joint, features of the welding and testing setups, design of experiment methods, and welding procedures have been considered in the empirical and experimental investigation presented. In addition, material preparation before and after the welding and testing have been described.

Chapter four, Accumulated Knowledge, investigates experimental tests and numerical simulations that have been performed to predict welding parameters based on weld quality levels, optimization of process parameters including for different electrode work angles, automatically generate optimal welding parameters for all accessible EWA and investigation of the influence of electrode work angles on mechanical and microstructural characterization have been presented and discussed in particulars.

Chapter five, Presents the contribution to knowledge, investigation, and concluding remarks of the dissertation, summarizing the results of the theoretical findings and experimental work. Furthermore, briefly suggestions and recommendations for future research areas and possible research direction have been presented.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

The ever-increasing demand for higher product quality at lower cost combined with shorter delivery time forces the manufacturing industry to look for improved and innovative manufacturing processes and technologies. In line with this, the processes of assembly and joining of materials correspond to the lion's share of the manufacturing industry even though the customary process of joining is time-consuming and requires skilled workers. This is reported by the AWS as “Welding process is an important part of everyday life. From pipe channels to highways, automobiles to high-rise buildings, aero-planes to space rockets, none of it would be possible without a welding process (Kah, et al., 2015). According to McQuaid, by the year 2025, the U.S. will be challenged with a deficiency of greater than 400,000 welding specialists.

According to Kah, *et al.*, (2015) a “welder deficit” is surely not a new idea, that amount seems to have developed considerably over the earlier few years as worries about the skills gap rise with newer generations entering the labor force and mature, more skillful age groups retiring. Welding costs signify a great contribution to the U.S. economy. Welding process-related manufacturing and fabrication costs (all non-capital expenses) were \$30.7 billion in 2000. This signified an average of 1.4% of the corresponding total expenses in these manufacturing industries.

The GMAW process is either a conventional or automated process used for joining similar and dissimilar materials. The joining has been made by applying heat or pressure or a combination of both on faying surfaces. The basic idea of the robotic GMAW process is the melting and joining of various metals by an established arc among parent metals and electrode wires (Messler, N.D. 2004; Ramos-Jaime, *et al.*, 2013; Srivastava and Garg, 2017). At the current time, various joining processes have been developed to join most of the known engineering materials. The processes need constant upgrading and parameter optimization to enhance weldment joints for high structural integrity and efficiency. The robotic GMAW process consists of a robot controller, visual sensor, robot, welding power source, gas source, workbench, wire feeding

motor drive, welding equipment, and computer controller as demonstrated in Fig. 2.1 (Xu, *et al.*, 2014).

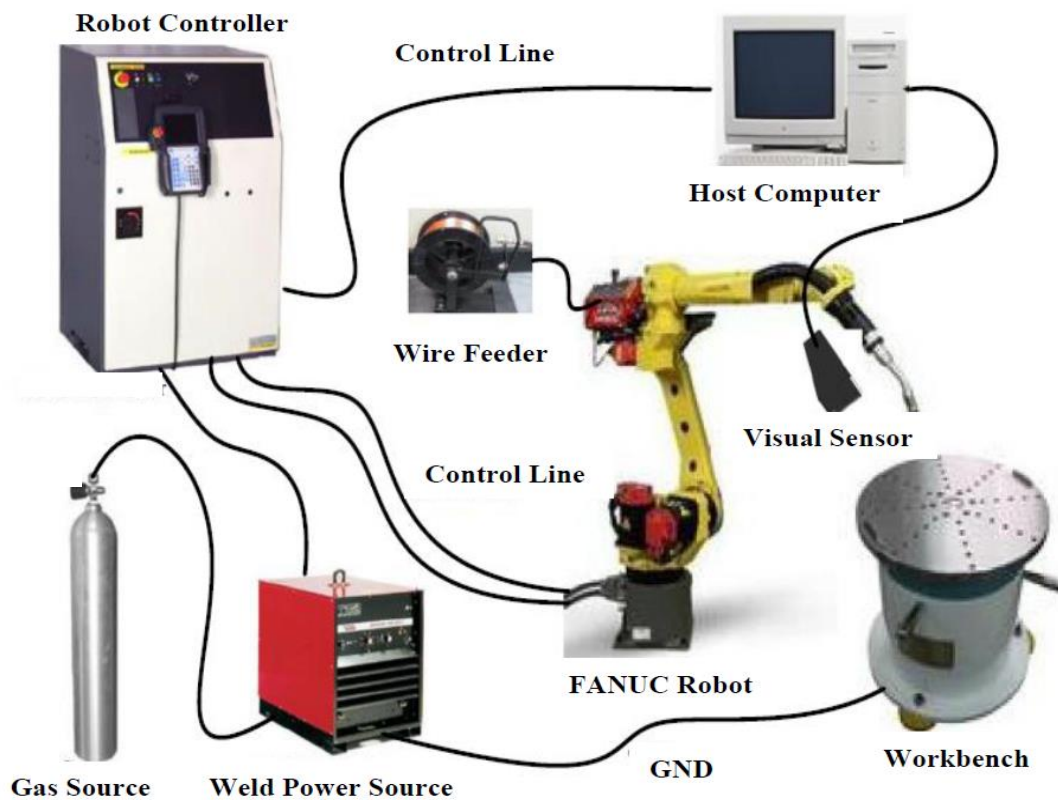


Figure 2.1: Schematic diagram of the experimental apparatus (Xu, et al., 2014)

In the robotic GMAW, the researchers attempted to address the major problems, prospects, optimization process parameters, prediction optimal process parameters, and programming robotic GMAW. The exploited Robotic GMAW process parameters, responses, and optimization methods and techniques are presented in Table 2.1.

Table 1.1 Robotic GMAW parameters, responses and optimization methods

Welding Parameters and Variables	Welding Responses and Quality characteristics	Optimization Methods and Techniques
Arc voltage	Joint strength	Artificial intelligence system
Welding current	Joint penetration	Design of experiment
Travel speed	Tensile strength	Taguchi method
Wire feed rate	Shear strength	Multiple regression analysis
Electrode to work angle	Bend test	Fuzzy method
Travel angle	Fracture tests	Factorial design
Contact tip-to-work distance	Notch toughness tests	Greedy search techniques
Wire diameter	Hardness tests	Mathematical models
Electrode composition	Nick break test	Regression equations
Arc length	Fillet weld break test	Response surface methodology
Heat input	Depth of penetration	Gaussian process regression
Type of shielding gas	Insufficient throat thickness	Hybrid optimization
Gas flow rate	Excessive throat thickness	Neuro-fuzzy interface system
Modes of metal transfer	Excess penetration	Seam tracking technique
Electrode sickout	Lack of fusion	Machine learning models
Nozzle-to-plate distance	Lack of side wall fusion	Deep learning model
Welding position	Porosity/gas pore	A simulated annealing algorithm
Joint geometry	Excessive asymmetry	Soft computing tools
Root opening	Percentage dilution	Multilayer perceptron architecture
Welding current	Heat affected zone	Genetic algorithm
Welding polarity	Fatigue strength	Motion planning algorithms
Welding technique	Impact test	Image capturing, seam tracking and image processing
Material thickness	Microstructure	
	Macrostructure	Vision-based seam tracking system

2.2 Prediction of robotic GMAW input parameters

Kim, S. and Yarlagadda, (2003) presented an algorithm through neural network and regression methods to create a mathematical model for predicting top-bead width and identified that there are several problems and difficulties related to the robotic GMAW process including the detecting/sensing, modeling, and process control. Tham, *et al.*, (2012) predicted the GMAW in the 3F position of 'T' joint fillet weld bead geometry and their parameters, welded by OTC DAIHEN, DP-400 P30026 model robotic GMAW welder and having 6mm thick carbon steel plates, welding gun positioned at 45° from the base metal and 15° from the horizon, pointing weld current: 100-250A, arc voltage: 18-30V, weld speed: 15- 72cm/min, wire extension: 13mm have been used for investigation and prediction of throat thickness, leg length, and bead width. The accuracy of prediction has been gauged by the Mean Absolute Deviation (MAD) and recorded less than 1.0mm; these results validated the reliability and accuracy of the predictions. Butdee and Thanomsin, (2019) have modeled a robotic GMAW process using fuzzy logic to predict the depth of penetration for the weldment of oil pipelines. The main parameters are voltage, welding current, electrode work angle, travel speed, weld rod type, clearance gap, and material property. The output penetration depends on travel speed, welding current, electrode work angle, and clearance priority, besides explained that fuzzy results give good results for effective decision-making to identify optimum input process parameters.

Gyasi, *et al.*, (2017) developed a model of an artificial intelligence system to predict structural integrity in robotic GMAW of UHSS S960QC fillet welded joints, that noted nonlinear variables related to the GMAW process, such as heat input, torch angle, and contact tip to work distance and their associated factors, which pose weldability challenges, and conclude AI systems such as artificial neural networks, neural-fuzzy networks, fuzzy logic systems, genetic algorithms, adaptive neuro-fuzzy inference systems, and swam particle optimization systems, which are mathematically based, can be used as data modeling tools to forecast the desired weld quality characteristics. Kim, S. *et al.*, (2014) predicted the GMA welding characteristics by the ANN system for the prediction of the Mahalanobis Distance (MD) as a quality factor in the GMAW process; this system had been examined in Multilayer Perceptron (MLP) architecture and obtained the optimal result. For the validation of the model welded a steel plate BV-AH32 with

12mm thickness by automated GMAW setup, their investigation has seen a low error value (about 0.008) reflecting the good accuracy of the model. Likewise, the comparison of the test data set and predicted results by ANN indicated a very good promise that discloses the predictive power of the model. Shim, *et al.*, (2018) investigated the effect of arc voltage, welding current, travel speed, electrode-to-work angle, and contact tip-to-work distance on weld bead reinforcement area for automated GMAW processes using a central composite design and generated RSM and ANN models. They suggested that among ANOVA, RSM, and ANN, ANN was the best tool for the prediction of input process parameters. Sudhakaran *et al.*, (2019) predicted an angular distortion of the weldment welded by the GTAW process of 202-grade stainless steel plates using an ANN. The selected welding parameters were current, travel speed, torch angle, gas flow rate, and plate thickness, as chosen as a response of data for angular distortion to evaluate the input process parameters and concluded that ANN has been an effective tool for the prediction angular distortion of the weldment. Hu, Z. *et al.*, (2020) predicted input process parameters for arbitrary layer height in robotic wire and arc additive manufacturing. By applying the full factorial experimental design matrix and forward artificial neural network (FANN) was built to predict the bead geometry. Then, the genetic algorithm (GA) was combined with a closed-loop iteration method and the FANN model (FANN-GA) was established to hunt for the maximum optimal input process parameters, In agreement with the chosen bead geometrical factors. The outcomes showed that the FANN-GA model has a good performance on the backward forecasting of the input parameters. Rout, et al., (2020) proposed fuzzy-regression-particle swarm optimization to forecast weld quality in terms of the strength of the welded joints and depth of penetration. The predicted weld quality characteristics or the multi-performance characteristic index values with combined weld strength and weld bead geometry were found to be highly associated with the weld input process factors.

Devaraj, *et al.*, (2021) developed prediction models and parametric optimization by using grey-based Taguchi optimization approaches for the input process (current, wire feed speed, travel speed, and contact tip to work distance for prediction of dilution and bead geometry by using machine learning models like adaptive neuro-fuzzy interface system (ANFIS) and ANN, the optimal formation of input parameters for ideal results was I4F1S4Z3, which had current 90A, wire feed speed 3.1m/min, travel speed 420mm/min, and CTWD of 3mm, as the recorded

experimental result the performance of the welding process to a noticeable extent for example, 5.7% was attained for dilution and bead width enhanced by 12.7%. The results illustrated that the ANFIS logic generated a slightly better prediction than the ANN for bead width and depth of penetration. ANN model provided better prediction for reinforcement and dilution, whereas both ANFIS and ANN achieved much better regression analysis outside the range of the initial experimental design.

Nomura, *et al.*, (2021) predicted and estimated the burn-through and depth of penetration by deep learning model to control the molten weld pool in the GMAW process with gap fluctuation. Devendran and Ashoka (2021) automated the GMAW process with the 'Robot Arc mate 100iC/12' robot using fuzzy system of triangular membership function and trapezoidal membership function, gas flow level (10 and 15l/min), wire feed speed (4, 4.5 and 5mmmin⁻¹), travel speed (25, 35 and 45cmmin⁻¹) and welding current (120, 130 and 140A) has been used as input parameters to predict weldment quality characteristics such as impact strength, hardness, and ultimate tensile strength. The verified prediction performance has indicated a lesser average error rate recorded in all three factors, such as impact strength has 1.08%, hardness has 0.83, and UTS has 0.56%, this shows that a fuzzy system gives reliable prediction of input process parameters as well.

Rao, *et al.*, (2022) investigated additive manufacturing of mild steel to study the influence of wire feed rate, travel speed, and torch angle on the weld bead geometry, including bead width, bead height, and depth of penetration. Weld bead geometry was predicted through developed ANN and validated the optimum input parameters to enhance the quality characteristics of weld bead geometry. The optimal working conditions of wire feed speed of 6 m/min, travel speed of 0.4m/min, and torch angle of 60° were collected; under the optimal employed conditions, the recorded amount of width, height, and depth of the weld bead 7.615, 3.910, and 2.000mm respectively. The validated and comparison result showed that simulation and an experimental result discovered good agreements; and confirmed that ANN-based technique can predict the targeted quality requirement in a shorter time with fewer steps and support to improve the dimensional accuracy of parts that have been fabricated by additive manufacturing.

2.3 Programming and controlling of robotic GMAW process

In the welding process automated robot welding system plays a substantial contribution in the manufacturing industry which can generate robot programs directly from computer-aided design and online programming when the robot is in an operational mode. These lead to diminished production costs, increase the desired product quality characteristics, and improve the productivity of the process in the manufacturing industry (Norberto, *et al.*, 2016). In addition to this due to access programming offline it provides advantages like capability to generate complex paths, reusable generated code, flexibility for modification and reduction in production downtime for setup of a new part. Nevertheless, some problems have been faced like the complexity of the process, programming environments, limited remote facilities, and restricted software interfaces, and development software for offline programming requires high-level programming skills and time-consuming which are the main difficulties and challenges in the process (Norberto, *et al.*, 2016).

The practice of the manual online software design process needs no special hardware or software on-site other than used for the production process. The major limitation of online programming is; only capable of controlling simple robot paths and a quite inflexible process and discontinuities in production when the programming stage (Pan, *et al.*, 2012). Pires, *et al.*, (2004) studied automatic robot welding programming from a CAD interface and recommended a solution able to extract robot motion data from CAD files. The solution was proven by extracting welding definitions from the CAD data for linear welding on a piece for the construction industry. The study permits a great decrease in the programming process just by taking out welding information from CAD files and permitting the fastest preprogram that is very easy to adjust and simulate.

Ferreira, *et al.*, (2017) proposed a hyper-flexible welding robotic cell with 9 degrees of freedom that permits the automation of welding processes through CAD. The vision system detects the part and the operator parameterizes the seams that have to be welded. Then, the trajectory and robot program are automatically generated. Siminski, (2016) studied the effects of weld path design of rapid prototyping and wear replacement by GMAW hypothetically. In that adoption

hypothesis, geometric improvement and thermal stability happened by considering the heat input and optimized material by controlling the welding route. Zhang, *et al.*, (2011) showed that robot automatic path planning in multi-pass weaving is a vital technology to recognize automatic robot welding for thick materials. A user self-define mathematic model of path layout and developed an offline teach module based on the graph operators can design pass numbers, layer numbers, and input parameters of multi-pass processes based on the welding technology. Path factors such as attitude, position, weaving amplitude of weld torch, and so on can be extracted automatically. Larkin, *et al.*, (2016) developed an automated offline programming system for a steel manufacturing company detailed the motion planning algorithms, and employed greedy search techniques to decompose the welding route motion planning problem into consecutive sub-problems. The results showed that these programming approaches are effective for the robot welding process and reduce programming effort without cost.

Xu, *et al.*, (2014) presented real-time image processing for vision-based weld seam tracking in the robotic GMAW process investigate an automatic identification and localization of welding seams for robotic GMAW using a computer vision system; real-time image processing has certain challenges like reflections, scratches, textureless images, poor contrast, and imperfections on the surface of the welded materials. Results showed that the image processing precision range can be controlled to be within $\pm 0.3\text{mm}$, which can achieve the condition of real-time seam tracking. The image treating is critical and mainly consists of the design of the vision sensor, image capturing, image selecting, and image processing algorithm, power supply of welding, and an industrial personal computer (Xu, *et al.*, 2014; Xu, *et al.*, 2017).

Dinham and Fang, (2013) developed an advanced autonomous fillet welded joint identification method for the robotic GMAW process. The methods presented a new line-growing technique for adaptively sensing welding seams. The adaptive line growing method can detect the welding joint successfully based on the confidence that the weld joint is darker than the surface of the welded metal on either side of the seams. In general, the mean position error is within 1.3pixels with the resulting localization errors within $\pm 1\text{mm}$ which are acceptable in most industrial robotic GMAW applications. The investigational results showed that this method can automatically recognize the weld seams for distinctive fillet seam formations for mild steel and

aluminum with painted scratched and rusted surfaces. Xu, *et al.*, (2017) developed a vision-based robotic GMAW seam tracking system and proved through experimental work, by analyzing the features of robotic GMAW. The developed software included the image capturing, image processing, robot communication, welding expert database, welding power control, intelligence parameters setting, and path planning modules. The results verified welding seam tracking system was accurate for most robotic GMAW applications.

Kuss, *et al.*, (2017) developed a novel ontological representation of continuous-path industrial robotic welding tasks. The developed model recognized the part feature automatically and generate manufacturing task descriptions for the robotic GMAW process. He, *et al.*, (2016) studied effective potential methods to autonomously extract the weld joint profile and edges from the molten background from robotic MAG welding. Pan, *et al.*, (2012) presented an automated offline programming (AOLP) approach for a robotic welding process with a high degree of freedom. The offered methods automatically plan and program for a robotic welding process take the CAD model as input, and extract the robot program without any extra programming effort.

Rios-Cabrera, *et al.*, (2016) presented an experimental analysis of parameters, using well-defined statistical patterns applied to the key welding input parameters; online/off-line training and testing techniques confirmed that welding robots acquired an important knowledge base without human interference to train and reproduce weld bead geometries; an online testing investigation including depth of penetration, that is used to learn an artificial neural network.

Larkin, *et al.*, (2018) bounded an AOLP framework and generated robot programs from CAD models with minimal human input, the main phases of this method were presented and a specific application for joining complex pipe constructions was also shown. The outcomes confirmed the feasibility of the technique to enable accurately flexible robotic welding automation. Hou, *et al.*, (2020) studied a teaching-free welding system based on a laser visual sensing system (LVSS) for robotic GMAW. To improve the calibration efficiency, a fast unified calibration technique for LVSS was projected. The results showed that the control precision on the fillet welds and V-grooves was suitable for most robotic GMAW application

Zheng, *et al.*, (2022) proposed a hybrid offline programming method combining vision-based, CAD-based, and vision & CAD interactive actions to overcome the restrictions of present automatic program generation approaches for robotic welding systems. The efficiency of the suggested hybrid offline programming system was demonstrated by integrating it into a subassembly welding robotic system. The experimental results indicated that this technique improved the accuracy, efficiency, and flexibility of the robotic welding system.

2.4 Optimization of robotic GMAW input process parameters

Welding order and input parameters optimization method is a very significant research tool that has enhanced the relationship between dependent and independent variables. Welding input parameters affect the mechanical performance, chemical compositions, and metallurgical characteristics of the weld joints. However, in full and semi-automated welding systems it is required to determine suitable welding sequences and parameter sets for the process, based on the boundary conditions of the application, while taking material composition variations, process instabilities, external environmental factors like humidity and temperature, etc. (Islam, *et al.*, 2014; Jafari, *et al.*, 2021). The weld quality and productivity mainly depend on welding input parameters (Han, *et al.*, 2019). To discover and determine the effect of each parameter and the optimum combination of input parameters to become the greatest desire and robustness of weld qualities various researchers have used different tools and methods such as design experiment method, screen design, fractional/full factorial design, Taguchi method, response surface design, artificial neural networks. Fuzzy logic, evolutionary computation, simulated annealing algorithm, particle swarm optimization, genetic algorithm, combined methods, etc. (Benyounis and Olabi, 2008; Tham, *et al.*, 2012; Rahman, 2014; Srivastava and Garg, 2017). In general, GMAW process is a multifarious process because includes numerous physical, chemical, and mechanical occurrences (Benyounis and Olabi, 2008; Ramos-Jaime, *et al.*, 2013; Rahman, 2014). Robotic GMAW is a welding process that is useful to yield strong joints and can be exploited in automation systems to improve productivity (Kim, S. *et al.*, 2004).

Kim, *et al.*, (2003) developed a mathematical model for the prediction of weld bead geometry (bead height, bead width, and depth of penetration) and selection of input process factors (arc voltage, welding current and welding speed) in the robotic GMAW process. For optimization of

process parameters, a factorial design can be employed. The relative influence of three input process factors on bead geometry is compared by conducting a sensitivity analysis to confirm the measurement errors on the values of the uncertainty in estimated factors. The result found by mathematical models shows that bead height and bead width are affected by input parameters than depth of penetration. Kolahan and Heidari, (2009) modeled and optimized the GMAW process by a set of experimental results and regression analysis. The Taguchi method and regression modeling are applied to create the relationships among input factors (wire feed speed, arc voltage, torch angle, travel speed, and nozzle-to-plate distance) and output response (bead width, bead height, and depth of penetration). According to the evaluated analysis of variance (ANOVA), the proposed model and optimization procedures are effective for the optimization of input parameters that can produce the desired bead geometry.

Guillermo, *et al.*, (2018) proposed a method to capture the welding parameters and send stimuli to a conventional GMAW process, the estimator which consents to weld bead geometry with an open-loop control was trained and validated off-line with data from a novel algorithm established to extract the features of the infrared image, to measure the bead dimensions a laser profilometer was implemented and depth of penetration measured by a longitudinal cut of the weldment followed by image processing algorithm, These estimators are optimized for embedded devices and real-time processing and were implemented on a field-programmable gate array device. The proposed system and methods are beneficial for industrial and research environments.

Ghazvinloo and Shadfar, (2010) said that there are numerous factors affect weld quality characteristics and, in their investigation, concluded that a strong weld and good tensile value can be achieved with a 99% confidence level using optimum welding parameters. The weld quality characteristics are mainly represented by joint strength, penetration, weld bead geometry, heat affected zone, microstructures, mechanical properties, welded joint distortion, and deposition efficiency (Kamble and Rao, 2013; Achebo and Odinikuku, 2015; Cruz, *et al.*, 2015; Srivastava and Garg, 2017). Sterling and Chen, (2016) made optimization for robotic GMAW process parameters by applying Gaussian process regression and Bayesian optimization algorithm methods; they derived and modeled the association between welding variables and welding quality characteristics. French, *et al.*, (2019) introduced the industrial informatics and

process monitoring by adopting the specification of welding procedure for the additive manufacturing of aero-engine components with the GMAW process. Rout, *et al.*, (2020) proposed hybrid optimization based on fuzzy-regression-particle swarm optimization (PSO) for getting maximum joint strength and depth of penetration of AISI 1030 mild steel material using robotic GMAW. Yan, *et al.*, (2016) proposed an optimization method to maximize the section area of the weld bead. A knowledge database has been used to obtain the relationship between the welding factors and bead geometry; the welding passes of a deep groove are planned using the proposed method. Kim, *et al.*, (2003) established a mathematical model using neural network, backpropagation, and multiple regression methods to predict the relationship among welding factors (welding current, welding voltage, travel speed, and pass number) and width of top-bead. The experimental data have achieved good covenant with the established mathematical model and yielded satisfactory results, it was evident that the backpropagation neural network algorithm was significantly more precise than multiple regression techniques. Ramos-Jaime, *et al.*, (2013) used a radial basis function neural network applied for the forecasting weld bead cross-sectional area by applying a three-level factorial DOE developed a mathematical models from the experimental data can be employed to study the associations between process factors and weld bead geometry to forecast the weld bead sizes within 0-20% precision. Experimental outcomes have shown that process factors such as arc voltage, wire feed rate, and welding speed influence the bead area in the GMAW processes.

2.5 Effect welding parameters on weld quality characteristics of steel materials

Among the several input variables, arc voltage, welding current, wire feed rate, travel speed, contact tip-to-work distance (CTWD), shielding gas flow rate, electrode work angle, and heat input are considered to comprehend the level of effects of each factor on weld quality characteristics of steel materials. The complete welding process, materials, and welding parameters cited from various works of literature are presented in Table 2.2.

Table 2.1 Welding process type, materials, and parameters

Authors and year	Welding process type	Materials and consumables	Welding parameters
Adak, <i>et al.</i> , 2015	Universal MIG/MAG	– Mild steel plate of 150mm×150mm×9mm	– Arc Voltage (AV):19.8 and 24V

	machine	- having 0.15% carbon - Uncoated electrode wire 1.2mm diameter. - Shielding gas mixture 70% Ar and 30% CO₂.	- Wire feed rate (WFR): 3.5 and 5.5m/min - Contact tip to work distance (CTWD): 15 and 25mm - Travel speed (TS): 250 mm/min - Angle maintained at 20°
Chaudhari, <i>et al.</i> , 2018	Autogenously mode of GMAW process.	- SS316L stainless steel plate, 100mm×50mm×6mm. - Shielding gas Ar+CO₂ - Two fluxes used Cr₂O₃ and SiO₂	- Welding current (WC): 150-180A - AV: 20-24V - TS: 150-180mm/min - Shielding gas flow rate (SGFR): 15 l/min.
Cho, <i>et al.</i> , 2019	GMAW, TPS 2700 Trans-pulse synergic welding machine.	- Mild steel SS400 - Wire filler ER70S-6 diameter 1mm. - Shielding gas Ar and 5% CO₂	- CTWD: 15mm - WFR: 7m/min - TS: 0.8m/min - SGFR: 20 l/min
Dagostini, <i>et al.</i> , 2021	Automatic GMAW system with Panasonic robotic arm TM-1400WG III	- API 5LX70M steel, size 175mm×85mm×16.5m m - Filler metal WIM 2594, electrode diameter 1.2mm. - Shielding gas Argon+20% CO₂	- AV: 18.5V - TS:: 1.23, 1.48, and 1.85 mm/s - Heat inputs: 3.0, 2.5, and 2.0kJ/mm - SGFR: 15 L/min - Welding frequency: 0.5Hz
Filho and Ferraresi, 2010	MIG/MAG welding process, and LAPROSOLD A gas mixer	- Parent metal Ferritic stainless steel bi-stabilized with niobium and titanium - Filler wire used Ferritic stainless steel ER430. Wire diameter 1.2mm. - shielding gas (pure Ar , and Ar with mixed O₂ and CO₂)	- Shielding gases (Ar; Ar + 4% O₂, Ar + 2% O₂, Ar + 8% CO₂, Ar + 4% CO₂ and Ar + 2% CO₂) - CTWD: 12, 14, 16, and 18mm - Constant AV: 20V - WFR: 5.3m/min - TS: 20cm/min - SGFR: 14l/min.
Ghosh, <i>et al.</i> , 2017	MAG welding machine, K-400MIG	- Stainless steel AISI 409 (Ferritic) of size 100×65×3mm - Austenitic electrode wire AISI 316 L. diameter of 1.2mm.	- WC (A): 100, 112, 124 - SGFR (l/min): 10, 15, 20 - Nozzle to plate distance (mm): 9, 12, 15
Gupta, <i>et al.</i> , 2013	GMAW process	stainless steel (Ferritic) plates of SS 409L	- TS: 300, 400, 500mm/min - WC: 130A

		dimensions 200×50×3mm – Austenitic stainless steel filler wire ER304L diameter 1.2mm. – Shielding gas type - pure argon	– AV: 20V – SGFR: 18l/min – Root gap of 1.2mm
Hackenhaar, <i>et al.</i> , 2018	Welding robot MA1400A composed of Fronius Trans Puls Synergic 4000R welding machine.	– AISI 1010 steel 250mm×150mm×6.35mm. – Electrode diameter 1.2mm, AWS ER70S-6 – Shielding gas mixture of Ar+25% CO ₂	– WRF: 3.5 4.5 5.5m/min – AV: 18, 20, and 22V – TS: 4.0, 5.5, 7.0mm/s – SGFR: 15l/min
Ibrahim, <i>et al.</i> , 2012	B4 welding robots, OTC ALMEGA AII	– Mild steel plate dimension of 100mm×100mm×6mm – Electrode wire 1.2mm diameter (AWS classification ER70S-6) – Shielding gas 100% CO ₂	– AV: 22, 26 and 30V – WC: 90, 150 and 210A – TS: 20, 40 and 60cm/min – Torch angle: 5° – Nozzle to work distance:12mm
Kamble and Rao, 2013	GMAW semiautomatic air cooling machine 3-phase, 50Hz, 300A.	– AISI321 stabilized austenite stainless steel plate size 150mm×120mm×10mm – AISI308 grade filler wire – Argon and oxygen mixture	– AV: 27, 28, 29, 30 and 31V – SGFR: 16–20l/min – Welding torch is fixed 90° to the workpiece – V-groove prepared at 30°
Karadeniz, <i>et al.</i> , 2007	Welding robot capacity of 0-500A and 0-50V ranges. DAIHEN, DR Series ARK ROBO 1100	– Erdemir 6842 steel specimens having 60mm×30mm×2.5mm – G3Si 1 (SG2) wire electrode of 1mm diameter – Shielding gas is 82wt% Ar+18 wt% CO ₂ mixture	– WC: 95, 105, 115A – AV: 22, 24, and 26V – TS: 40, 60 and 80cm/min – Root gap fixed as 0.8mm – Welding torch is centered
Kim, S. <i>et al.</i> , 2003	Robotic CO ₂ arc welding process	– Mild steel AS 1204 specimen dimension of 200mm×75mm×12mm – SS400 using steel wires of 1.2 diameters – Shielding gas Ar (80%)	– AV: 20, 25, 30V – TS: 250, 330, 410 mm/min – WC:180, 260, 360A

		and CO ₂ (20%) composition.	
Kumar, <i>et al.</i> , 2016	INVA MIG 400 welding machine	– AISI 1020 carbon steels specimens having 200mm×50mm×6mm – ER 70 S-6 wire electrode having 0.8mm diameter – CO₂ shielding gas used.	– AV: 26, 27 and 28V – TS: 42, 47, and 52cm/min – WC: 160, 170, and 180A
Lee and Rhee, 2000	Welding robot system	– Base metal mild steel with 90mm×100mm×60mm – Wire diameter is 1.2mm. – Shielding gas 100% CO₂	– SGFR: 15l/min – CTWD: 15mm
Lee, <i>et al.</i> , 2018	Robot gas metal arc welding	– SGAPH590 and SGAPH440 steel material of 2.3mm and 2.0mm×80mm×140mm – Filler wire ER70S-3 1.2mm diameter. – Shield gas Ar+10%CO₂	– WC: 170 and 200A – Travel angle 0, 17.5 and 35° – SGFR: 20l/min
Lermen, <i>et al.</i> , 2018	Robot gas metal arc welding process	– High strength steel, LNE 700 size 50mm×100mm×4.5mm. – wire diameter of 1mm OK Aristorod TM 79 – Shielding gas mixture argon (82%) and CO₂ (18%).	– AV: 23.5, 26.5 and 30V – TS: 8.3, 9.2 and 10mm/s – WFR: 12.6, 14.2 and 16m/min
Ley, <i>et al.</i> , 2015	Automatic welding process	– DH36 steel plate dimension 150mm×500mm×8mm, – Filler wire 1.2mm diameter Nittetsu SF-1A. – Shielding gas two supplies premixed Ar+20% CO₂ and pure He.	– Gas delivery methods – Ar/CO₂ constant – He constant – Ar/CO₂/He (Alternating at 2, 4, 6, 8 Hz). – SGFR: 5, 10, 15l/min – TS: 3.2mm/s – Constant standoff distance 10mm – WC: 210A – AV:24.7V
Park, <i>et al.</i> , 2020	Pulsed GMAW process, trans-pulse synergic mode, TPS	– Mild steel SS400 10-mm-thick specimen. – Wire ER70S-6, 1mm diameter	– TS: 18 and 33cm/min – WFR: 7m/min – SGFR: 20l/min

	2700 welding machine.	– Shielding gas Ar+5% CO₂	– CTWD: 17mm – Root gap size 0, 1 and 2mm – Average WC: 159A – Average AV: 20V
Pérez Pozo, <i>et al.</i> , 2015	A KUKA KR 125/2 robot arm, incorporates an ESS welding machine	– AISI-SAE 1020 structural Steel 300mm×50mm×5mm. – Filler material diameter 1.2mm, AWS: ER-70S-6/ER-48S-6. – Shielding gas mixture of Ar and 20% CO₂	– AV: 65, 70 and 85V – TS: 15m/min – WFR: 4m/min – SGFR: 16l/min – Swinging length 2mm
Ramos-Jaime, <i>et al.</i> , 2013	Robot gas metal arc welding	– Base material Steel 1018 (4,3/4" × 1,1/2" × 1/2") – Electrode Steel LS-69 (0.035") – Shielding gas 99.999 %Ar.	– WFR: 6.35, 7.62, 8.89 m/min – AV: 23, 25, 27V – TS: 0.007, 0.009, 0.011m/s – Gas pressure 40 PSI – Torch angle 90°
Rizvi and Tewari, 2017	GMAW process	– Structural steel plates IS 2062 size of 300mm×120mm×10mm – ER 70S6 filler metal – Shielding gas Ar+25% CO₂	– AV: 25, 26 and 27V – WC: 198, 200, 206, 208, 220, and 230A – SGFR: 10, 15 and 20l/min
Saha, <i>et al.</i> , 2019	GMAW process	– Low alloy steel, E350 – Wire electrode austenite stainless steel (316) – Shielding gas 100% CO₂	– WC: 120, 140, 150, 160, 170, 180, 190, 200 and 220A – AV: 22, 23, 24, 25, 26, 27, 28, 29, and 30V – TS: 360, 420, and 690mm/min – Heat input: 0.35, 0.43, 0.48, 0.49, 0.54, 0.60, 0.61, 0.66, and 0.75kJ/mm – SGFR: 16l/min
Sathiya, <i>et al.</i> , 2011	GMAW process	– Super austenitic stainless AISI 904L size 100mm×40mm× 5mm. – Filler wire 1.20mm diameter. – Shielding gas type is Argon	– AV: 28, 30, and 32V – TS: 90, 100, and 110mm/min – WFR: 1.5, 1.75, and 2.0m/min – SGFR: 12, 14, 16l/min – Nozzle to electrode tip distance is kept as 15mm
Sathiya, <i>et</i>	GMAW process	– Super austenitic	– AV: 28-32V

al., 2013		stainless steel 904L size 100mm× 40mm× 5mm – Electrode wire 1.2mm diameter. – Shielding gas - Ar	– WFR: 1.5-2m/min – TS: 90-110mm/min – SGFR: 12-16l/min
Sen, <i>et al.</i> , 2015	GMAW process with double pulsed (DP-GMAW).	– Mild steel plate 0.15% carbon, size 150mm×150mm×9mm – ER80S-G, uncoated welding wire of diameter 1.2mm. – Shielding gas mixture 92% Ar+8% CO ₂	– WC: 220, 240, 260, 280, and 300A – AV: 20, 23, 26, 29 and 32V – Thermal pulse frequency: 0.4, 0.6, 0.8, 1.0 and 1.2Hz – Pulse frequency: 70, 120, 170, 220 and 270Hz – CTWD: 18mm – TS: 400mm/min
Singh, <i>et al.</i> , 2020	GMAW setup FRONIUS TPS 3200 and The travel speed are controlled by mechanized trolley.	– Base material AISI 201LN 150mm×130mm×3mm – Shielding gas mixture of 98% Ar+2% CO ₂	– WC: 145, 176, 176A – AV: 17, 17, 18V – TS: 250, 280, 250mm/min – Heat input: 0.59, 0.64, 0.76kJ/mm – SGFR: 18l/min – Root gap: 2mm
Srivastava and Garg, 2017	GMAW process with automatic operation	– IS 2062 mild steel plate of 100mm×50mm×6mm – Electrode copper coated mild steel wire, diameter 1.2mm – Shielding gas CO ₂	– AV: 24, 28, and 32V – TS: 160, 190, and 220mm/min – SGFR: 10, 14 and 18l/min – WFR: 4.5, 7, and 9.5m/min – Torch position-inclined – WC: 150-250A
Tagimalek, <i>et al.</i> , 2017	Nanoparticles - Electrode gas metal arc welding devices including FP4M machine and MIG 501 wire feed system.	– Heat resistance steel (SUH 310S) dimensions 10mm×30mm×50mm. – Filler wire diameter of 1mm, AWS/ASME ER 309. – Shielding gas CO ₂	– AV: 17 – 32V – WFR: 210 – 253cm/min – TS: 200 - 400mm/min
Tham, <i>et al.</i> , 2012	GMAW process with OTC DAIHEN, DP-400 P30026 articulated robotic arc welder and jig	– Carbon steel plates 6mm thick , – Filler wire ER70S-6, 1.2mm diameter – Shielding gas CO ₂	– WC: 100 -250A – AV: 18–30V – TS: 15-72cm/min. – SGFR: 15l/min – Constant wire extension: 13mm – Welding torch inclined from

	for downhill welding position.		the plate: 45° – and from horizon: 15°
Thompson Martinez, <i>et al.</i> , 2021	Gas metal arc welding process	– Steel 1020 dimension 6.35mm×300mm×40m m. – Wire electrode 1.2mm of diameter – Shielding gas 96% Ar and 4% CO2	– WFR: 4.8, 5.5, 6.5, 7.5 and 8.2m/min – AV: 17, 20, 24.5, 29 and 32V – TS: 6.6, 8, 10, 12 and 13.4mm/s

2.5.1 Effect of arc voltage

Arc voltage is an amount of electric potential that exists on a small gap between the metal to be welded and the end of the electrode which causes an electric discharge across the gap. The voltage drops within the electrode extension beyond the contact tip are included (Dean, 2003). Arc voltage is a major input parameter directly proportional to the arc length and is used in order to create a stable arc Phillips, David H. Welding engineering: an introduction (David H. Phillips, 2015). Various studies revealed that arc voltage is one of the critical variables in arc welding process control (Dean, 2003; Fernando, *et al.*, 2015). The arc voltage is determined mostly through arc length, which would be determined through the electrode diameter (Kamble and Rao, 2013). Depending on the process inclination, an excessively high arc voltage leads to arc instability, spatter, undercut, porosity, erosion, and sprinkling depending on the inclination of the process (Pires, *et al.*, 2003; Fernando, *et al.*, 2015). There are some quality characteristics affected by the arc voltage. These are: -

Penetration: Arc voltage has a remarkable influence on monitoring the arc force which controls the primary depth of penetration. The greater arc force at higher arc voltage pushes the melted metal toward the bottom of the weld pool and raises the primary penetration region to a certain level (Adak, *et al.*, 2015). The arc voltage impacts the arc pressure/force that in turn influences the penetration depth. When arc voltage increases, the melting of the parent metal and weld penetration increases (Badheka, 2013; Kamble and Rao, 2013). However, arc voltage influences the depth of penetration not much as welding current influence (Karadeniz, *et al.*, 2007; Gothi and Ramavat, 2017). The influence of arc voltage was less sensitive to penetration than to other bead shape parameters (Kim, *et al.*, 2003, Ramos-Jaime, *et al.*, 2013).

Bead height: Arc voltage is more suitable in the control of bead height. The variation of arc voltage causes big changes in bead height in the meantime the sensitivity of arc voltage on bead height is much greater than that of current and travel speed (Kim, *et al.*, 2003). Low arc voltage produces narrower beads with greater convexity (Adak, *et al.*, 2015). The relationship described by different authors entails that bead height decreases when an arc voltage increases; because the same volume of weld metal is deposited at a constant wire feed rate (Kim, *et al.*, 2003; Badheka, 2013).

Bead width: Arc voltage maintains arc dome stability and controls the arc width; rising welding voltage increased arc width, which outcomes in bead width improvement (Adak, *et al.*, 2015). Arc voltage is more suitable for controlling bead width within which variations cause large improvements. An increase in welding voltage increases arc length and the size of droplets, resulting in a flatter and wider weld bead (Kim, *et al.*, 2003; Pires, *et al.*, 2003; Tham, *et al.*, 2012; Badheka, 2013; Kamble and Rao, 2013; Gupta, *et al.*, 2019).

Heat-affected zone: HAZ is a non-melted zone of parent material and achieves different metallurgical properties other than the base materials. Arc voltage is crucial in boosting HAZ because it can produce more heat input and a compressive weld pool (Tagimalek, *et al.*, 2021). The influence of arc voltage was observed in HAZ due to the variation in the material morphology; as the arc voltage increases, the HAZ width increases (Adak, *et al.*, 2015; Lermen, *et al.*, 2018).

2.5.2 Effect of welding current

Welding current plays a main role in arc heating and key operating parameter for monitoring the melting quantity. High-level current results in more heat input at the electrode, melting the filler wire nearer and transferring more amount of heat to the workpiece to generate a bigger weld pool (David H. Phillips, 2015). Welding current has a robust positive direct relationship and is the first and most significant effect among all bead geometry characteristics since that gets to decide the wire feed rate, heat input of welding, melted base metal, weld fusion area, and amount of deposited metal (Lee and Rhee, 2000; Dean, 2003; Sathiya, *et al.*, 2013). Ghosh, *et al.*, (2017) studied the percentage of elongation and the maximization of ultimate tensile strength obtained

in the optimal parametric condition (the current is 124A, the gas flow rate is 10l/min, and the nozzle-to-plate distance is 9mm). It was found that welding current has a more influential parameter than gas flow rate followed by the nozzle-to-workpiece distance. The quality characteristics are mainly affected by the welding current explained in the following section.

Penetration: An increase in the level of welding current raises the depth of penetration. Thus, if the current is too high, there will be a larger amount of heat generated resulting in excessive deep penetration that can potentially waste filler metal and cause burn-through and undercut. When using too low a welding current for a given electrode yields poor penetration (Lee and Rhee, 2000; Ibrahim, *et al.*, 2012; Badheka, 2013; Gothi and Ramavat, 2017). Karadeniz, *et al.*, (2007) studied Erdemir 6842 steel sheets using 2.5mm thickness and a filler wire was a G3Si 1 (SG2) electrode with a diameter of 1mm, and the outcomes showed that perhaps the depth of penetration raises linearly with a rising welding current between 95A and 115A, with the average depth of penetration continuing to increase to 0.0225mm for a 1A rise in welding current. The influence of current on penetration is nearly 2.5 times higher than that of welding speed and arc voltage. The average arcing current has a robust effect on the amount of depth of penetration (Dean, 2003).

Bead height: Bead height is one of the characteristics of quality weld affected by current. Bead height increase with an increase in mean current at fixed thermal pulse frequency (Sen, 2015).

Bead width: The width of the welded bead depends upon welding processing variables including welding current, arc voltage, travel speed, electrode size, gas flow rate, contact tip to workpiece distance, etc. With increasing welding current, the width of the weld bead grows (Sen, 2015; Gupta, *et al.*, 2019).

2.5.3 Effect of wire feed rate

Wire feed rate refers to the rate at which filler wire is fed through into the weld joint, which has a major effect on the amount of current and weld penetration. The convexity index is affected by the wire feed rate; a positive rate of the wire feed coefficient has a positive impact on the convexity index (Adak, *et al.*, 2015). An excessive increase in wire feed rate results in an excess

of filler metal, which causes improper adherence to the weld zone and an increase in heat input due to a larger number of short circuits formed at the same time (Fernando, *et al.*, 2015). Srivastava and Garg, (2017) optimized welding parameters (wire feed rate 4.5m/min, arc voltage 32V, gas flow rate 10.3lpm, travel speed 160mm/min) to obtain 0.891mm bead height, 7.53mm bead width, and 4.02mm depth of penetration. As the results of an investigation, the significance of input process parameters to weld bead determination is wire feed rate followed by voltage and travel speed. The major impacts of wire feed rate on weld quality characteristics are discussed in the following section.

Penetration: Wire feed rate affects the extent of depth of penetration considerably. The deposition rate was effectively stated as a role of numerous parameters and mostly determined by wire feed rate (Adak, *et al.*, 2015). Increasing the rate of wire feed deposits more molten metal and increases the depth of penetration (Badheka, 2013; Kamble and Rao, 2013; Ramos-Jaime, *et al.*, 2013). A higher feed rate increases the amount of heat input in the weld pool zone which in turn results in an increased depth of penetration (Sathiya, *et al.*, 2013).

Bead height: the rate of wire feed is one of the key input parameters that affect bead height too. The wire feed rate plays a critical role in predicting weld area, accounting for 33.48% of the variation within linear a model, Even though welding wire acts as filler metal, rates of wire feed are positively found to correlate to bead height and a higher wire feeding rate results more welding filler materials per second (Ramos-Jaime, *et al.*, 2013).

Bead width: According to Kamble and Rao, (2013) enhancing the rate of wire feed results in a rise in bead width because of a rise in the amount of material deposited inside the weld joint. An increase in the rate of wire feed leads to a rise in joining temperature, and liquefying a large amount of filler wire to the weld pool leads to a rise in bead width (Fernando, *et al.*, 2015). The relationship among the rates of wire feed and bead width is not statistically significant, but the result is a positive correlation (Ramos-Jaime, *et al.*, 2013).

Heat affected zone: An increase in the level of wire feed rate results in a more comprehensive weld pool and heat transfer within the weld zone, which results in coarser grains (Tagimalek, *et al.*, 2021). When a welding speed of 10mm/s, an arc voltage of 23.5V, and a wire-speed rate of

12.6m/min are used for LNE 700 high-strength steel material of 4.5mm thickness and 1mm diameter filler metals, the smallest (22mm²) HAZ is obtained (Lermen, *et al.*, 2018). Due to the diminishing effect on the width of HAZ, the width of HAZ is stated as a function of the wire feed rate (Adak, *et al.*, 2015).

2.5.4 Effect of travel speed

The distance travelled demonstrates the length of time that weld materials are deposited from arc initiation to termination. The linear rate that an arc travels along the weld joint is defined as the speed of travel (Labesh kumar, *et al.*, 2017). It plays a significant role in the quantity of heat generated into the welded joint per unit length of the weld. The travel speed is among the most challenging variable to anticipate inside the weld-making procedure (Lee and Rhee, 2000), and it has a significant effect on the quantity of heat generated in the joint per unit length of the weld (Phillips, 2016). Excessive travel speed leads to a shortage of filler metal accumulation at the parent metal (lower metal deposit in the bead), resulting in inadequate welding beads. Also, because the arc exerts its effects on the parent metal, the quantity of thermal energy transmitted from the arc to the parent metal reduces as travel speed increases (Pires, *et al.*, 2003, Fernando, *et al.*, 2015).

Amit Kumar, *et al.*, (2016) studied the effect of welding variables and parameters on bead width and height, weld penetration, and HAZ. The optimal bead width of 6.42mm, bead height of 1.78mm, welds penetration of 2.92mm, and HAZ 5.26mm was obtained in the setting of welding parameters current 170A, arc voltage 27V, and welding speed of 52cm/min, the percentage contributions of welding speed, voltage, and welding current on weld bead geometry were 90.08%, 4.55%, and 0.66% respectively. The speed of travel along the weld joint impacts the bead shape, depth of fusion, heat input, and weld bead appearance, all of which impact the microstructure of the weldment (Kim, *et al.*, 2003; Ramos-Jaime, *et al.*, 2013; Gupta, *et al.*, 2019). Weld quality characteristics that are affected by travel speed are incorporated in the following section.

Penetration: Weld bead penetration decreases when the welding speed increases due to decreases the time it takes the arc force to penetrate the surface of the parent material including

the volume of material deposited decreases (Kim, *et al.*, 2003; Kamble and Rao, 2013; Ramos-Jaime, *et al.*, 2013; Gyasi, *et al.*, 2017; Gupta, *et al.*, 2019). Besides that, when the travel speed is reduced, the concentration of heat input rises, resulting in greater penetration (Sathiya, *et al.*, 2011). When traveling at a high speed, the arc forces, arc heat, and droplet impingement are not concentrating on the molten weld pool; the downward molten pool is smaller, the downward flow pattern is relatively weak, and the quantity of molten weld pool that penetrates the root gap is relatively small (Park, *et al.*, 2020).

A study conducted on Erdemir 6842 steel having 2.5mm thickness using a G3Si1 wire electrode of 1mm diameter attains a relationship that conforms to an increase in the depth of penetration. In this case, the optimum values of travel speed, current, and voltage for higher possible penetration were reported as 60cm/min, 115A, and 26V respectively. Between 40 and 60cm/min, the penetration increases from 0.03 to 0.08mm. After the optimal point, the value decreased (Karadeniz, *et al.*, 2007). Again Karadeniz, *et al.*, (2007) explored and obtained the optimal weld penetration of 4.53mm with optimum combinations of welding parameters (travel speed 60cm/min, welding current 110amp, and wire diameter 1.2mm). Travel speed contributes 46.61%, welding current contributes 21.24%, and wire diameter contributes 27.25% to the depth of penetration. The results showed that travel speed has the greatest influencing factor on penetration depth.

Bead height: Travel speeds have a critical effect on bead height. The size of the weld pool and the rate of wire deposition decreases as travel speed increases, which means bead height decrease, Reduction in bead height due to the weld pool size was affected by the cooling rate (Badheka, 2013; Ramos-Jaime, *et al.*, 2013). With increased travel speed, less filler wire per unit length is deposited on the parent materials resulting in lower bead height (Kamble and Rao, 2013; Gupta, *et al.*, 2019).

Bead width: There is an inverse correlation between the speed of travel and bead width; an increase in arc-travel rate decreases the size of bead width (Badheka, 2013; Kamble and Rao, 2013; Ramos-Jaime, *et al.*, 2013). It can be observed that bead width becomes higher as travel speed decreases (Hackenhaar, *et al.*, 2018). When the travel speed increase from 5cm/min to 7cm/min bead width also increases from 7mm to 8mm, an increase in welding voltage creates a

longer arc and increases the size of droplets, which in turn, causes a wider and flatter weld bead (Tham, *et al.*, 2012).

Heat-affected zone: Lermen, *et al.*, (2018) well-defined HAZ as a function of travel speed whereby they confirmed that ‘on average the HAZ decreased when the speed of travel increases’. There are great contributions of travel speed on cooling rate and heat affected zone throughout and after welding, as the depth of penetration rises with decreasing travel speed, the cooling rate determine the final metallurgical structure of the weld zone (Gyasi, *et al.*, 2017). In agreement with all the above Tagimalek, *et al.*, (2021) underscored that ‘as travel speed increases the HAZ decreases significantly’.

2.5.5 Effect of contact tip-to-work distance

Contact tip-to-work distance (CTWD), the gap between both the end of a contact tip and the workpiece surface, is a significant welding parameter that mainly affects the amperage, arc voltage, shielding gas used as well as metal transfer mode (Filho and Ferraresi, 2010). Gyasi, *et al.*, (2017) noted that the CTWD controls the welding current as a function of the arc length, the control characteristics portrayed and finding showed that when the CTWD raises the welding current decreases, and when the CTWD decreases the welding currents increase. Hence, CTWD and the current have an inverse relationship; CTWD significantly influences the amount of arc length. Welding process stability and weld quality were sensitive to CTWD (Sterjovski, 2010). The quality characteristics of weldment affected by CTWD are included in the following section.

Penetration: The relationship between depth of penetration and CTWD is linearly proportional, penetration increases with an increase in the nozzle-to-workpiece distance (Badheka, 2013). The increase in the CTWD means an increase energized length of the electrode before the fusion of the electrode occurs, due to more resistance in the conductor (the Joule effect) (Filho and Ferraresi, 2010). However, other works of literature incorporated a finding that contradicts the above; Higher CTWD reduces the arc pressure and decreases penetration; because, when CTWD increases the length of electrode extension increases, and an increase in resistance to the flow of current consequences in a decreasing welding current resulting in arc pressure decreased (Adak, *et al.*, 2015).

Bead height: The relationship between CTWD and bead profile has been described in various works of literature. Weld bead profiles are sensitive to CTWD (Sterjovski, 2010). Greater CTWD diminishes arc pressure and increases the reinforcement height (Adak, *et al.*, 2015).

Bead width: The aspect of the association between bead width and CTWD seems to be direct proportionality. The width of the weld bead rises with the increasing CTWD (Gupta, *et al.*, 2019). Higher CTWD, on the other hand, decreases arc pressure and decreases bead width (Adak, *et al.*, 2015).

Heat-affected zone: In the steel welding processes, the HAZ region is very critical due to metallurgical and allotropic weld transformations which impact mechanical characteristics (Dagostini, *et al.*, 2021). The width of HAZ is defined in terms of CTWD, Thus, CTWD has a positive impact on the width of HAZ; higher CTWD reduces the amount of width of HAZ (Adak, *et al.*, 2015). Increasing the gap between the end of the filler wire and the parent materials can reduce the heat-affected zone (Tagimalek, *et al.*, 2021).

2.5.6 Effect of shielding gas flow rate

The flow rate of shielding gas is one of the welding input variables that affect the geometry/profile of the weld bead for the reason that the gas flow pressure allows the distribution or well spreading of molten materials (Fernando, *et al.*, 2015). The value of hardness increases as the rate of gas flow increases because of the high velocity of its arc created (melted more filler metal) and fill groove of weld bead (Kamble and Rao, 2013). Microhardness values change throughout the weld bead varying by shielding gas flow rate (Rizvi and Tewari, 2017). Uncontrolled shielded of the weld pool and arc occurred due to an excessive gas flow rate that causes turbulence (Gothi and Ramavat, 2017). The right flow rate of shielding gas is important such as offering appropriate safeguards to it the welding region throughout the stages of heat generation, liquidation, and solidification. A too-low gas flow rate will result in porosity and excess spatter development due to the insufficient shield of the arc area. In contrast, too high a gas flow rate will result in poor penetrating and/or porosity owing attributable to instabilities within the gas column (Ley, *et al.*, 2015). The quality characteristics of a weld affected by the shielding gas flow rate are included in the following section.

Penetration: Gas flow rate is one of the influencing parameters that affect the depth of penetration (Gothi and Ramavat, 2017). If the gas flow rate is too high penetration has been poor (Ley, *et al.*, 2015). Increasing the gas flow rate increases the depth of penetration (Kamble and Rao, 2013). On the contrary, other works of literature noted that gas flow rate does not affect weld penetration (Badheka, 2013).

Bead height: A rise in the rate of shielding gas flow increases the fusion area and height of the bead because it produces high-velocity plasma (Kamble and Rao, 2013). When the velocity of the gas flow increases an increase in bead height is expected due to low imparting pressure (Badheka, 2013).

Bead width: Its connection between the rate of gas flow and the bead width follows positive proportionality. Thus, a rise within the rate of gas flow melts more filler metals because of high velocity and increases bead width (Kamble and Rao, 2013; Gupta, *et al.*, 2019).

Heat-affected zone: The thermal property occurring in the solidified weld, shielding gas flow rate plays a significant role (Ley, *et al.*, 2015). As verified, Like a higher specific heat capacity, lower thermal expansion, and worthy thermal conductivity beneficial behaviour exhibits with a lower shielding gas flow rate than a higher shielding gas flow rate. Reducing the rate flow of shielding gas within identical heat input raises the heat transfer efficiency factor and a lesser degree of distortion. At larger flow rates of shielding gas, thermal expansion/extension of coefficients is greater through temperature variety series. In addition, its leads to the highest volumetric contraction and expansion inside a weld metal and larger residual stress and HAZ within the structure of the material (Ley, *et al.*, 2015; Rizvi and Tewari, 2017).

2.5.7 Effect of electrode work angle

The electrode work angle is the relationship among the center of the electrode and the surface of the workpiece. The literature revealed that macrostructure, microstructure, arc shape, and mechanical properties are sensitive to the traveling angle of the torch and electrode work angle (position of the torch), the rate of deposition is lower at the torch is offset/incorrect placement through a cross-section to the groove. Mostly, within fillet weld, a welding position like down-

hand horizontal (2F) has projected which an angle of torch within respect towards the position of the torch must be 45–50° and the traveling angle of the torch would be 10–15° in the welding direction (Gyasi, *et al.*, 2017). Electrode work angle has a major effect on determining leg length (creating an asymmetry) by altering the angle of the torch proceeding to a vertical plane of the welding direction; it has a negative linear relationship with leg length (Lee and Rhee, 2000).

Penetration: Torch angle inconsistencies result in insufficient fusion and undercut, mostly in the vertical structure component of the fillet weld. This occurrence leads to quality problems and a lack of penetration between the vertical plate and the base metal (Gyasi, *et al.*, 2017). Penetration declines with an increase in electrode-to-work angle (Lee and Rhee, 2000; Badheka, 2013).

Bead height: Work angle is one of a parameter of welding that impact on penetration and bead of weld shape (Dean, 2003). The weld bead geometry (like, bead height and bead width) influences the mechanical properties of the weld. Weld bead height/reinforcements are influenced by torch angle (Badheka, 2013).

Bead width: Changing the inclination angle and direction of the torch and the amount of power per unit length of the weld influences the behaviour of the weld shape. As soon as welding through the electrode slanted bestowing toward its workmanship motion/movement, an arc penetrates deeper and thickness occurred by the zone of fusion decrease and, while at an opposite inclination width of the weld bead increases and the depth of penetration decreases (Winczek, *et al.*, 2019).

Heat-affected zone: Torch angels exhibit a significant effect on the heat-affected zone (Gyasi, *et al.*, 2017). For the study, the influence of electrode inclination S235 steel plate numerical analysis was shown, and the padding of a rectangle element (0.4m x 0.6m) having a thickness of 0.03m was investigated to suit the requirements of the semi-infinite modelling of a body. In this situation, the inclination of the electrode work angle causes a reduction in the depth of its action. An electrode-to-work angle of 60° inclinations produces broader but shallower HAZ at substantially higher temperatures than an angle greater than 90°. The dimensions of the HAZ are intermediate when the angle is equal to 120°, while the narrowest and the deepest HAZ are acquired for electrode work angle is less than 90° (Winczek, *et al.*, 2019).

2.5.8 Effect of heat input

The quantity of electrical energy expressed as energy per unit length is referred to as heat input. Heat input is determined principally by current, voltage, and travel speed (David H. Phillips, 2015). Heat input affects the way molten filler material transfers, arc stability, weld bead profile development, solidification mechanism, and metallurgical transformation which influence the morphology and efficiency of the welded metal (Gyasi, *et al.*, 2017); Singh, *et al.*, 2020). Heat transfer to the workpiece has a substantial impact on weld fusion, and a linear relationship occurs between heat input and fusion area (Dean, 2003). In line with this, too low heat input makes inadequate melting of weld deposit, but a big weld pool is generated due to excessive heat input, which causes metal flow in front of the arc deterring the melting of parent metal (Gothi and Ramavat, 2017). The quantity of heat input controls the radius of the arc, and the effective radius of the arc is the primary essential element for the creation of weld bead penetration (Cho, *et al.*, 2019). The next section describes the quality features of welds that are affected by heat input.

Penetration: Penetration depth has linear relationships with heat source parameters. The heat input provided to the parent metal per unit length which turn is determined by that of the welding variable and parameters of the process, applying more heat input per unit length to the parent metal causes more melting of the parent metal which results in more depth of penetration (Badheka, 2013; Jia, *et al.*, 2014). Larger heat input (i.e., more heat deposited on the surface of the parent metal) leads to more penetration (Sathiya, *et al.*, 2011). A More amount of heat applied to the weld pool region implies a deep penetration (Sathiya, *et al.*, 2013). If the heat input has become too insufficient, the possibility of fusion failure increases (Paul Kah, *et al.*, 2014).

Bead height: Bead height is one of the weld quality characteristics and it is mostly determined by the amount of heat input and the mode of metal transfer. It plays a significant role to form weld bead geometry; higher heat input yields low reinforcement (Saha, *et al.*, 2019).

Bead width: The variance in weld bead width is caused by differences in temperature distribution between the parent material and filler wire. Whenever the parent material got lower heat input per unit length, the quantity of melting of base metal was reduced and the deposited

amount of filler electrode decreased, which resulted in a smaller weld bead (Badheka, 2013). A larger heat input resulted in a broader weld bead (Saha, *et al.*, 2019). Welding fusion width has directly related to heat source parameters (Jia, *et al.*, 2014). The quantity of heat input in the weld zone has a strong linear connection with bead width (Dean, 2003).

Heat affected zone: The width of the HAZ is shown as a function of heat input. More heat input results in a coarser microstructure in the weld zone (Singh, *et al.*, 2020). A larger heat input might cause serious destruction in the HAZ, which creates a weak spot in the welded materials (Dagostini, *et al.*, 2021). At greater heat input, the primary ferrite, polygonal ferrite, and ferrite side morphology of HAZ grew significantly. When the heat input is significant, the width of the HAZ grows because the grains become coarser as the heat input rises. In principle, HAZ and grain size of weld metal are mostly impacted by heat input and rise as heat input rises (Adak, *et al.*, 2015).

2.6 Summary of welding input parameters impacts on weld quality characteristics

GMAW has several input variables that affect weld quality characteristics. Controlling these parameters in different conditions is a very challenging task. Different researchers attained to optimize the input of welding parameters to obtain the desired weld quality characteristics. Moreover, it is challenging to get the optimum combinations of welding parameters for different conditions. This summary focuses on summarizing the existing works of literature based on the investigations undertaken the impact of GMAW input parameters on the weld quality characteristics of steels as:

- *Arc voltage* which influences the bead width and bead height. A rise throughout arc voltage leads to a longer arc and larger droplets, resulting in a wider and flatter weld bead. Based upon that slope of a process, an excess arc voltage causes arc instabilities, spatter, undercut, porosity, and degradation subject to the inclination of the process. Low arc voltage produces narrower beads with greater convexity.
- *Welding current* effect the strong linear positive connection with all bead geometrical characteristics. Thus, too high a welding current at a specified welding speed generates a large amount of heat and raises the depth of fusion.

- *Wire feed rate* results in increased penetration, bead height, bead width, and HAZ. An excessive rise in wire feed rate causes an excess of the filler material usage and raises the temperature which results in wide weld bead and excessive penetration.
- *Travel speed* affects the amount of input temperature, which in turn impacts on welded metal metallurgical structure (heat-affected zone). It has an inverse influence on the size of the weld beads (bead height, bead width, and penetration).
- *Contact tip-to-work distance* affects the amperage, arc voltage, and shielding gas used as well as metal transfer mode. Welding process stability, weld bead profiles, and weld quality are sensitive to contact tip-to-work distance.
- *Shielding gas flow rate* influence the weld bead geometry. A lower flow rate of shielding gas revealed useful properties as well as a smaller thermal expansion, greater specific heat capacity, and thermal conductivity than a larger flow rate of shielding gas. At greater flow rates of shielding gas, coefficients of thermal expansion were greater through a temperature variety range series that directed and resulted in the largest volumetric contraction and expansion inside a weld metal and larger residual stress and HAZ into the structure of the material.
- *Electrode Work angle* variations result in insufficient fusion and undercut, mostly in the vertical material of the fillet weld. Macrostructure, mechanical properties, and microstructure are sensitive to electrode work angle and torch travel angle.
- *Heat input* is a function of arc voltage, current, and travel speed. The amount of heat input determines the radius of the arc, an effective radius of the arc is the most significant variable influencing the establishment of robust geometry on weld bead.

2.7 Research gap analysis

From the detailed investigation and observation from the literature summery, it is been understood that input process parameters impact and their combinations leads to the weld joints quality. Automated process like the robotic GMAW process consists of many process parameters with different ranges. The selection of optimum parameters in a proper range can lead the best weld quality characteristics, enhances repeatability and consistency of welding, increases the productivity industry, reduces welding costs, and minimizes human input for the selection of

weld parameters. From the literature review, prediction of optimum welding parameters, welding robot programming and controlling, and input process parameter optimization were considered. From various scientific works the following observations are made.

2.7.1 Prediction of optimum welding parameters

The application of different artificial intelligence methods for welding input process parameters prediction for enhancing the desired weld quality levels is the aim of future research work. Furthermore, prediction of welding parameters for different quality levels is important for manufacturing industry to be produced the products as desired quality levels.

2.7.2 Welding robot programming and controlling

Online quality monitoring of robot welding processes, automatic generation of optimum combination of welding order and parameters sets from CAD files extract relevant geometric, material, and production information from the computer-aided drawing and computer-aided manufacturing still needs more research work and investigation. Furthermore, it needs to design and optimize sensor-based intelligent systems that are strongly integrated with the robot controller, which limits the performance of robotic GMAW systems. An improvement of autonomous corrective decision-making using sensors and a robust control system on the welding process are other investigation spaces. Stereo Matching and Triangulation Methods designed for weld seams on a single plane, and image matching for 3D seams on curved surfaces are the other aims of upcoming research areas.

2.7.3 Input process parameter optimization

The quality characteristics of weld such as joint strength, weld bead geometry, weld penetration shape factors, weld reinforcement shape factors, depth of penetration, heat affected zone, presence of crack and porosity, need to be more exploration. Plus an insufficient application of practically useful techniques such as the design of experiments, robust design, statistical process control, etc. to realize the optimum combination of welding parameters to achieve the optimum quality characteristics. There is a lack of research work to determine the optimal welding sequence and welding parameters sets for a given objective function that trade-off various

criteria, such as quality, collision-free motion, and time. Furthermore, there are very limited studies on the effects of torch orientation on weld quality characteristics and the influence of EWA on mechanical and microstructure of the weldment has not been extensively studied and documented.

CHAPTER THREE: MATERIALS AND METHODOLOGIES

This chapter includes the detailed description of the methodologies followed for the dissertation works. Majorly, base material considered for the welding, machines used for welding and characterizations, design of experiments implemented for optimizations of input process parameters, and software used for auto-generation of optimum parameters from input parameters. The research works have been carried out as per the standard procedures. The proceeding section has been made as per the research objectives and described the points.

3.1 Base material and its properties

AISI SAE 4130 alloy steel was selected as base material due to its applicability in various industries. The chemical composition was tested using a spectrometer (Fig. 3.1). The obtained chemical composition of *AISI SAE 4130* alloy steel is tabulated in Table 3.1.



Figure 3.1: Spectrometer setup for material composition test

Table 3.1 Chemical composition of *AISI SAE 4130* alloy steel wt. in (%)

Materials	Fe	C	Si	Mn	Cr	Co	Mo	Ni	S	P	Cu	Ti
4130 steel	97.5	0.33	0.25	0.50	0.85	0.0268	0.134	0.0115	0.035	0.035	0.0675	0.108

From the chemical composition, it has been identified as *AISI SAE 4130* grade alloying steel that has Cr, Mn and Mo as major elements. Due to a high level of Cr content, the possibility of

resistance to corrosion, wear, and abrasion along with hardenability increment in base steel material. Whereas Mn improves the steel's resistance to creep. Collectively with other alloying elements, *AISI SAE 4130* alloy steel has high corrosion resistance, high strength-to-weight ratio, and good machinability and weldability. Due to these properties, 4130 steel is used in aircraft and automotive construction, structural frames, and fasteners for ships, bridges, and buildings. The properties of *AISI SAE 4130* alloy steel have been presented in Table 3.2 (Heidary, *et al.*, 2020).

Table 3.2 Properties of *AISI SAE 4130* alloy steel

Property	Value
Density (kg/m ³)	7861
Ultimate tensile strength (MPa)	669
Yield strength (MPa)	436
Elongation (%)	25.5
Hardness, Vickers (HVN)	228
Elongation at break (%)	25
Reduction of area (%)	60
Modulus of elasticity (GPa)	205
Bulk modulus (GPa)	140
Poisson's ratio	0.29
Melting point (°C)	1416
Machinability (%)	70
Thermal expansion (°C ⁻¹)	20-100

For this dissertation work, three different thicknesses of the base metals: including 2, 4, and 6mm thickness plates were adopted. Fig. 3.2 (a), (b) and (c).



(a) 2mm



(b) 4mm



(c) 6mm

Figure 3.2: Thickness of base metal (a) 2mm, (b) 4mm, (c) 6mm

3.2 Electrode for robotic GMAW process

The selection of the welding electrode wire was principally based on matching the mechanical properties and physical characteristics of the base metal and weld size. Copper-coated solid wire is suited for universal GMAW application in structural steel engineering and provides excellent feeding characteristics. It has good mechanical properties with which it is optimally suited for welding thick-walled components. The copper-coated version of the solid wire BOHLER N ER 70S-6 is designed for low spatter formation and excellent feeding properties for extremely high wire feed rates. These types are especially suited for the robotic GMAW process. The obtained chemical composition of solid wire is shown in Table 3.3.

Table 3.3 Chemical composition of copper coated solid wire in wt. (%)

Materials	Fe	C	Si	Mn	Cr	Co	Mo	Ni	S	P	Cu	Ti
Solid wire	--	0.07	0.85	1.5	0.04	--	0.003	0.04	0.018	0.012	0.35	--

3.3 Input process parameters of robotic GMAW process

3.3.1 Identification and selection of processes parameters

Robotic GMAW process and variables can be categorized in to three categories (Ramos-Jaime, *et al.*, 2013): variables that can be varied on-line during the process, variables that are set prior to the start of the welding process, and variables that cannot be modified. The variables belonging to the first group are the voltage and polarity supplied by the power source, the wire feed speed,

the resulting current and the travel speed of the welding torch. The variables belonging to the second group are the composition and flow rate of the shielding gas, the torch angle, CTWD, and the composition and diameter of the electrode. The variables that cannot be modified are the thickness of the base metal, the joint geometry and the physical properties of the base metal (Ramos-Jaime, *et al.*, 2013).

In the robotic GMAW process, there are several input parameters and variables which affect weld quality characteristics including arc voltage, welding current, wire feed rate, travel speed, contact tip-to-work distance, shielding gas flow rate, electrode work angle, heat input etc. Among the several input parameters, wire feed rate, travel speed, electrode work angle, and contact tip-to-work distance, are considered to investigate the level of effects of each factor on weld quality characteristics. The working ranges of welding parameters were assigned based on the industry range that has been used and reinforced by conducting pilot experiment works. Variable and constant parameters have been distinguished and continuous or discrete variables have been identified. The input process parameters and their considered levels are shown in Table 3.4.

Table 3.4 Process parameters with their levels considered for Robotic GMAW

Parameters/ Levels	WFR (m/min)	TS (mm/min)	EWA (deg.)	CTWD (mm)	Data Respondent	
					Voltage (V)	Current (A)
1	1	150	35	10	16.2	124
2	3	250	40	15	16.8	128
3	5	350	45	20	18.9	190
4	7	450	50	-	20.4	232
5	9	550	55	-	24.0	260

A. Wire feed rate

Wire feed rate refers to the rate at which filler wire is fed through into the weld joint, which has a major effect on the amount of current and weld penetration. The convexity index is affected by the wire feed rate; a positive rate of the wire feed coefficient has a positive impact on the convexity index (Adak, *et al.*, 2015). An excessive increase in wire feed rate results in an excess

of filler metal, which causes improper adherence to the weld zone and an increase in heat input due to a larger number of short circuits formed at the same time (Fernando, *et al.*, 2015).

B. Travel speed

The distance travelled demonstrates the length of time that weld materials are deposited from arc initiation to termination. The linear rate at which an arc travels along the weld joint is defined as the speed of travel (Ghosh, *et al.*, 2017). It plays a significant role in the quantity of heat generated into the welded joint per unit length of the weld. The travel speed is among the most challenging variables to anticipate inside the weld-making procedure (Lee and Rhee, 2000). And it has a significant effect on the quantity of heat generated in the joint per unit length of the weld (Węglowski, *et al.*, 2016). Excessive travel speed leads to a shortage of filler metal accumulation at the parent metal (lower metal deposit in the bead), resulting in inadequate welding beads. Also, because the arc exerts its effects on the parent metal, the quantity of thermal energy transmitted from the arc to the parent metal reduces as travel speed increases (Pires, *et al.*, 2003; Fernando *et al.*, 2015). The speed of travel along the weld joint impacts the bead shape, depth of fusion, heat input, and weld bead appearance, all of which impact the microstructure of the weldment (Kim, *et al.*, 2003; Ramos-Jaime, *et al.*, 2013; Gupta, *et al.*, 2019).

C. Electrode work angles

The electrode work angle is the relationship between the centre of the electrode and the surface of the workpiece. The literature revealed that macrostructure, microstructure, arc shape, and mechanical properties are sensitive to the traveling angle of the torch and electrode work angle (Lee and Rhee, 2000; Gyasi, *et al.*, 2017). The rate of deposition is lower at the torch is offset/incorrect placement through a cross-section to the groove. Mostly, within fillet weld, a welding position like down-hand horizontal (PB) has projected which an angle of torch within respect towards the position of the torch must be 45–50° and the travelling angle of the torch would be 10–15° in the welding direction (Gyasi, *et al.*, 2017). Electrode work angle has a major impact on determining leg length (creating an asymmetry) by altering the angle of the torch proceeding to a vertical plane of the welding direction (Lee and Rhee, 2000). The torch angle influences the quality of the weld bead and the weld geometry. The torch angle is characterized

by its orientation (torch travel angle) and its linearity (torch position). Both torch travel angle and torch position are shown in Fig. 3.3 schematically. Torch angle discrepancies result in an undercut and insufficient fusion, mostly in the upright member of the fillet weld (Badheka, 2013; Gyasi, *et al.*, 2017). This phenomenon leads to quality problems and a lack of penetration between the upright member and the base member. The researcher (Gyasi, *et al.*, 2017) concludes arc shape, macrostructure, microstructure, and mechanical properties of weldment are sensitive to torch angle variations.

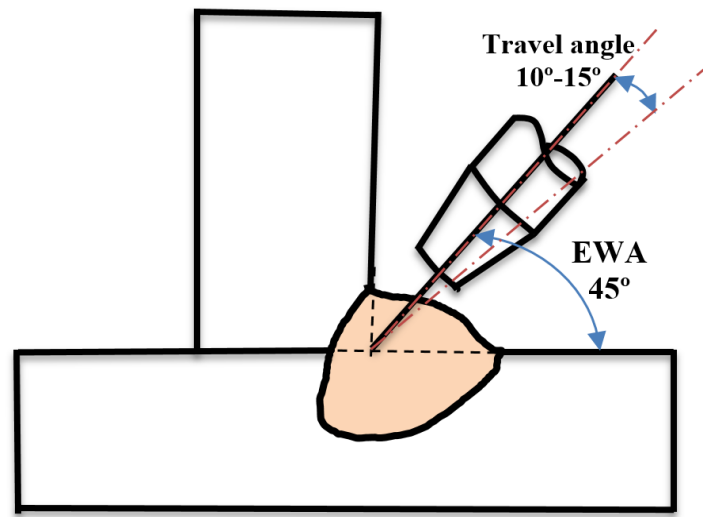


Figure 3.3: Schematic representation of t-joint fillet weld

D. Contact tip to work distance

Contact tip-to-work distance (CTWD), the gap between both the end of a contact tip and the workpiece surface is a significant welding parameter that mainly affects the amperage, arc voltage, shielding gas used as well as metal transfer mode (Filho and Ferraresi, 2010). Gyasi, *et al.*, (2017) noted that the CTWD controls the welding current as a function of the arc length. Welding process stability and weld quality were sensitive to CTWD (Sterjovski, 2010). One common way to independently manipulate the welding current from the WFS is by adjusting the CTWD. This phenomenon is understood by applying Ohm's law, $V=IR$ (V =Voltage, I =Current, and R =Resistance), to the electric extension segment of the welding wire. To see the effect of CTWD variations on welding current, rearrange the equation to $I=V/R$.

3.3.2 Constants of welding parameters and variables

The welding parameters which were used and maintained constant in all welding conditions are tabulated in Table 3.5.

Table 3.5 Welding set parameters and description for Robotic GMAW

Parameters	Description
Joint geometry	Fillet weld
Droplet transfer	Short-arc
Polarity	DC +
Filler diameter	1.2mm
Shielding gas type	80% Ar and 20% CO ₂
Gas flow rate	15 lit/min
Dimension of plate	2mm, 4mm, and 6mm
Filler metal type	BOHLER N ER 70S-6

3.4 JMP and design of experiments

3.4.1 JMP

JMP is a suite of computer programs for statistical analysis developed by the JMP business unit of the SAS Institute. JMP also offers an innovative custom design capability that tailors the design to answer specific questions without wasting precious resources. Once the data has been collected, JMP streamlines the analysis and model building can easily see the pattern of response, identify active factors and optimize responses. By exploring and exploiting the multifactor opportunities efficiently and effectively to solve science and engineering problems by strategically exploring the opportunity space and designing a controlled set of tests to model and explore the relationship between the inputs and outputs of the process (Draper, 2012).

In general, JMP custom design platform constructs an optimal design to solve process problems by manipulating process factors, constraints on factor settings, information from covariates, and other experimental conditions and resource restrictions. Custom design platform creates a wide array of design types capable of addressing a wide range of experimental goals. By exploring the

optimum combination of parameters for the process's optimum responses by using the maximize desirability function (Draper, 2012).

3.4.2 Design of experiments for robotic GMAW parameters optimization

Design of Experiments (DOE) is a powerful technique used for exploring new processes, gaining increased knowledge of the existing processes and optimizing these processes for achieving world class performance (Antony, 2023). To optimize welding process parameters by developing a predictive model of the relationship between the factors and weld quality characteristics the custom design response surface method was used. The experiments were designed using the JMP-13 pro software package for which a set of significant parameters were selected which included WFR, TS, EWA, and CTWD. Each welding parameter consists of lower and upper values. Depending on the process parameters, other welding parameters, such as welding current is set automatically. The welding current and wire feed rate are directly proportional, thus only one of them is controlled vis-à-vis wire feed rate in the present investigation. It is well known that the voltage changes the bead width but does not affect the weld penetration. Thus, the voltage is kept constant. The minimum number of experiments recommended by JMP has been made with additional experiments for enhancing the certainty of the results. Each run was randomized and replicated based on three repetitions for each specimen, and the average was calculated. Design of experiments for study and investigations of an artificial intelligence system for quality level-based prediction of welding parameters, process parameter optimization, optimization of welding parameters for different electrode work angles, and mechanical and microstructural characterization of welded joints influence of electrode work angle in 'T' welded joints has been presented in Table 3.6, 3.7, 3.8, and 3.9 respectively.

Note: In order to identify the experimental design for each objective the experimental runs has been abbreviated. The abbreviation allocated for prediction of welding parameters: PTJ, process parameter optimization: OTJ, input parameter optimization at a set of EWA: OSTJ, and mechanical and microstructural characterization: MTJ.

Table 3.6 Experimental design for prediction of welding parameters

Run	WFR (m/min)			TS (mm/min)	EWA (deg.)	CTWD (mm)
	2mm	4mm	6mm			
PTJ1	3	5	7	250	50	10
PTJ2	3	5	7	150	45	15
PTJ3	1	3	5	450	40	15
PTJ4	3	5	7	350	40	20
PTJ5	1	3	5	250	40	15
PTJ6	3	5	7	450	50	15
PTJ7	1	3	5	550	45	20
PTJ8	1	3	5	350	45	10
PTJ9	5	7	9	550	50	20
PTJ10	5	7	9	350	50	15
PTJ11	5	7	9	250	45	20
PTJ12	3	5	7	550	40	10
PTJ13	1	3	5	150	40	15
PTJ14	5	7	9	450	45	10
PTJ15	1	3	5	350	50	15
PTJ16	5	7	9	150	45	10
PTJ17	5	7	9	150	45	15
PTJ18	3	5	7	250	40	15
PTJ19	1	3	5	250	45	20
PTJ20	3	5	7	350	45	10
PTJ21	5	7	9	250	50	10
PTJ22	1	3	5	150	50	20
PTJ23	3	5	7	450	45	20
PTJ24	5	7	9	350	40	20
PTJ25	3	5	7	550	50	20
PTJ26	1	3	5	450	50	10
PTJ27	5	7	9	550	40	15

PTJ: prediction 'T' joint

Table 3.7 Experimental design for process parameter optimization

Run	WFR (m/min)	TS (mm/min)	EWA (deg.)	CTWD (mm)
OTJ1	7	350	45	20
OTJ2	5	250	45	15
OTJ3	7	250	40	10
OTJ4	9	250	45	10
OTJ5	9	450	40	20
OTJ6	7	450	50	15
OTJ7	3	350	40	10
OTJ8	3	150	45	15
OTJ9	5	450	50	10
OTJ10	7	150	45	10
OTJ11	5	350	40	15
OTJ12	9	350	50	20
OTJ13	5	150	50	20
OTJ14	3	250	50	10
OTJ15	9	150	40	15
OTJ16	3	450	45	20

OTJ: optimization for ‘T’ joint**Table 3.8** Experimental design for input parameter optimization for a set of EWA

Run	WFR (m/min)	TS (mm/min)	CTWD (mm)
OSTJ1	7	250	15
OSTJ2	7	150	20
OSTJ3	5	450	20
OSTJ4	7	450	10
OSTJ5	3	150	20
OSTJ6	5	350	10
OSTJ7	5	150	15
OSTJ8	9	150	10
OSTJ9	9	350	20
OSTJ10	5	250	15

OSTJ11	9	250	20
OSTJ12	3	450	10
OSTJ13	3	250	10
OSTJ14	9	450	15
OSTJ15	3	350	15
OSTJ16	7	350	10

OSTJ: optimization for a set of electrode work angle 'T' joint

Table 3.9 Experimental design for mechanical and microstructural characterization

Run	WFR (m/min)	TS (mm/min)	EWA (°)	CTWD (mm)
MTJ1	7	250	55	15
MTJ2	9	450	45	15
MTJ3	3	150	55	20
MTJ4	5	150	35	20
MTJ5	9	250	35	20
MTJ6	3	450	35	15
MTJ7	5	250	55	10
MTJ8	5	450	45	10
MTJ9	7	350	45	20
MTJ10	9	350	55	20
MTJ11	7	350	35	15

MTJ: mechanical and microstructural 'T' joint

3.5 Robotic GMAW process setup

3.5.1 Transpuls synergic 2700 CMT power sources

The transpuls synergic 2700 CMT power sources are fully digitised microprocessor-controlled inverter power sources. The modular design and potential for system add-ons ensure a high degree of flexibility. The Transpuls synergic 2700 features an integral 4-roller drive. There is no longer an interconnecting hosepack between the power source and wire-feed unit. Its compact design makes the TPS 2700 particularly suitable for mobile applications. The TPS 2700 CMT power source power sources are designed for the automobile and component supply industry,

machinery and rail vehicle construction, chemical plant construction, equipment construction, shipyards, etc. (Instructions, O.N.D.). Transpuls synergic 2700 CMT power sources specification has been presented in Table 3.10.

Table 3.10 Transpuls synergic 2700 CMT power source technical data

Title	Description
Mains voltage	3 × 400 V
Mains frequency	50 / 60Hz
Welding current range MIG/MAG	3 - 270A
Welding voltage range	14.2 - 27.5V
Max. welding voltage	34.6V
Open circuit voltage	50V
Supply voltage in wire-feed unit	55V DC
Nominal current in wire-feed unit	4A
Wire feed speed	0.5 - 22m/min
Wirespool types	All standard
Wire diameter	0.8 - 1.6mm
Maximum shielding gas pressure	7bar
Power source efficiency at 400V	50W

3.5.2 Welding robot system (KUKA KR 5)

KUKA KR 5 welding robot was used to weld the samples. KUKA is one of the world's leading industrial robots companies and its main customers are from the automotive manufacturing field. The KR 5 Arc HW (Hollow Wrist) is a new type of robot that is considered to be the arc welding specialist. Its attributes truly put it in a class of its own. For instance, it has a 50mm opening in the arm and wrist to enable the internal routing of the arc welding dress package. This is a huge advantage as it helps to protect the dress package from mechanical influences and whiplash. There are a variety of dress package options available such as torsion-type and infinitely rotating. The KR 5 can handle up to 5 kg in payload and a reach of up to 1423 mm. additionally; the KR 5 arc HW design provides more accessible components and a simplified offline programming platform. This robot will be paired with the KR C4 controller (Instructions,

P. 2010). The detailed welding robot specifications, robot motion speed, and robot motion range of the KUKA KR 5 welding robot are shown in Table 3.11 (Instructions, P. 2010). Fig. 3.4 shows the welding robot system with detailed labelling which is located in the advanced welding research laboratory at CV Raman Global University, India.

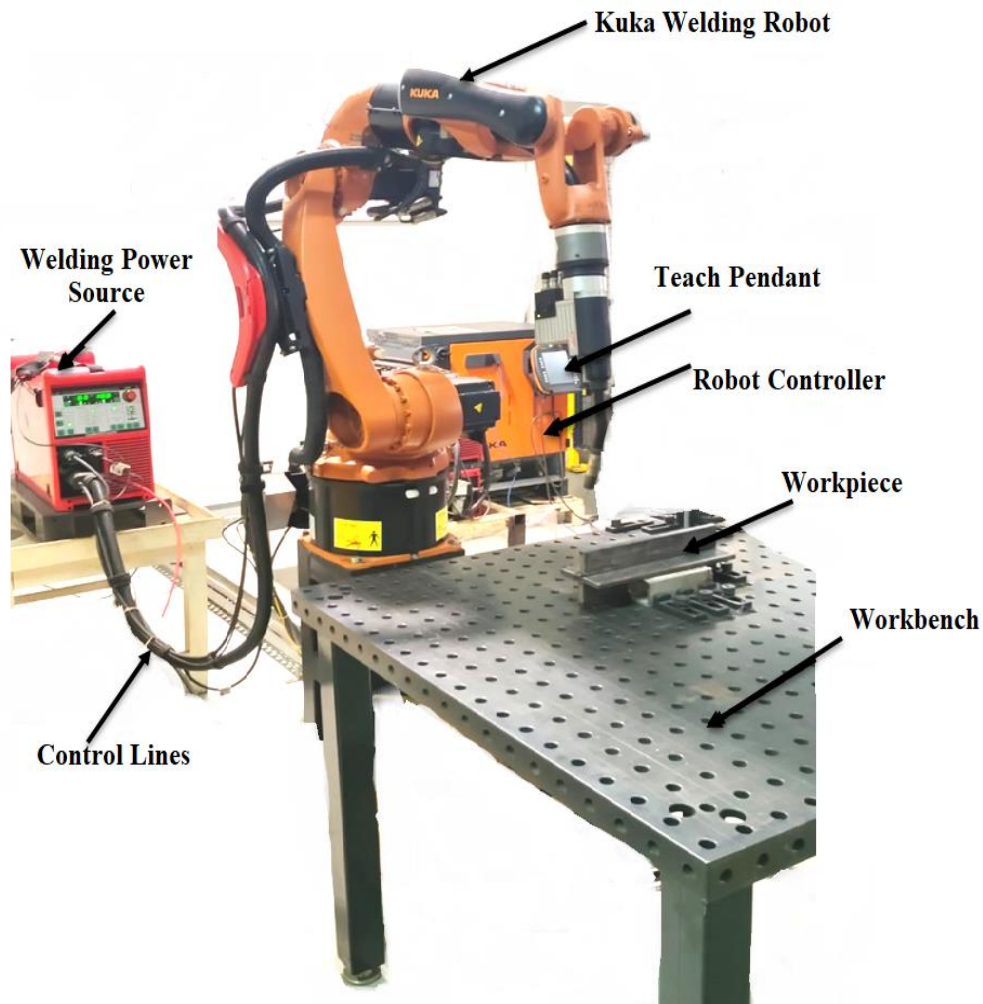


Figure 3.4: Robot welding system (CVRGU, India)

Table 3.11 KUKA KR 5 welding robot technical specification

Robot specifications	Title	Description
	Type	KR C4
	Mains voltage	3 × 400 V
	Frequency	50 / 60 Hz
	Carge full load current	22A
	Axes	6
	Payload	5 kg
	H-Reach	1423 mm
	Repeatability	± 0.04 mm
	Robot Mass	126 kg
	Structure	Articulated
	Mounting	Floor, Inverted
Robot motion speed	Robot joints	Motion speed
	J1	156 °/s (2.72 rad/s)
	J2	156 °/s (2.72 rad/s)
	J3	227 °/s (3.96 rad/s)
	J4	390 °/s (6.81 rad/s)
	J5	390 °/s (6.81 rad/s)
	J6	858°/s (9.73 rad/s)
Robot motion range	Robot joints	Motion range
	J1	±155°
	J2	+65° - 180°
	J3	+170° - 110°
	J4	±165°
	J5	±140°
	J6	Infinitely rotating

3.6 Specimens preparation and welding test specimens

A critical summary of the current state-of-the-art is that fillet welds are hard to specify and fabricate with the right size the measuring method is incapable and the connection between size and strength is weak (Astrand, *et al.*, 2013). In this work, T-joint (horizontal plate of 152×101×6mm and a vertical plate of 152×76×6mm) specimens were prepared for visual examination, throat thickness, joint penetration, joint strength, microstructural examination and micro hardness test. The dimension and type of tests were designed based on AWS B4.0:2016 standards of horizontal fillet weld position (PB): In this position, both the axis of the weld and the lower plate of the joint assembly are horizontal. 'T' joint 3D model specimen with its dimension has been shown in Fig. 3.5.

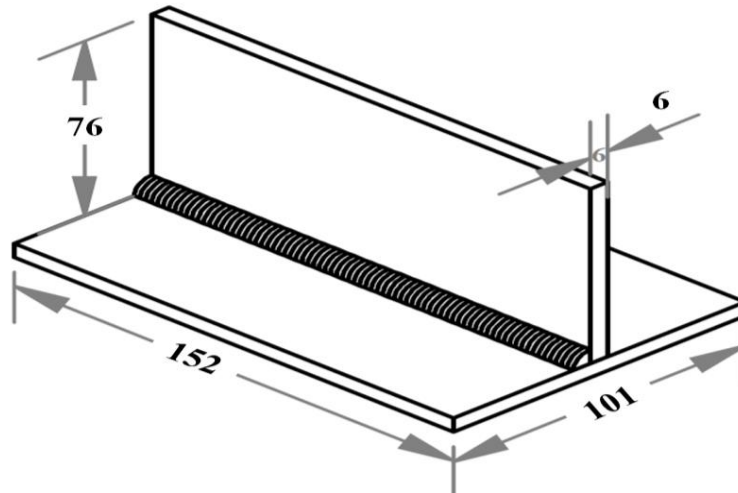


Figure 3.5: 'T' joint 3D model with dimensions (mm)

3.6.1 Test specimens preparation

Prepare the specimen and consumable materials, cutting / sectioning 2mm, 4mm and 6mm 4130 steel plate based on the specified drawing, the edge of each vertical plate and horizontal plate shall be square cut-machining/ grinding based on welding procedure and standards of AWS B4.0:2016. The welded test specimen presented as shown in Fig. 3.6. Welding procedure specification format have been prepared for each test specimen based on AWS B4.0:2016. As attached as Appendix VII.

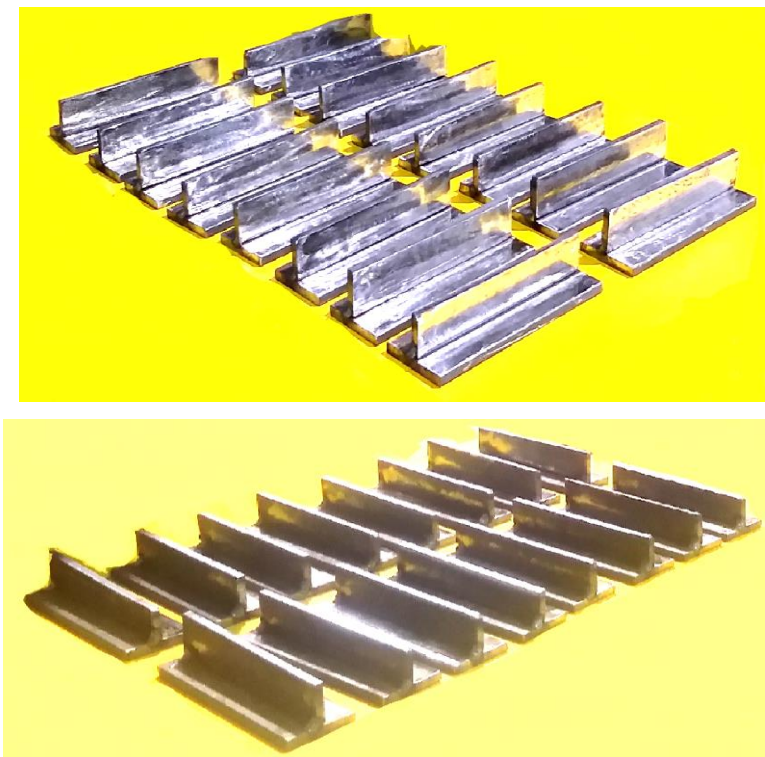
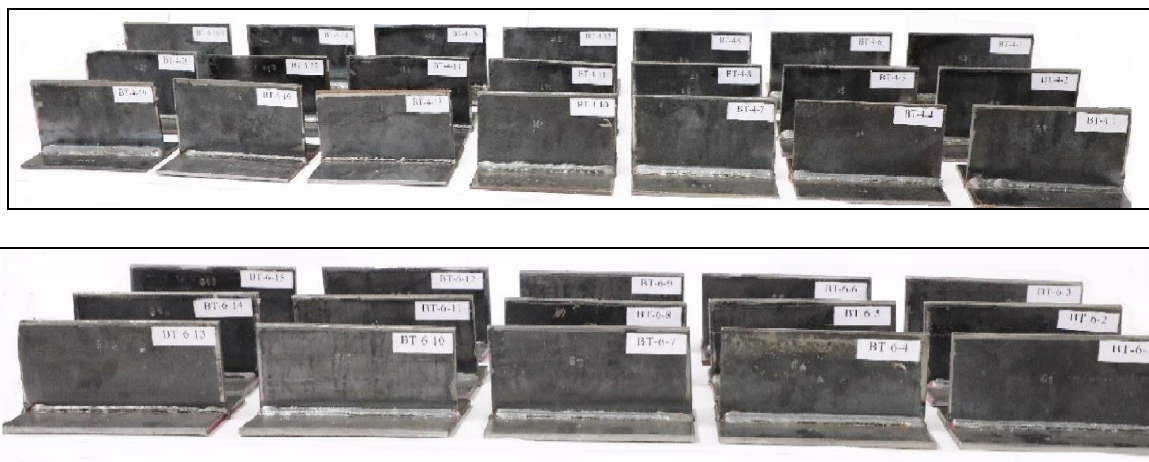


Figure 3.6: 'T'-joint test specimens

3.6.2 Welding test specimens

The prepared billets welded as per the design and AWS B4.0:2016 standard on horizontal fillet weld position (PB). Some 'T' joint welded samples as shown in Fig.3.7.



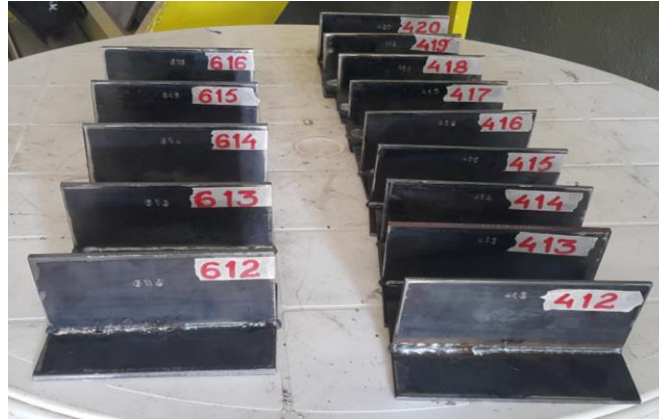


Figure 3.7: ‘T’-joint welded samples

3.7 Quality characteristics and limits for imperfection

The welded part has to fulfil the basic quality and meet the required strength based on the desired standards, the finished products satisfy the design dimension and strength requirement. The weld quality of a joint depends on welding variables, input process parameters, cooling rate, design, process and service environment and weld material factors including the chemical composition of materials, smelting and rolling state, heat treatment and mechanical properties (Kim, *et al.*, 2003; Kamble and Rao, 2013; Cruz, *et al.*, 2015); Amit Kumar, *et al.*, 2016; Srivastava and Garg, 2017).

The weldment limits for imperfections were specified for each weld class in ISO 5817:2014, which designates imperfections. The quality levels, grades 'D', 'C', and 'B', allow for a wide application range in welded fabrication. Specifically, there are limits for imperfections in grades 'D', 'C', and 'B'. In most of the fabrication industry, the typical grade is 'C', but 'B' grade is also required for structures where high quality or strength is mandatory. This is crucial for withstanding various loads, such as static, pressure, thermal, and corrosion. According to BS EN ISO 5817:2014, quality levels for imperfections have been specified in terms of permitted and unpermitted imperfections for different quality levels. For this study, the limits for quality levels of imperfections in T-joints (TJ) were calculated. Limits for imperfections, and range of imperfections for 'D', 'C', and 'B' quality levels are presented in Tables 3.12 and 3.13

respectively. Weld proportions in relation to throat thickness and joint penetration as shown Fig. 3.8. The EN ISO 5817:2014 standard has been contained in Appendix IX.

Table 3.12 Limits for imperfections, EN ISO 5817:2014 imperfection designation

ID	PT (mm)	Limits for imperfections for quality levels (mm)		
		D(Low)	C (Medium)	B (High)
Insufficient throat thickness (H')		$d' = H' \leq 0.2 + 0.1a$	$c' = H' \leq 0.2$	$b' = H'$ Not permitted
	2	0.34	0.2	Not permitted
		$d' = H' \leq 0.3 + 0.1a$ but max.2	$c' = H' \leq 0.3 + 0.1a$ but max.1	$b' = H'$ Not permitted
	4	0.6	0.6	Not permitted
	6	0.72	0.72	Not permitted
Excessive throat thickness (H)		$d = H$ Permitted	$c = H \leq 1 + 0.2a$ but max.4	$b = H \leq 1 + 0.15a$ but max.3
	2	Permitted	1.28	1.21
	4	Permitted	1.6	1.45
	6	Permitted	1.84	1.63
Lack of penetration (h')		$d' = h' \leq 0.2a$ but max.2	$c' = h' \leq 0.1a$ but max.1.5	$b' = h'$ Not permitted
	2	0.28	0.14	Not permitted
	4	0.6	0.3	Not permitted
	6	0.848	0.424	Not permitted
Excessive penetration (h)		$d = h \leq 1 + 0.6b$	$c = h \leq 1 + 0.3b$	$b = h \leq 1 + 0.1b$
	2	1+ (max.3)	1+ (max.2)	1+ (max.1)
		$d = h \leq 1 + 1.0b$ but max. 5	$c = h \leq 1 + 0.6b$ but max. 4	$b = h \leq 1 + 0.2b$ but max.3
	4	max.5	Max.4	Max.3
	6	max.5	Max.4	Max.3

ID: Imperfection designation, PT: Plate thickness

Table 3.13 Range of imperfections for 'D', 'C', and 'B' quality levels

ID	PT (mm)	TV (mm)	Limits for imperfections for quality levels (mm)					
			D		C		B	
			[d' d]	[d'-T T+d]	[c' c]	[c'-T T+c]	[b' b]	[b'-T T+b]
Throat thickness [H' H]	2	1.414	[0.34 permitted)	[1.07 permitted)	[0.2 1.28]	[1.21 2.69]	[Not permitted 1.21]	[1.414 2.62]
	4	2.828	[0.6 permitted)	[2.22 permitted)	[0.6 1.6]	[2.22 4.42]	[Not permitted 1.45]	[2.828 4.27]
	6	4.242	[0.72 permitted)	[3.52 permitted)	[0.72 1.84]	[3.52 6.08]	[Not permitted 1.63]	[4.242 5.87]
Joint penetration [h' h]	2	2	[0.28 3]	[1.72 6]	[0.14 2]	[1.86 5]	[Not permitted 1]	[2 4]
	4	4	[0.6 5]	[3.4 9]	[0.3 4]	[3.7 8]	[Not permitted 3]	[4 7]
	6	6	[0.84 5]	[5.16 11]	[0.424 4]	[5.57 10]	[Not permitted 3]	[6 9]

TV: Targeted value

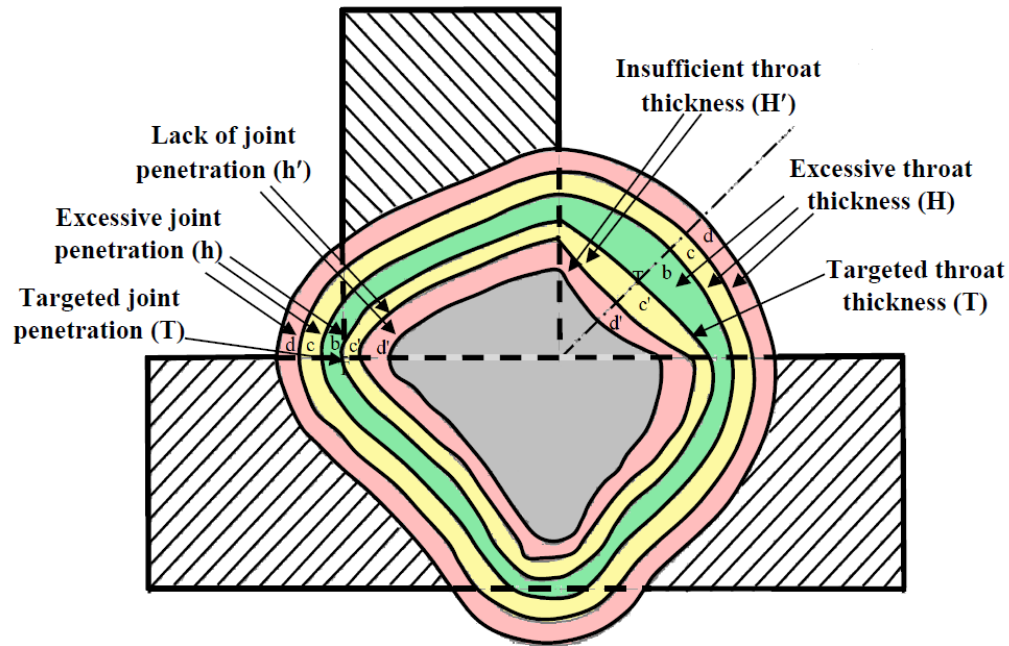


Figure 3.8: Weld proportions in relation to throat thickness and joint penetration

3.8 Weld inspections, tests and examination

In this dissertation, destructive and non-destructive tests have been performed including; joint strength, throat thickness, joint penetration, microstructural analysis, the extent of HAZ, and micro hardness test. The test and examination has been used in this dissertation discussed in the following section.

3.8.1 Joint strength tests

This type of testing involves breaking a fillet weld sample and noting the load-carrying capacity. The failed samples were inspected to establish the presence and extent of any welding discontinuities. The break strength test was performed as per AWS B4.0:2016 standard using a universal testing machine of model 1000HDX (Fig. 3.9) with 1000kN capacity.

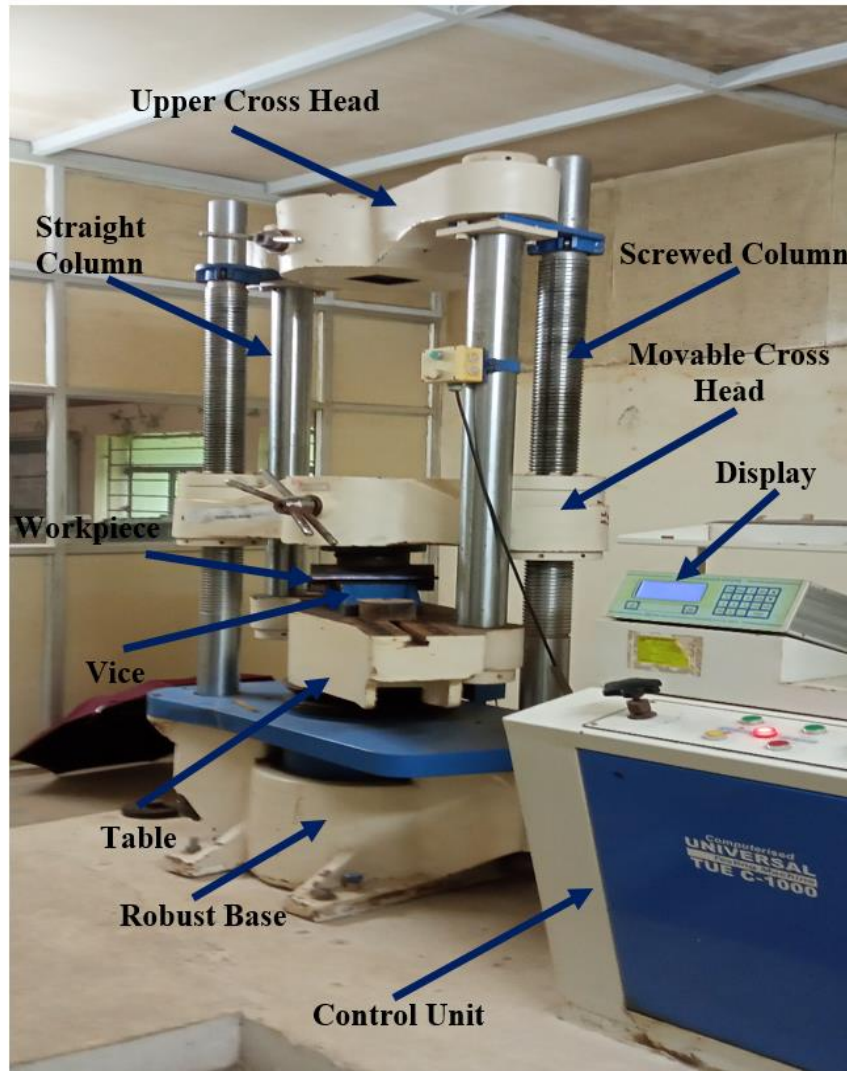


Figure 3.9: Universal testing machine for fillet weld break strength (CVRGU, India)

Joint strength tests procedure. A force and the fillet weld methods of testing has been performed as shown as in Fig. 3.10 or other forces causing the root of the weld to be in tension shall be applied to the specimen. One leg of a T-joint is bent upon the other to place the root of the weld in tension. The load is maintained until the legs of the joint come into contact with each other or the joint fractures. The test shall be examined according to the criteria of applicable AWS B4.0:2016 standard. Figure 3.11 shows break strength testing of fillet weld ‘T’ joints.

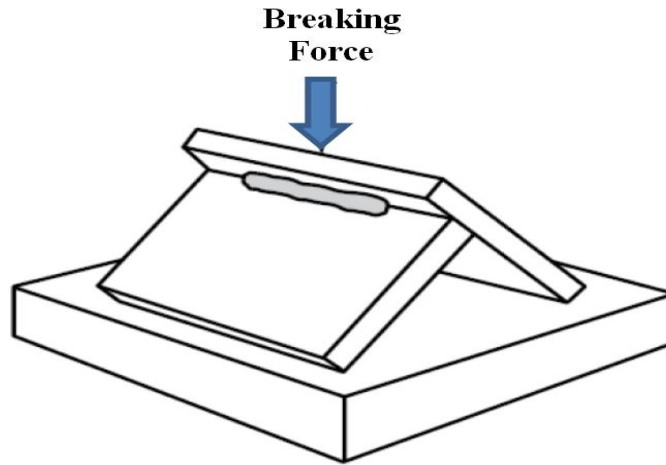


Figure 3.10: Fillet weld method of testing



Figure 3.11: Break strength testing (CVRGU, India)

3.8.2 Throat thickness measurement

The nominal throat thickness of a fillet weld is the shortest distance from the corner of the joint to the hypotenuse of the largest right-angled Fig. 3.12. The effective throat of a fillet weld is a structural way to understand how strong a fillet weld to be. The calculation of nominal throat thickness (a) is executed by Eq. (3.1) as per ISO 2553 (Muzana Enterprais, 2017; Umut and Hamdullah, 2022; Dnvgl, 2020). Nominal throat thickness for fillet welds is presented in Table 3.14.

$$a = \frac{Z}{\sqrt{2}} \dots\dots\dots(3.1)$$

Where;-

a - Nominal throat thickness of the fillet weld in mm

Z -Leg length of fillet weld in mm

The standard fillet weld gauge set (Fig. 3.13) was adopted to measure the throat thickness of the welded joints. From the measurement, one can actualize the size of a fillet weld including; insufficient throat thickness, excessive throat thickness and targeted throat thickness.

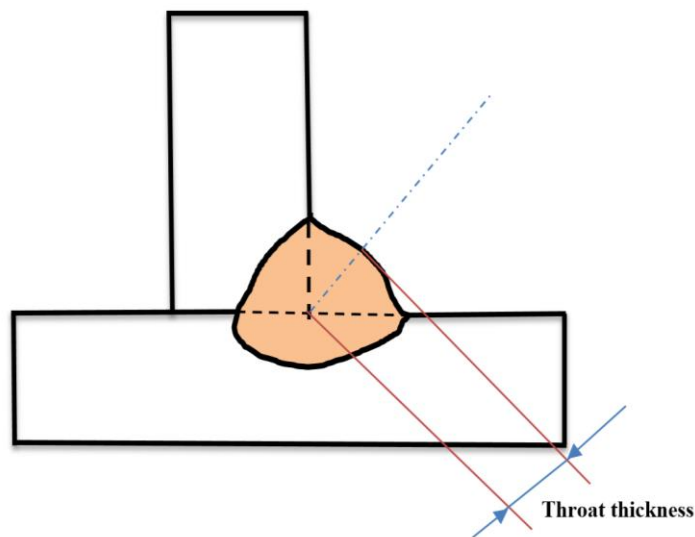


Figure 3.12: Schematic diagram of throat thickness

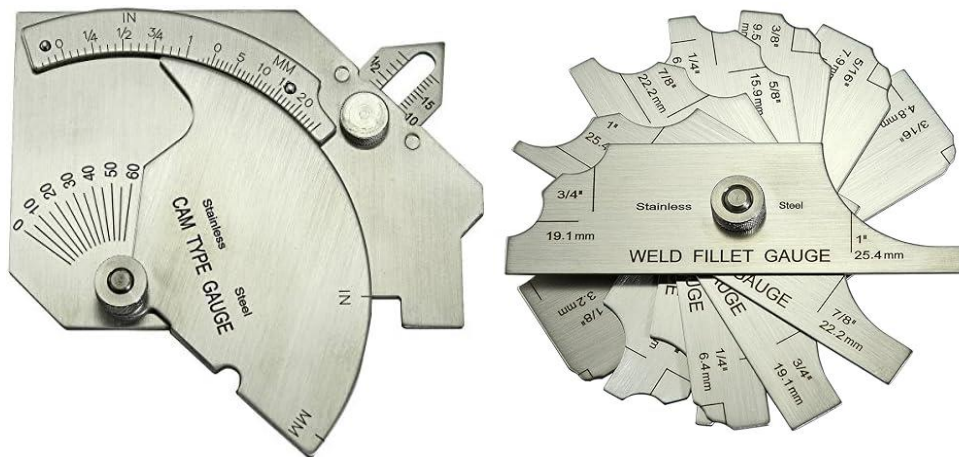


Figure 3.13: Fillet weld guage (ASTU, Ethiopia)

3.8.3 Joint penetration measurement

Joint penetration is the distance to which fusion extends, creating a common joint in both plates (vertical and horizontal, as shown in Fig. 3.14 schematically). In the T-joint, the depth of penetration in the weldment primarily occurs in the horizontal plate (referred to as root penetration). Nevertheless, joint penetration stands out as the most critical quality characteristic in weldments. Inadequate joint penetration can lead to the failure of joint structures and damage to resources. Conversely, excessive joint penetration diminishes the weld's strength by inducing residual stress on the weld toe, aligning with the quality standards outlined in AWS A30 fillet weld with joint penetration and BS EN ISO 5817:2014 limits for imperfections. Nominal joint penetration for fillet welds is presented in Table 3.14.

Table 3.14 Nominal throat thickness and joint penetration for fillet welds

Material thickness (mm)	Throat thickness (a) (mm)	Joint penetration (JP) (mm)
2	1.414	2
4	2.828	4
6	4.242	6

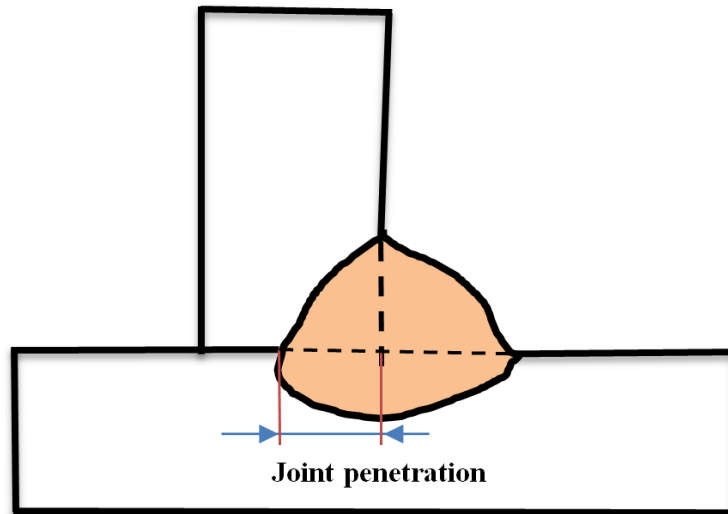


Figure 3.14: Schematic diagram of joint penetration

3.8.4 Microstructural analysis of welded joints

The microstructural analysis was performed by using a metallographic microscope. The 'T' joint welded specimens were cut into transverse directions and the cross-section surface was prepared for microstructure examination following the guidelines of AWS B4.0:2016 and ASTM E384 standards. Samples were collected from the base material and welded joints from the optimized parameters. An abrasive cutter (RB 203 Abcut-M) machine (Fig. 3.15, located in ASTU) was used to cut the samples from base metal and welded joints for microstructure and micro-hardness tests.



Figure 3.15: Abrasive cutting machine (ASTU, Ethiopia)

The preparation involved grinding the welded samples successively with 240, 500, 1000, 2000, and 2400 grits, followed by mirror polishing using the RB 204 Metpol-II polisher machine Fig 3.16. Subsequently, the polished specimens underwent etching in a nital etchant solution (2% nitric acid and 98% ethanol) for 10 seconds Fig. 3.17. Microstructural examinations were performed using a Huvitz HR-300 series metallurgical microscope in ASTU Fig. 3.18.



Figure 3.16: Polishing machine (ASTU, Ethiopia)



Figure 3.17: Welded specimens for mechanical test and microstructural examination

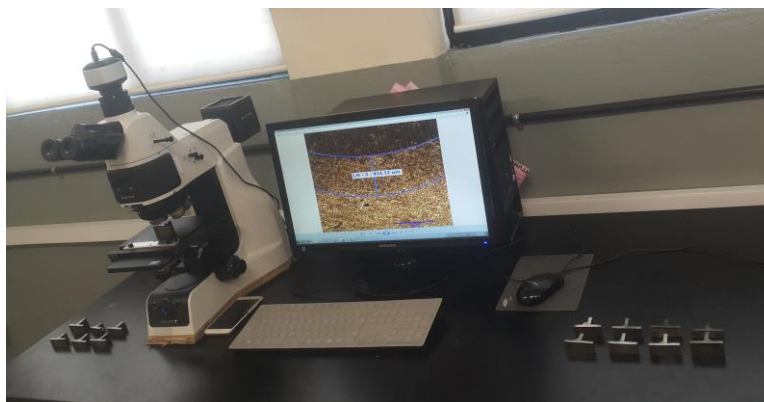


Figure 3.18: Metallurgical microscope (ASTU, Ethiopia)

The scanning electron microscopy (JEOL JCM-6000 model) (Fig. 3.19, located in ASTU) process was used for fracture analysis of faying surfaces of weldments. The crystallographic structure of the base material and weld fusion zone were studied using an X-ray diffractometer (XRD-7000 MAXIma) (Fig. 3.20, located in ASTU). The operating conditions were with a target tube voltage of 40 kV, tube current of 40 mA, scans between 10° and 90° at a scanning speed of 3° min⁻¹, and monochromatization. XRD was used to determine the size of the crystal (crystallite size) with phase certain. The determination refers to the main peaks of the pattern diffractogram through the approach of Debye Scherrer's equation formulated in Eq. 3.2 (Fatimah, et al., 2022).

$$\text{Crystallite size (D)} = \frac{K\lambda}{\beta \cos \theta} \dots \dots \dots (3.2)$$

Where D is the crystallite size, K is the Scherrer constant (0.9), λ is the wavelength of the X-rays used (0.15406 nm), β is the Full Width at Half Maximum (FWHM, radians), and θ is the angle of diffraction (radians).



Figure 3.19: Scanning electron microscopy (ASTU, Ethiopia)



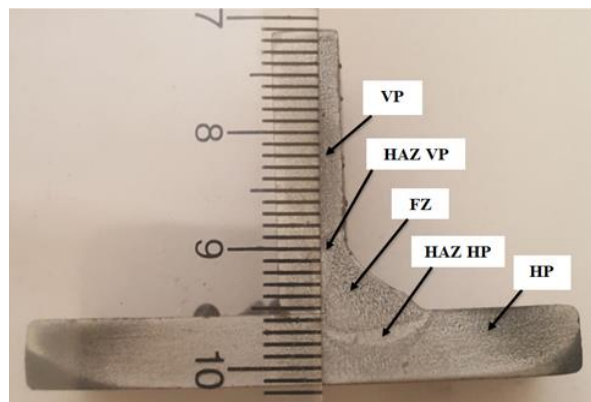
Figure 3.20: X-ray diffractometer (ASTU, Ethiopia)

3.8.5 Extent of HAZ Measurement

The heat-affected zone (HAZ) is a non-melted area of metal that has changed material properties as a result of being exposed to high temperatures. These changes in material properties are usually a result of welding (Gyasi, *et al.*, 2017). The HAZ area can vary in severity and size depending on the properties of the materials, the concentration and intensity of the heat, and efficiency of the welded metal (Singh, *et al.*, 2020). The size of a heat-affected zone is influenced by the level of thermal diffusivity, which is dependent on the thermal conductivity, density and specific heat of a substance as well as the amount of heat going into the material (Adak, *et al.*, 2015). The methods extent of HAZ measurement (Fig. 3.21) and the selection of testing locations for HAZ were in accordance with the AWS B4.0:2016 standard, as depicted in Fig. 3.22.



Figure 3.21: Extent of HAZ measurement (ASTU, Ethiopia)



VP: vertical plate, HP: horizontal plate, HAZ VP: HAZ on vertical plate, HAZ HP: HAZ on horizontal plate

Figure 3.22: HAZ measurement locations on VP and HP

3.8.6 Micro hardness testing

Vickers micro-hardness tester (HVS-50), with a diamond pyramid indenter, was used to test the micro-hardness of the BM, HAZ, and FZ by applying a load of 10kgf and a dwell time of 15s. Three indents on each region (BM, HAZ and FZ,) were taken for reputation and average hardness numbers were recorded. Vickers micro-hardness tester is shown in Fig. 3.23. The selection of testing locations for hardness was following the AWS B4.0:2016 standard, as depicted schematically in Fig. 3.24.



Figure 3.23: Vickers micro-hardness tester (ASTU, Ethiopia)

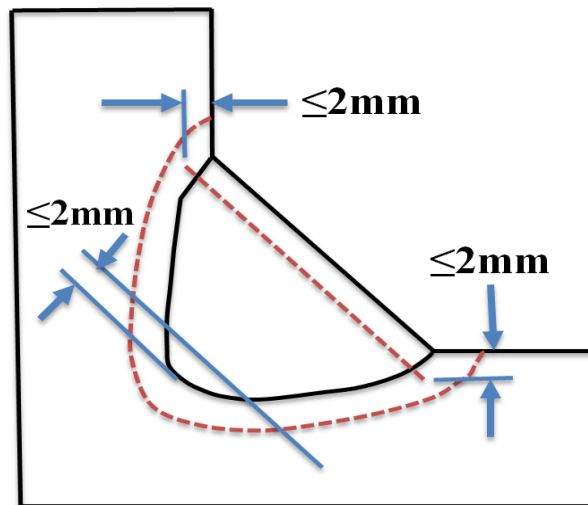


Figure 3.24: Hardness test locations on fillet weld specimen

3.9 MATLAB programming

MATLAB is a programming platform designed specifically for engineers and scientists to analyze and design systems. MATLAB is a high-level programming language. It incorporates algorithm development, modelling, simulation, prototyping, data analysis, exploration, visualization, creation of user interfaces, and interfacing with programs written in other languages. It is designed for a range of applications including;- deep learning and machine learning, signal processing and communications, image and video processing and control systems (Jang, J. 1997; Shtovba, 2014). For this dissertation, fuzzy logic model and MATLAB cubic spline interpolation methods were used for predicting the optimum welding parameters and automatic generation of optimum combination welding parameters for the robot gas metal arc welding process.

3.9.1 Fuzzy logic

The concept of fuzzy logic was introduced by Lotfi Aliasker Zadeh in 1965, a professor at the University of California at Berkley. Zadeh was best known for proposing fuzzy mathematics consisting of these fuzzy-related concepts: fuzzy sets, fuzzy logic, fuzzy algorithms, fuzzy semantics, fuzzy languages, fuzzy control, fuzzy systems, fuzzy probabilities, fuzzy events, and fuzzy information. Fuzzy logic is a form of multi-valued logic derived from fuzzy set theory to deal with reasoning that is approximate rather than accurate. Fuzzy logic was applied to many fields ranging from control theory to artificial intelligence (Ross Timothy, 2010; Yuanxi, *et al.*, 2012; Nweze and Achebo, 2019).

3.9.2 Cubic spline interpolation

Cubic spline interpolation methods are one of the advanced numerical types of interpolation methods that are commonly used in numerical analysis to estimate a function that passes through a set of data points. It is smoother and has smaller errors than some other interpolating polynomials, such as Lagrange polynomials and Newton polynomials. In general, Cubic spline interpolation is a powerful data analysis tool used to correlate data effectively and efficiently. A cubic spline is a spline constructed of piecewise third-order polynomials which pass through a

set of control points. The second derivative of each polynomial is commonly set to zero at the endpoints since this provides a boundary condition that completes the system of 'm-2' equations. This produces a "natural" cubic spline and leads to a simple tridiagonal system to give the coefficients of the polynomials (Unser, *et al.*, 1993). In this dissertation, quadratic and cubic functions have been used to get good fit, accurate data and smoother functions (Ferrer, *et al.*, 2013; Erdogan, *et al.*, 2013).

3.10 Optimization models and techniques

To optimize welding input parameters different optimization methods have been used including the mathematical model: Regression analysis, Optimization and desirability analysis, Response surface methodology, and Cubic Spline Interpolation. In the analysis and optimization process it should be bounded the output results by fixing constraints.

3.10.1 Constraints for bounded robotic GMAW parameter optimization

The linear factor constraints established from maximum and minimum heat input and based on the upper and lower level of welding parameters effect and entered into the software to make the experiment a more realistic replica of the situation. To calculate the heat input Eq. 3.2 has been used (Quintino, *et al.*, 2013). The constraint value has been presented in Table 3.15.

$$H_i = \frac{V \times I \times 60}{S \times 1000} \eta \dots \dots \dots (3.2)$$

Where,

H_i - Heat input required in kJ/mm; V - Arc voltage in volts; I - Welding current in amps; S - Welding speed in mm/min; η - GMAW process efficiency (0.85).

Table 3.15 Factor constraints robotic GMAW parameter optimization

Sources	Factors effect	Constraints
Heat input	Min. heat input (kJ/mm)= 0.231	$0.231 \leq 0.048(V \times I)/S \leq 1.997$
	Max. heat input (kJ/mm)= 1.997	
Parameters	Min. effect, WFR=3 TS=450, CTWD=20	$3-450+20 \leq -427$
	Max. effect, WFR=9 TS=150, CTWD=20	$9-150+20 \leq -121$

3.10.2 Statistical analyses

The strengths and limitations of experimental design have been checked using the JMP evaluate design platform which determines the ability of design to detect the effects associated with meaningful changes in the responses, and address prediction variance and the precision of parameter estimates. The best fit from the developed models and adequacy has been determined by the analysis of variance (ANOVA) and the statistical significance has been evaluated.

3.10.3 Mathematical model: Regression analysis

Regression analysis is a set of statistical methods used for the estimation of relationships between a dependent variable and independent variables. Multiple linear regressions are a dependence method that looks at the relationship between one dependent variable and two or more independent variables. To gather representative results of each and collective tests, the experiments have been designed and the factors influencing the response are also included in the design. While including the factors, main effects, two-level interaction effects (2nd interaction effect), and the full quadratic effect of the parameters included. Main-effects models contain only first-order terms in each experimental factor. A full main-effects model used to represent the response surface is given in Eq. 3.3:

$$Y = \beta_0 + \sum_{i=1}^4 \beta_i x_i + \varepsilon \dots \dots \dots (3.3)$$

A two-factor interaction effect is one kind of second-order effect. A full two-factor interaction effect used to represent the response surface is given in Eq. 3.4:

$$Y = \beta_0 + \sum_{i=1}^4 \beta_i x_i + \sum_{i=1}^2 \sum_{j=i+1}^6 \beta_{ij} x_i x_j + \varepsilon \dots \dots \dots (3.4)$$

Based on the objective for an optimal combination of welding parameters, it has been included the quadratic effect of input process parameters; representing a variety of relationships between the experimental factors and the response variable. The full quadratic model in four continuous factors has fifteen terms (Eq. 3.5). The full quadratic model used to represent the response surface ‘BS and JP’ is given by:

$$Y = \beta_0 + \sum_{i=1}^4 \beta_i x_i + \sum_{i=1}^2 \sum_{j=i+1}^6 \beta_{ij} x_i x_j + \sum_{i=1}^4 \beta_{ii} x_i^2 + \varepsilon \dots \dots \dots (3.5)$$

Where $\beta_1, \beta_2 \dots$ are the regression coefficients and β_0 is the average response in the fractional experiment. The term ‘ ε ’ is the random error component which is approximately normally and independently distributed with mean zero and constant variance σ^2 . The regression coefficient $\beta_{12}, \beta_{13} \dots$ corresponds to the interaction between the process parameter $x_1 x_2, x_1 x_3 \dots$ and $\beta_{11}, \beta_{22} \dots$ relates to the process parameters interact with itself $x_1 x_1, x_2 x_2 \dots$

3.10.4 Optimization and desirability analysis

It has included residuals from the fitted regression to estimate the error variance to check whether to miss some important effect. To test the goodness of fit of the developed models, adequacy is determined by the analysis of variance technique (ANOVA) to evaluate the statistical significance of the fitted models and variables involved therein for response parameters break strength and joint penetration. The goodness of fit of the models is also evaluated through the “lack of fit test”. The probability of values of “Prob > F” is found more than 0.05, implying that the lack of fit is insignificant, and the probability of values of “Prob > F” is less than 0.05 which indicates that the contribution of these terms to the model is significant. One more criterion that is commonly used to illustrate the adequacy of a fitted regression model is the multiple squares of R and the adjusted coefficient of determination (R^2). The coefficient of determination indicates that the data points fit a line or curve.

Desirability analysis is the method of finding the optimal setting of input parameters for the most desirable weld quality characteristics. The desirability function is a transformation of the response variable to a 0 to 1 scale. The transformed responses can have many different shapes. Regardless of the shape, a response of 0 represents a completely undesirable response and 1 represents the most desirable response. In this dissertation, the desirability function is used in the prediction profiler to find optimal input parameter settings. The prediction profiler shows different settings. When you maximize the desirability function, JMP identifies one combination of factor level settings usually out of many possible combinations.

3.10.5 Response surface methodology

Response surface methodology (RSM) is a collection of mathematical and statistical methods suitable for modelling and analysis of the problem in which a response of interest is influenced by several parameters and the objective is optimizing, and refining the response parameters in the process. A response surface model can identify a point where a minimum or maximum value of the response occurs. In the real-time application of the welding process, there are a few input parameters deriving the quality of welded joints. In this dissertation, RSM with a central composite design is applied to find out the region where the optimal response occurs and determine the optimal setting for each input parameter in the robotic arc welding process.

3.10.6 Prediction and validation of the model

Prediction models were constructed for each response variable to find the optimum combination of input parameters on the break strength and joint penetration. The derived equations are built using standard least square regression. The main effect, second interaction effects, and quadratic effect among the input variables were also taken into consideration. The optimal parameters values and regression model have been predicted by using prediction profilers, the prediction formula used to see predicted ratings for all the experiments.

CHAPTER FOUR: RESULTS AND DISCUSSION

The detailed results and their discussion have been made in this chapter. The most the procedures, planned experiments and detail of the materials, research tools, and equipment have been used and optimization methods were explained in chapter 3. In the following section accrued knowledge, investigation on experimental tests and numerical simulations has been performed under the objectives of an artificial intelligence system for quality level-based prediction of welding parameters for robotic gas metal arc welding, process parameter optimization of robot gas metal arc welding process on *AISI SAE 4130* steel plate, optimization of welding parameters for different torch angles on robotic gas metal arc welding process, automatic generation of optimal combination welding parameters for robotic gas metal arc welding process and mechanical and microstructural characterization of *AISI SAE 4130* steel welded joints made by robotic gas metal arc welding process have been presented and discussed in particulars

4.1 Base material and its properties

AISI SAE 4130 alloy low-carbon steel has been selected as base material with 2, 4 and 6mm thickness. The details of the chemical composition and mechanical properties were tabulated in Table 3.1 and 3.2. The complete description on base material is indicated in previous chapter section 3.1

4.2 Robotic GMAW process setup and consumables

The details of robotic GMAW setup and its parameters range has been indicated in section 3.2 and 3.3, design of experiments using JMP for robotic GMAW in 3.4 and robotic GMAW process setup in 3.5 (Chapter 3). Based on the selected process parameters, various methods have been followed to predict, optimize and characterize the robotic GMAW welded joints. The prediction and optimization has been made on joint penetration, and throat thickness at different quality levels using artificial intelligence systems. The characterization of welded joints on optimized parameters has been investigated through mechanical break strength test and micro-structural observations. The following section will dealt the detailed results and their descriptions.

4.3 Quality level-based prediction of welding parameters

To predict throat thickness and joint penetration a fuzzy logic-based model has been developed to grasp the acceptable combination of welding parameters for the range of different quality levels, such as quality levels 'D', 'C', and 'B'. For this investigation, four input process parameters (wire feed rate (WFR), travel speed (TS), electrode work angle (EWA), and contact tip to work distance (CTWD)) and two weld quality characteristics (throat thickness (TT) and joint penetration (JP)) have been considered. Three triangular membership functions (trimf) have been used to model and predict the acceptable combination of input parameters

4.3.1 Modeling and prediction of weld quality characteristics using fuzzy logic

A general fuzzy controller consists of four modules: fuzzification, fuzzy rule base, fuzzy inference engine, and defuzzification. The details of a fuzzy logic model and its functional architecture are shown in Fig. 4.1.

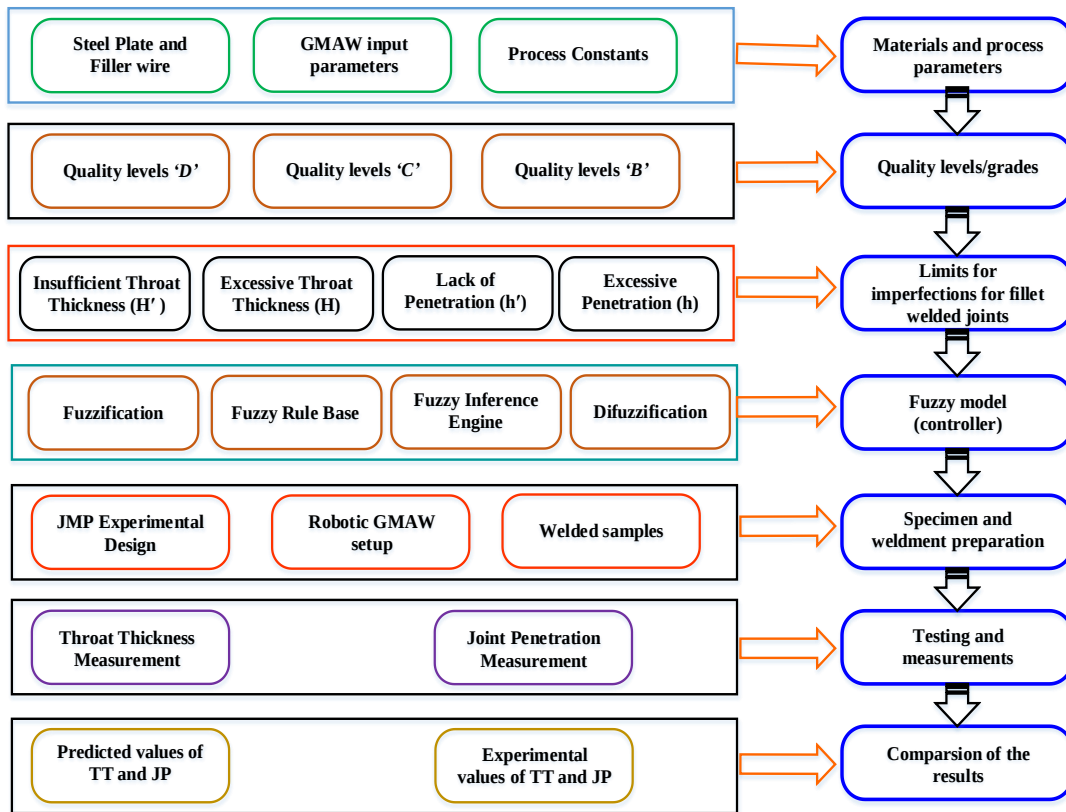


Figure 4.1: Architecture of fuzzy logic model and robotic GMAW process

In the fuzzification process, the measurements of all parameters were taken and changed into appropriate fuzzy sets, and inputs were converted into linguistic variables. These sets represent linguistic labels in terms of 'very low', 'low', 'medium', 'high', and 'very high'. The fuzzy rule base also called the knowledge base; contains data and rules with detailed descriptions and definitions of each parameter. In the case of the inference mechanism, the system module applies logical rules to the knowledge base to deduce new information. The fuzzy inference engine consists of 135 rules, obtained by four parameters with the factorial of $3 \times 5 \times 3 \times 3$ rules, as mentioned in Table 3.3. The defuzzification unit is composed of mathematical equations that convert the fuzzy values into usable values in the real world.

4.3.2 Membership function and fuzzy set

The membership function of the set is the association between the elements of the set and their degree of belonging. A membership function for a fuzzy set 'A' on the universe of discourse X is defined as $\mu_A: X \rightarrow [0, 1]$, where each element of X is mapped to a value between 0 and 1. This value, called membership value or degree of membership, measures the element's membership grade in X to the fuzzy set 'A'. Membership functions permit a fuzzy set to be represented graphically. The x-axis signifies the universe of discourse, whereas the y-axis signifies the degrees of membership in the [0, 1] interval. Without much difficulty in accessing the main effects of input parameters in weld quality characteristics, in actual practice, it is difficult to get the optimal combination of input parameters since there are interaction effects (second-order interaction effects and quadratic effects) between factors. The degree to which a combination of welding parameters approaches optimum is fuzzy.

4.3.3 Triangular-shaped membership function

$$y = \text{trimf}(x, \text{params})$$

$$y = \text{trimf}(x, [a \ b \ c])$$

The triangular curve is a function of a vector, x, and depends on three scalar parameters a, b, and c, as given by Eq. 4.1.

$$f = (x, a, b, c) = \left\{ \begin{array}{ll} 0, & X \leq a \\ \frac{x-a}{b-a}, & a \leq X \leq b \\ \frac{c-x}{c-b}, & b \leq X \leq c \\ 0, & c \leq x \end{array} \right\} \dots\dots\dots(4.1)$$

More compactly, the function is as follows. $f = (x, a, b, c) = \max \left(\min \left(\frac{x-a}{b-a}, \frac{c-x}{c-b} \right), 0 \right)$

The parameters 'a' and 'c' set the triangle's left and right feet or base points. The parameter 'b' sets the location of the triangle peak.

4.3.4 Defining the linguistic variables and terms

Linguistic variables are the input or output variables of the system whose values are words or sentences from a natural language instead of numerical values. A linguistic variable is generally decomposed into a set of linguistic terms. Consider a welding process aimed at predicting the weld quality characteristics (throat thickness (TT) and joint penetration (JP)) and antecedent variables wire feed rate (WFR), travel speed (TS), contact tip to work distance (CTWD), and electrode work angle (EWA) be the linguistic variables that represent the weld factors. The linguistic values of fuzzy input are:-

- WFR-(m/min) --- [low medium high]
- TS-(mm/min) --- [very-low low medium high very-high]
- CTWD-(mm) --- [low medium high]
- EWA (deg) --- [low medium high]

In a similar manner, the output variables are (throat thickness and joint penetration)

- TT (mm) --- [unacceptable-insufficient insufficient intermediate excessive unacceptable-excessive]
- JP (mm) --- [unacceptable-lack lack intermediate excessive unacceptable-excessive]

The terms in the bracket represent the set of decompositions for the linguistic variables. Each member of this decomposition is called a linguistic term. For this study, the linguistic input variables and their range are presented in Table 4.2, and the fuzzy output membership function and sets for quality levels 'D', 'C', and 'B' are presented in Tables 4.3, 4.4, and 4.5, respectively.

4.3.5 Create membership function

For input variables WFR, EWA, and CTWD, three membership functions were selected, namely low, medium, and high, and for input variable TS, five membership functions were selected, namely very low, low, medium, high, and very high. For output variables (throat thickness and joint penetration) based on the standard BS EN ISO 5817:2014, four and five membership functions were assigned for each quality level, namely unacceptable insufficient (UN-INS), insufficient (INS), targeted value (TV), excessive (EXC), unacceptable excessive (UN-EXC). Figure 4.2 shows a fuzzy logic control model for travel speed input parameters. Figure 4.3 and 4.4 shows the indication of the output membership function for the 'D', 'C', and 'B' quality levels.

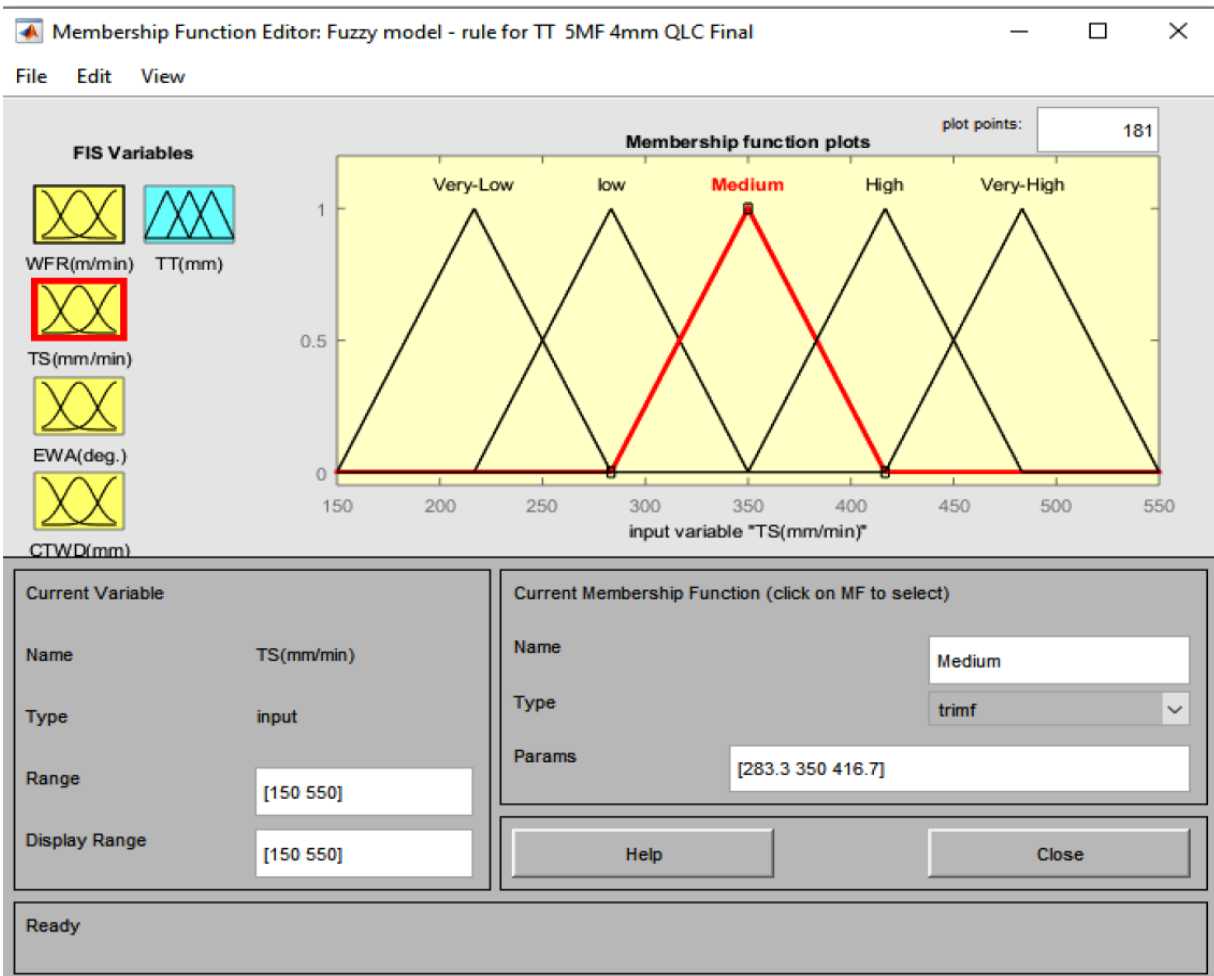


Figure 4.2: Fuzzy logic control model for travel speed input parameters

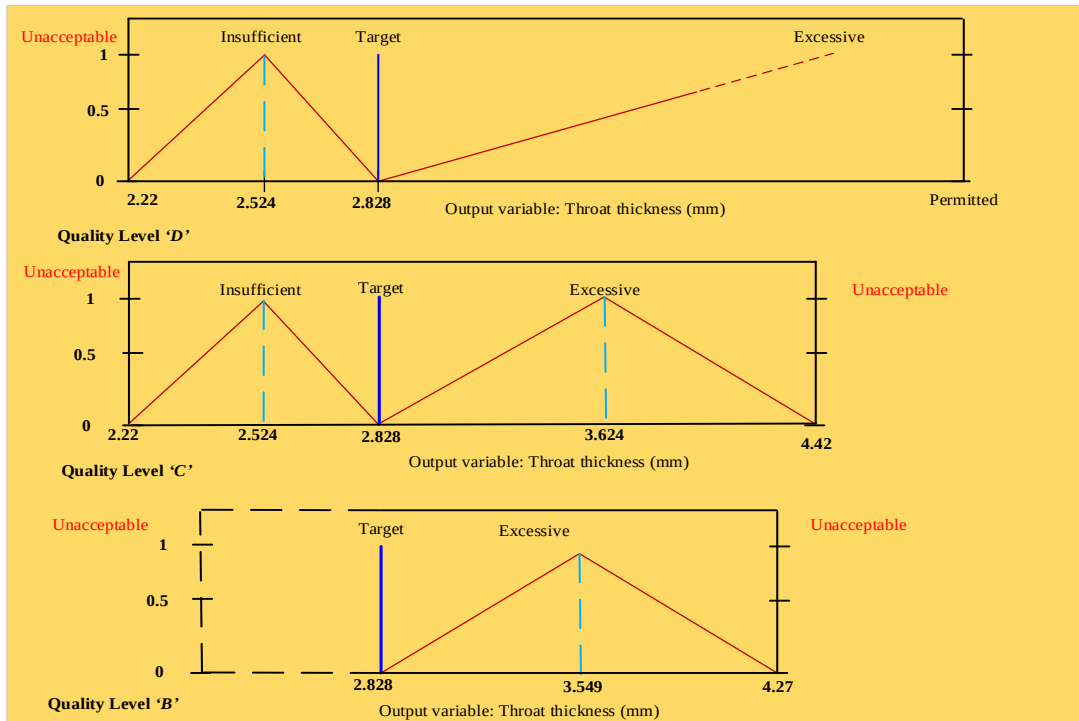


Figure 4.3: Membership function for throat thickness of 4mm plate

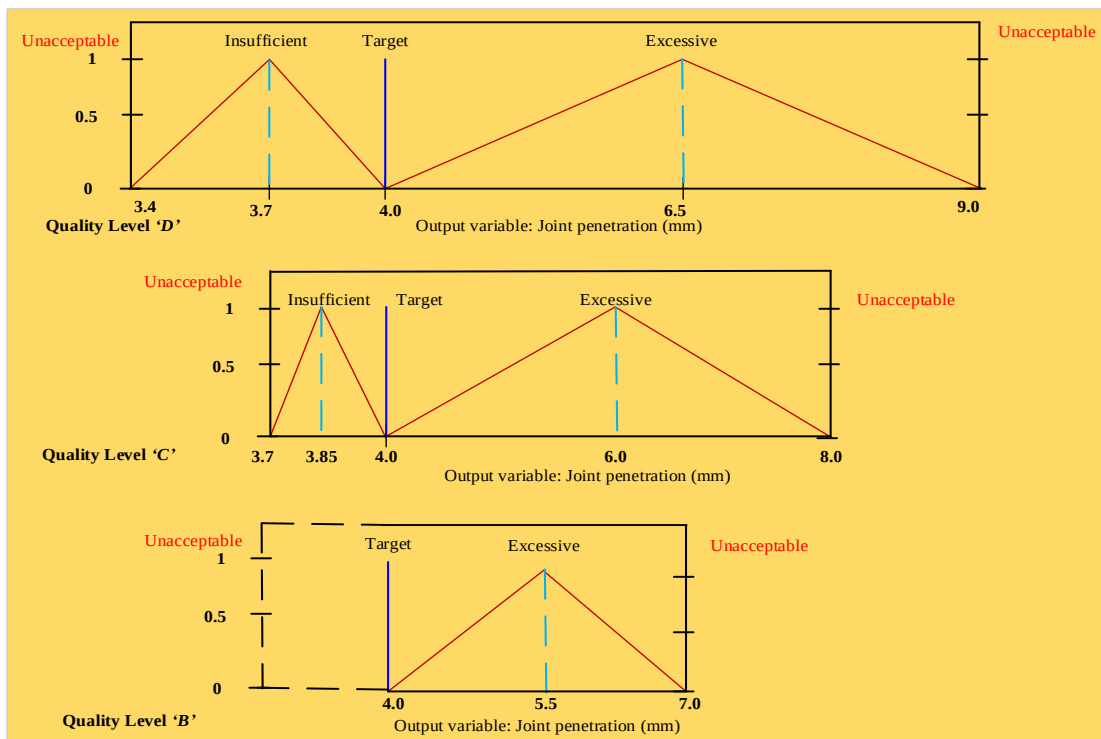


Figure 4.4: Membership function for joint penetration of 4mm plate

4.3.6 Construct the rule base expert systems

An expert system usually comprises two main elements: an inference mechanism and a knowledge base. The inference mechanism is part of an expert system that manipulates the stored knowledge to produce solutions to problems. The knowledge base contains domain knowledge expressed as a combination of "IF-THEN" rules. The knowledge database can accurately predict the relationship between welding parameters (WFR, TS, EWA, and CTWD) and welding quality characteristics (throat thickness and joint penetration) that have been optimized. The knowledge contained in the system has been compiled from three main sources: human experts specializing in the area of welding, the existing scientific literature, and results through pilot experimentation. The mathematical model has been developed based on these investigations, as shown in Eq. (4.2). Equations (4.3) and (4.4) show the weightage of input parameters on TT and JP, respectively. Appendix-I

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{33} x_3^2 + \beta_{44} x_4^2 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{14} x_1 x_4 + \beta_{23} x_2 x_3 + \beta_{24} x_2 x_4 + \beta_{34} x_3 x_4 \dots\dots\dots (4.2)$$

$$\text{Input parameters impact on TT} = 0.39WFR + 0.30TS + 0.12EWA + 0.19CTWD \dots\dots\dots (4.3)$$

$$\text{Input parameters impact on JP} = 0.36WFR + 0.28TS + 0.21EWA + 0.15CTWD \dots\dots\dots (4.4)$$

The impact of each parameter and the impact of each level of parameters are assigned based on their effect on each response (Table 4.1). Weightage is calculated and appointed for each rule; the sum of weight assigned for all rules (135 rules for each response) equals 1. Appendix-II

Table 4.1 Rule base weight factors for fuzzy rule

Parameters	Plate thickness (mm)	Levels		Throat thickness (mm)		Joint penetration (mm)	
				Weightage for parameter	Weighted for levels	Weightage for parameter	Weighted for levels
WFR	2	1	Low	0.39	0.13	0.36	0.12
		3	Medium		0.26		0.24
		5	high		0.39		0.36
	4	3	Low	0.39	0.13	0.36	0.12
		5	Medium		0.26		0.24
		7	high		0.39		0.36
	6	5	Low	0.39	0.13	0.36	0.12
		7	Medium		0.26		0.24
		9	high		0.39		0.36
TS	2, 4 and 6	150	Very- low	0.30	0.30	0.28	0.28
		250	Low		0.24		0.224

		350	Medium		0.18		0.168
		450	high		0.12		0.112
		550	Very- high		0.06		0.056
EWA	2, 4 and 6	40	Low	0.12	0.12	0.21	0.21
		45	Medium		0.08		0.14
		50	high		0.04		0.07
CTWD	2, 4 and 6	10	Low	0.19	0.063	0.15	0.1
		15	Medium		0.19		0.15
		20	high		0.0126		0.05

a. Fuzzy rules for throat thickness weld characteristics

1. If (WFR (m/min) is Low) and (TS (mm/min) is Very-Low) and (EWA (deg.) is Low) and (CTWD (mm) is Low) then (TT (mm) is INT) (0.0070256)
2. If (WFR (m/min) is Low) and (TS (mm/min) is Very-Low) and (EWA (deg.) is Low) and (CTWD (mm) is Medium) then (TT (mm) is EXC) (0.008477)
3. If (WFR (m/min) is Low) and (TS (mm/min) is Very-Low) and (EWA (deg.) is Low) and (CTWD (mm) is High) then (TT (mm) is INT) (0.0077507)
4. If (WFR (m/min) is Low) and (TS (mm/min) is Very-Low) and (EWA (deg.) is Medium) and (CTWD (mm) is Low) then (TT (mm) is INS) (0.0065673)
5. If (WFR (m/min) is Low) and (TS (mm/min) is Very-Low) and (EWA (deg.) is Medium) and (CTWD (mm) is Medium) then (TT (mm) is EXC) (0.0080187)

• • •
• • •
• • •

135. If (WFR (m/min) is High) and (TS (mm/min) is Very-High) and (EWA (deg.) is High) and (CTWD (mm) is High) then (TT (mm) is INT) (0.0070634)

b. Fuzzy rules for joint penetration weld characteristics

1. If (WFR (m/min) is Low) and (TS (mm/min) is Very-Low) and (EWA (deg.) is Low) and (CTWD (mm) is Low) then (JP (mm) is EXC) (0.0081161)
2. If (WFR (m/min) is Low) and (TS (mm/min) is Very-Low) and (EWA (deg.) is Low) and (CTWD (mm) is Medium) then (JP (mm) is EXC) (0.0086877)
3. If (WFR (m/min) is Low) and (TS (mm/min) is Very-Low) and (EWA (deg.) is Low) and (CTWD (mm) is High) then (JP (mm) is INT) (0.0075446)
4. If (WFR (m/min) is Low) and (TS (mm/min) is Very-Low) and (EWA (deg.) is Medium) and (CTWD (mm) is Low) then (JP (mm) is INT) (0.007316)

5. If (WFR (m/min) is Low) and (TS (mm/min) is Very-Low) and (EWA (deg.) is Medium) and (CTWD (mm) is Medium) then (JP (mm) is INT) (0.0078875)

• • •
• • •
• • •

135. If (WFR (m/min) is High) and (TS (mm/min) is Very-High) and (EWA (deg.) is High) and (CTWD (mm) is High) then (JP (mm) is LAK) (0.0061271)

c. Fuzzy inference system

- Fuzzy inference system name = 'Fuzzy-model- of 2mm, 4mm and 6mm 4130 steel plate'
- Fuzzy inference system type = 'Mamdani'
- Number of input parameters =4
- Number of outputs (Quality characteristics) = 2
- Number of rules = 135 for each output
- AND fuzzy operator method = 'min'
- OR fuzzy operator method = 'max'
- Implication method = 'min'
- Aggregation method = 'max'
- Defuzzification method = 'centroid'

Table 4.2 Fuzzy input membership functions and sets

Input Name	Plate (mm)	Membership function				
		MF1 (Low)	MF2 (Medium)	MF3 (High)		
WFR (m/min)	2	[1 2 3]	[2 3 4]	[3 4 5]		
	4	[3 4 5]	[4 5 6]	[5 6 7]		
	6	[5 6 7]	[6 7 8]	[7 8 9]		
EWA (deg.)	4, 6 and 8	[40 42.5 45]	[42.5 45 47.5]	[45 47.5 50]		
CTWD(mm)	4, 6 and 8	[10 12.5 15]	[12.5 15 17.5]	[15 17.5 20]		
		MF1 (Very low)	MF2 (low)	MF3 (Medium)	MF4 (High)	MF5 (Very high)
TS (mm/min)	4, 6 and 8	[150 216.6 283.3]	[216.7 283.3 350]	[283.3 350 416.7]	[350 416.7 483.3]	[416.7 483.3 550]

Table 4.3 Fuzzy output membership functions and sets for quality level 'D'

Output Name	Plate (mm)	Membership function				
		MF1(UN-INS)	MF2 (INS)	MF3 (TV)	MF4 (PER EXC)	
Throat thickness (mm)	2	(< 1.07]	[1.07 1.242 1.414]	[1.414]	(permitted) (6)	
	4	(< 2.22]	[2.22 2.524 2.828]	[2.828]	(permitted) (7.5)	
	6	(< 3.52]	[3.52 3.881 4.242]	[4.242]	(permitted) (8)	
		MF1 (UN-INS)	MF2 (INS)	MF3 (TAR)	MF4 (EXC)	MF5 (UN-EXC)
Joint penetration (mm)	2	(< 1.72]	[1.72 1.86 2]	[2]	[2 4 6]	(>6]
	4	(< 3.4]	[3.4 3.7 4]	[4]	[4 6.5 9]	(>9]
	6	(< 5.16]	[5.16 5.58 6]	[6]	[6 8.5 11]	(>11]

Table 4.4 Fuzzy output membership functions and sets for quality level 'C'

Output Name	Plate (mm)	Membership function				
		MF1 (UN-INS)	MF2 (INS)	MF3 (TV)	MF4 (EXC)	MF5 (UN-EXC)
Throat thickness (mm)	2	(< 1.21]	[1.21 1.312 1.414]	[1.414]	[1.414 2.052 2.69]	(>2.69]
	4	(< 2.22]	[2.22 2.524 2.828]	[2.828]	[2.828 3.624 4.42]	(>4.42]
	6	(< 3.52]	[3.52 3.881 4.242]	[4.242]	[4.242 5.164 6.08]	(>6.08]
Joint penetration (mm)	2	(< 1.86]	[1.86 1.93 2]	[2]	[2 3.5 5]	(>5]
	4	(< 3.7]	[3.7 3.85 4]	[4]	[4 6 8]	(>8]
	6	(< 5.57]	[5.57 5.785 6]	[6]	[6 8 10]	(>10]

Table 4.5 Fuzzy output membership functions and sets for quality level 'B'

Output Name	Plate (mm)	Membership function			
		MF1 (UN-INS)	MF2 (TV)	MF3 (EXC)	MF4 (UN-EXC)
Throat thickness (mm)	2	(<1.414]	[1.414]	[1.414 2.017 2.62]	(>2.62]
	4	(<2.828]	[2.828]	[2.828 3.549 4.27]	(> 4.270]
	6	(<4.242]	[4.242]	[4.242 5.056 5.87]	(>5.87]
Joint penetration (mm)	2	(<2]	[2]	[2 3 4]	(>4]
	4	(<4]	[4]	[4 5.5 7]	(>7]
	6	(<6]	[6]	[6 7.5 9]	(>9]

As per the data in Tables 4.3, 4.4, and 4.5, quality levels have been defined within specific ranges and designated as 'D', 'C', and 'B'. Quality level 'B' encompasses both 'C' and 'D'. Similarly, quality Level 'C' includes quality level 'D'. Quality level 'D' permits excessive throat thickness. In the case of quality level 'B', insufficient throat thickness and lack of penetration are not permitted. Excessive throat thickness has been allowed for quality level 'D' based on experimental work conducted on plates with 2mm, 4mm, and 6mm thicknesses. The maximum values for excessive throat thickness have been taken as 6mm, 7.5mm, and 8mm, respectively. A fuzzy viewer model has been employed to assess the impact of input parameters on throat thickness and joint penetration, and a detailed discussion on the 4mm thickness plate has been conducted. Quality level 'C' was chosen because most industry products fall under this quality level. For the 4mm plate, WFR was set in the range of 3-7m/min, and the membership functions ranged from 2.22mm to 4.42mm for throat thickness and from 3.7mm to 8.0mm for joint penetration, considered for both weld characteristics. Full penetration requires welding on both sides in the case of 6mm thick steel plates. The experimental and predicted results indicated that all values fell within the range of unacceptable insufficient throat thickness, and unacceptable lack of joint penetration. For this investigation, Fuzzy logic models have been developed for predicting the throat thickness and joint penetration of plates with 2mm, 4mm, and 6mm thicknesses for different quality levels: 'D', 'C', and 'B'. Throat thickness and joint penetration are

the two main quality characteristics of the weldment that determine the strength of welded structures by providing external reinforcement and generating fusion among the welded parts. Experimental work has validated the predicted values presented in Table 4.6. The fuzzy model predicts the quality level ranges representing the best weld characteristics. If the value falls below or above the range (if the deviation exceeds the limit), the fuzzy logic functions are represented as unacceptable insufficient (UI) and Unacceptable Excessive (UE) without coding the values, i.e., not predicted (NP), as shown in Table 4.6. For 2mm thickness, the response of throat thickness and joint penetration of experiment numbers PTJ8, PTJ15, PTJ20, and PTJ22 are of the highest quality levels ('B') for both weld quality characteristics. Hence, they can be recorded as experiments with acceptable results. Also, for 4mm thickness, PTJ13, PTJ18, and PTJ21 are experiments with acceptable results. Based on the experimental plan, increasing the welding travel speed has improved productivity while maintaining the same quality levels. For example, for 2mm thickness, PTJ8, PTJ15, PTJ20, and PTJ22 have the same quality level 'B' for both weld quality characteristics. It is to be noted that the same quality level can be achieved at different sets of welding parameters, as shown in the case of 2 mm thickness in Fig. 4.5, though the use of different sets of parameters may have an impact on other aspects. For instance, by using PTJ8, PTJ15, and PTJ20 (350mm/min travel speed), productivity increases by 57.13% compared to PTJ22 (150mm/min travel speed). On the other hand, lower, lower TS (that results in a larger weld bead), in the case of PTJ22, necessitates higher CTWD to prevent the torch from touching the baed.

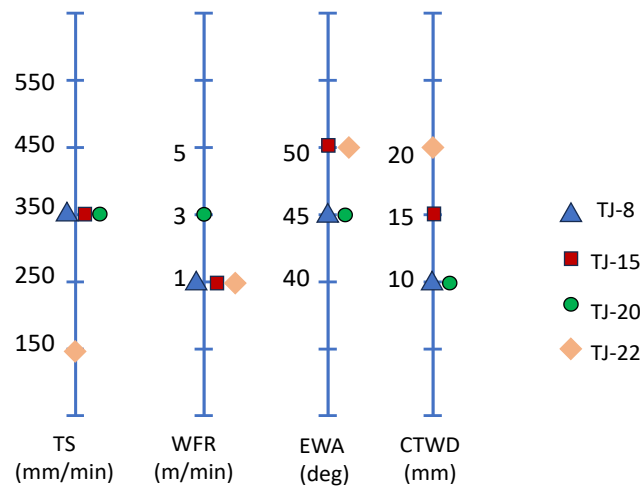


Figure 4.5: Acceptable process conditions for achieving quality level 'b' for 2mm plate

Based on the experimental results, increasing the welding travel speed has improved productivity while maintaining the same quality levels. For example, the throat thickness of 2mm thickness (PTJ3, PTJ6, PTJ8, PTJ12, PTJ14, PTJ15, PTJ20, PTJ22, PTJ23, and PTJ27) are all in the same quality level 'B'. Hence, by using PTJ12 and PTJ27 (550mm/min travel speed), productivity increases by 72.73%, which is higher than PTJ22 (150mm/min travel speed), 36.37% higher than PTJ8, PTJ15, and PTJ20 (350mm/min travel speed), and 18.19% higher than PTJ3, PTJ6, PTJ14, PTJ23 (450mm/min travel speed). A low-level WFR is recommended to reduce waste while maintaining the same quality level, which saves on filler materials and electric power.

In this context, meeting functional requirements with a low-quality level ('D') does not imply the need for a high-quality level 'B' (which would increase production cost). For instance, the same quality level has been recorded for 2mm plate thickness in quality level 'B' with PTJ20 (WFR at 3m/min, TS at 350mm/min, EWA at 45°, and CTWD at 10mm), which can be alternated with PTJ22 (WFR at 1m/min, TS at 150mm/min, EWA at 50°, and CTWD at 20mm). Also, comparing different quality levels for two responses in the weld joints is feasible. For example, throat thickness quality level 'D' and joint penetration quality level 'B' (PTJ1 for 2mm thick plate) or in the opposite throat thickness quality level 'B' and joint penetration quality level 'D' (PTJ1 for 4mm thick plate) input parameter settings can be used (Table 4.6). This analysis demonstrates that quality welds can be produced with the same and different levels for both weld quality characteristics. It has been found that results generated by the designed fuzzy model closely match the experimental results. The developed model is suitable for implementing a real-time automatic control system for the robotic gas metal arc welding process to produce desired weld quality levels.

Table 4.6 Predicted and experimental values for quality level D, C and B

Run	2mm thick plate						4mm thick plate						6mm thick plate					
	PV TT (mm)	EV TT (mm)	PEQL TT (mm)	PV JP (mm)	EV JP (mm)	PEQL JP (mm)	PV TT (mm)	EV TT (mm)	PEQL TT (mm)	PV JP (mm)	EV JP (mm)	PEQL JP (mm)	PV TT (mm)	EV TT (mm)	PEQL TT (mm)	PV JP (mm)	EV JP (mm)	PEQL JP (mm)
PTJ1	2.89	2.89	D	2.72	2.3	B	3.77	3.76	B	6.09	3.4	D	4.84	4.28	B	NP	3.6	UI
PTJ2	4.47	4.21	D	3.66	3.4	B	5.86	5.73	D	5.65	4.3	B	5.98	6.64	D	NP	4.6	UI
PTJ3	1.62	1.48	B	NP	1.1	UI	NP	1.71	UI	NP	1.5	UI	NP	2.91	UI	NP	1.8	UI
PTJ4	2.89	2.71	D	2.72	2.8	B	3.65	3.69	B	NP	3.2	UI	5.01	4.24	B	NP	3.3	UI
PTJ5	3.78	2.97	D	3.38	2.8	B	3.62	3.29	B	NP	3.0	UI	5.14	4.26	B	NP	3.7	UI
PTJ6	1.84	1.51	B	NP	1.3	UI	3.33	2.84	B	NP	1.6	UI	NP	3.33	UI	NP	2.0	UI
PTJ7	NP	1.06	UI	NP	0.7	UI	NP	1.41	UI	NP	1.1	UI	NP	2.25	UI	NP	1.1	UI
PTJ8	1.62	1.60	B	2.34	2.1	B	2.59	2.41	C	NP	2.6	UI	NP	3.39	UI	NP	3.2	UI
PTJ9	NP	1.06	UI	NP	1.0	UI	NP	2.20	UI	NP	1.6	UI	NP	3.51	UI	NP	2.0	UI
PTJ10	3.68	3.59	D	3.66	3.2	B	4.02	4.12	B	NP	3.3	UI	5.10	4.67	B	NP	3.5	UI
PTJ11	5.16	4.06	D	3.66	3.4	B	6.60	4.58	D	6.49	4.2	B	5.06	4.85	B	NP	3.9	UI
PTJ12	1.46	1.42	B	NP	1.1	UI	NP	2.15	UI	NP	1.3	UI	NP	2.86	UI	NP	1.9	UI
PTJ13	5.27	3.26	D	3.66	3.2	B	4.02	4.26	B	6.67	4.0	B	5.59	5.83	B	NP	4.4	UI
PTJ14	1.84	2.51	B	NP	1.6	UI	3.33	3.13	B	NP	2.2	UI	4.81	4.33	B	NP	2.5	UI
PTJ15	1.62	1.42	B	2.34	2.1	B	2.62	2.61	C	NP	2.6	UI	3.96	3.59	C	NP	3.2	UI
PTJ16	5.16	5.43	D	3.43	4.0	B	6.6	6.34	D	5.5	4.6	B	6.12	6.84	D	NP	4.8	UI
PTJ17	5.16	5.73	D	4.47	4.3	C	6.60	6.64	D	6.49	4.6	B	7.24	7.14	D	NP	4.9	UI
PTJ18	4.42	3.39	D	3.66	3.0	B	4.02	4.26	B	6.07	4.1	B	5.14	4.78	B	NP	3.9	UI
PTJ19	2.80	2.77	D	2.34	2.6	B	3.33	3.19	B	NP	2.9	UI	4.81	4.36	B	NP	3.4	UI
PTJ20	1.90	2.41	B	2.74	2.6	B	3.07	3.39	B	NP	3.2	UI	3.96	3.92	C	NP	3.3	UI
PTJ21	5.16	3.76	D	3.66	3.4	B	3.55	4.28	B	6.49	4.3	B	5.59	4.55	B	NP	3.9	UI
PTJ22	1.91	2.61	B	2.34	2.9	B	3.07	4.01	B	NP	3.3	UI	4.52	5.53	B	NP	4.1	UI
PTJ23	1.62	1.51	B	NP	1.5	UI	2.59	2.71	C	NP	1.5	UI	NP	3.33	UI	NP	2.1	UI
PTJ24	5.16	3.69	D	3.66	3.2	B	4.02	4.22	B	NP	3.3	UI	5.06	4.77	B	NP	3.5	UI
PTJ25	NP	1.05	UI	NP	1.0	UI	NP	2.15	UI	NP	1.0	UI	NP	2.86	UI	NP	1.6	UI
PTJ26	NP	0.98	UI	NP	0.6	UI	NP	1.21	UI	NP	1.2	UI	NP	2.41	UI	NP	1.6	UI
PTJ27	2.41	2.45	B	NP	1.4	UI	3.82	3.16	B	NP	2.0	UI	5.26	4.26	B	NP	2.4	UI

❖ PVTT; predicted value throat thickness, EVTT; experimental value throat thickness, PVJP; predicted value joint penetration, EVJP; experimental value joint penetration, PEQLTT; predicted and experimental quality level for throat thickness, PEQLJP; predicted and experimental quality level for joint penetration, UI; unacceptable insufficient, NP; not predicted

4.3.7 Throat thickness

One of the weld quality characteristics is throat thickness, which determines the quality of joint formation. The joint formation with respect to throat thickness is determined based on the selection of process parameters. The size of throat thickness is influenced more by changes in the level of WFR compared to TS and more by CTWD compared to EWA. Increasing the level of EWA also leads to an increase in throat thickness. This phenomenon occurs due to the arc distance, resulting in more filler metal being deposited. The filler metal deposition mechanism contributes to the variation in throat thickness. A decrease or increase in CTWD level affects throat thickness reduction. When the level of CTWD increases, the amount of filler metal deposited at the joint location on the workpiece increases. Conversely, when the CTWD level is reduced, the filler wire is closer to the joint and fuses with the weldment instead of being deposited on the surface, which affects the size of the throat thickness. The CTWD level is set in the middle for acceptable throat thickness. In the case of other parameters, the size of throat thickness is affected more by changes in the level of WFR than TS. Some welded joints exhibit different throat thicknesses, as shown in Fig. 4.6.

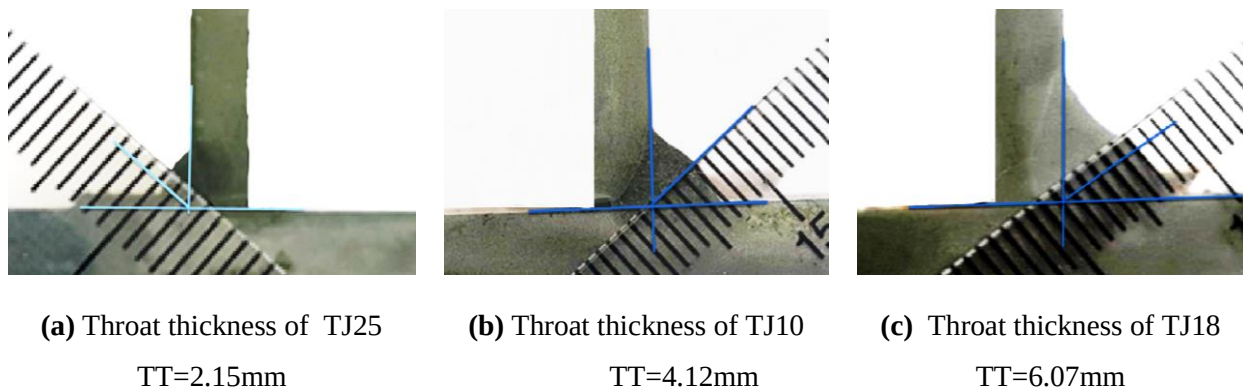


Figure 4.6: Welded samples for throat thickness measurement for a 4mm plate

The effect of process parameters on throat thickness is shown in Fig. 4.7 in a three-dimensional representation. The impact of WFR and TS on throat thickness is evident in their different combinations. For example, the maximum throat thickness of 4.42mm has been observed at a WFR of 3.2-4.7m/min and TS of 180-220mm/min; WFR 5-5.8m/min and TS of 230-350mm/min; WFR of 6.2-6.7m/min and TS of 380-570mm/min. The minimum throat thickness of 2.22mm has been noted at a WFR of 3.2-3.8m/min and TS of 350-470mm/min; WFR of 4.2-5mm/min and TS of 490-570mm/min. A throat thickness of 3.32mm is obtained

at WFR of 5-7m/min and TS of 150-210mm/min; WFR of 6.2-7m/min and TS of 210-350mm/min; WFR of 3-3.8m/min and TS of 490-550mm/min. Throat thickness is above the average at WFR of 3-5m/min and TS of 150-290mm/min; WFR of 4.5-6.2m/min and TS of 220-420mm/min; WFR of 5.2-7m/min and TS of 350-550mm/min. Throat thickness is lower, below 3.32mm, when WFR is at 3-4.5m/min and TS 275-490mm/min; WFR at 4-5.5m/min and TS 400-550mm/min (Fig. 4.7 (a)). The experimental result shows that WFR influences throat thickness more than other input parameters. Feeding too high WFR deposited extra filler materials in the weldment, resulting in excessive throat thickness; conversely, too low WFR deposited less filler metal in the weldment, resulting in insufficient throat thickness, which is in agreement with (Kamble and Rao, 2013; Adak, *et al.*, 2015) findings. The other set of combinations of parameters effect in terms of WFR and EWA on throat thickness is observed, with a maximum thickness of 4.42mm at WFR 5-5.8m/min and EWA 40.75-45°, and the minimum thickness is at WFR 3.3-3.8m/min and EWA 45-50°, measuring 2.22mm. In other combinations, such as WFR: 3-3.8m/min, 6.2-7m/min, 5-7m/min, and EWA: 40-42.1°, 40-50°, and 48-50°, the average throat thickness is calculated as 3.32mm. The above-average throat thickness, i.e. 3.32mm, is seen at WFR 4-6.2m/min and EWA 40-48° combinations. The lower thickness of the throat is noted at WFR 3-5m/min and EWA 42-50°, below the 3.32mm (Fig. 4.7 (b)). A similar trend has been observed from, (Dean, 2003; Winczek, *et al.*, 2019) findings that the throat thickness increases when EWA increases.

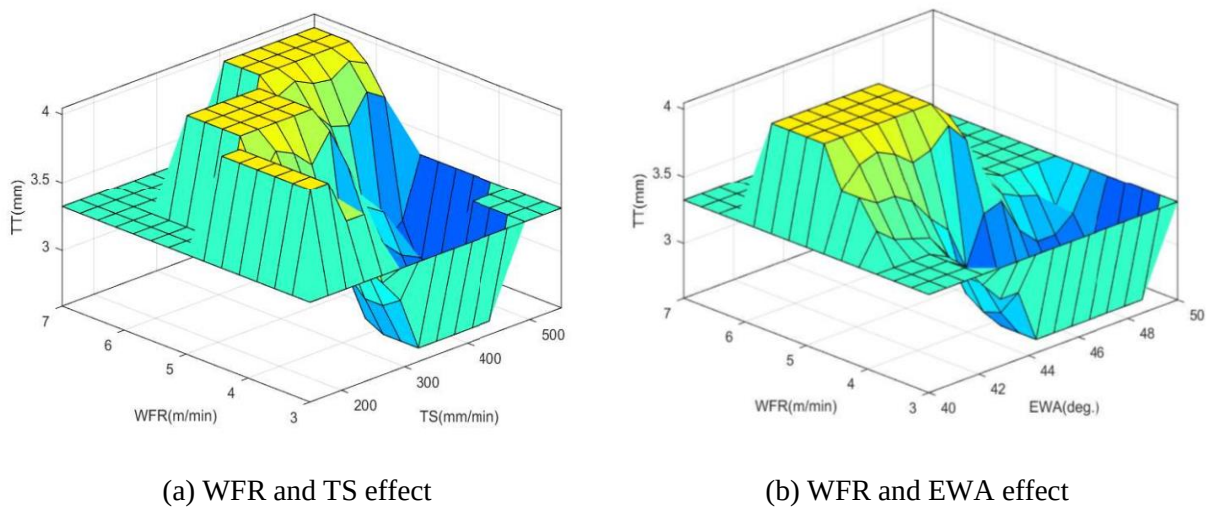


Figure 4.7: Surface plots of process parameters' effects on TT

Figure 4.8 (a &b) shows the effects of different combinations of WFR and CTWD, TS, and EWA on throat thickness. Based on the results combination from the fuzzy membership

functions of WFR and CTWD and TS and EWA, the maximum throat thickness is indicated as 4.42mm at WFR 6.2-6.7m/min and CTWD 10.6-14.2mm; WFR 6.2-6.7m/min and CTWD 15.7-19.3mm; WFR 4.7-5.8m/min and CTWD 15mm; Throat thickness is 3.32mm at WFR of 3-3.8m/min and CTWD 10-12mm. Throat thickness above average ($>3.32\text{mm}$) recorded at WFR of 4.3-7m/min and CTWD 10-20mm. Throat thickness below average ($<3.32\text{mm}$) recorded at WFR 3-3.5m/min and CTWD 10-20mm. The minimum is seen at WFR of 3.3-3.8m/min and CTWD of 12.9-19.10mm; WFR of 4.2-5m/min and CTWD of 10.8-12.1mm as 2.22mm. The weld throat thickness is sensitive to CTWD; the amount of throat thickness is increased at higher CTWD due to improvement in the arc pressure (Sterjovski, 2010; Adak, *et al.*, 2015).

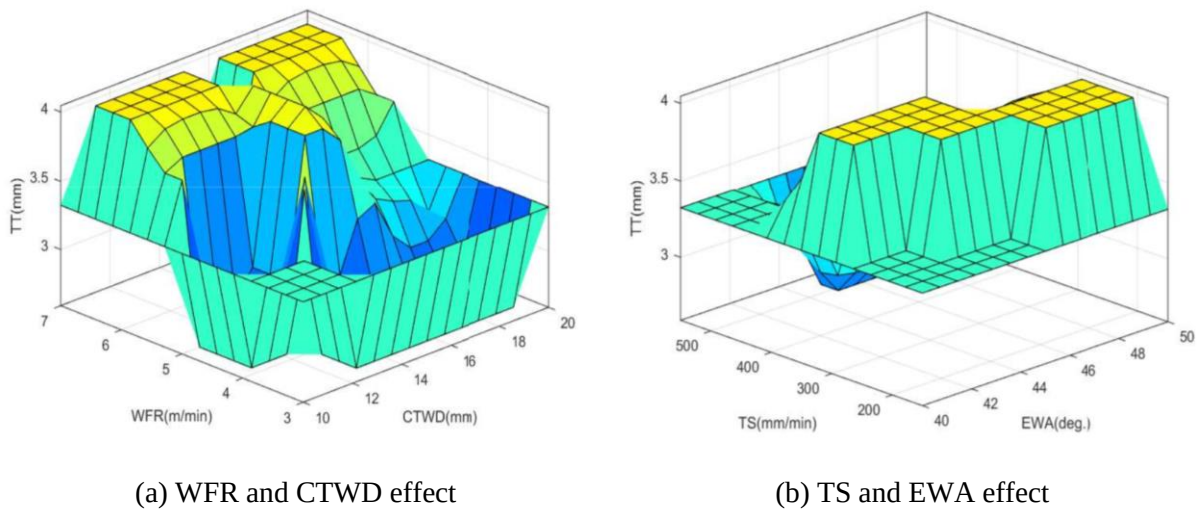


Figure 4.8: Surface plots of process parameters' effects on TT

In the case of TS and EWA combinations (Fig. 4.8 (b)), the throat thickness is a maximum of 4.42mm at TS:290-350mm/min and EWA:40-45°; TS:230-290mm/min and EWA:42.9-49.3°; and TS:175-270mm/min and EWA:45.8-49.3°. The lesser thickness value, 2.22mm, is noted at TS: 490-575mm/min and EWA: 45-49.1°. The average thickness is observed as 3.32mm at TS: 150-210mm/min and EWD: 40-45°; TS:150-270mm/min and EWD: 40-42.1°; TS:430-500mm/min and EWD: 40-42°; TS:325-390mm/min and EWD: 47.9-50°. The trends of these results show that increasing or decreasing TS influences TT. At higher TS, less electrode wire per unit length is deposited on the parent metals, resulting in smaller throat thickness and *vice-versa* (Kamble and Rao, 2013).

Similarly, the effects of TS, CTWD, EWA, and CTWD combinations are observed and plotted in the 3D form (Fig. 4.9 a&b). In the case of Fig. 4.9 (a), CTWD does not have a significant effect on throat thickness; throat thickness is higher (above 3.32mm) at lower

travel speeds (150-420mm/min). The throat thickness is below 3.32mm at higher travel speeds (375-550mm/min) and without significant effect of CTWD.

For EWA and CTWD combinations, throat thickness recorded a maximum of 4.42mm at 15mm CTWD and 40.9-45° EWA. The average throat thickness is 3.32mm at EWA:40-42.1° and CTWD: 10-12.1mm; EWA: 47.9-50° and CTWD: 15-20mm; EWA:40-50° and CTWD: 17.9-20mm. The throat thickness is recorded below 3.32mm at EWA: 42-50° and CTWD:10-15mm (Fig. 4.9 (b)).

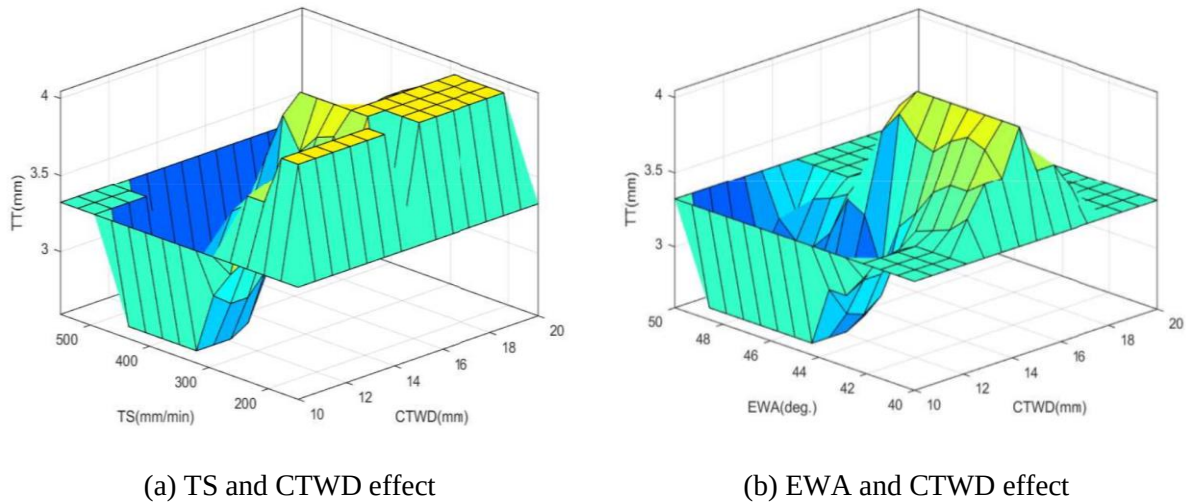


Figure 4.9: Surface plot of process parameters' effects on TT

EWA and CTWD are the main parameters determining the throat thickness amount. Generally, when the electrode-to-work angle increases, the throat thickness is reduced. Conversely, the throat thickness increases when the electrode-to-work angle is reduced below 45°. Additionally, when the CTWD is increased, the size of throat thickness also increases. Conversely, when the CTWD decreases, the filler materials and the parent metals are highly melted and fused down to the weldment joints, causing a significant reduction in throat thickness.

4.3.8 Joint penetration

The depth of joint penetration is influenced more by the changing WFR levels than TS and by EWA more than CTWD. When the level of EWA is decreased, the depth of joint penetration increases, and vice versa. A change in EWA, i.e., below 45°, leads to more arc penetration towards the vertical plate, which increases the joint penetration. This results in a greater effect on faying surfaces at the joint interface. Conversely, when the level of CTWD increases, the joint penetration decreases, and vice versa. This occurs due to the filler metal

being closer to the joints and the higher melting of the parent metal, which increases arc energy. Some welded joints represent different joint penetrations, as shown in Fig. 4.10.

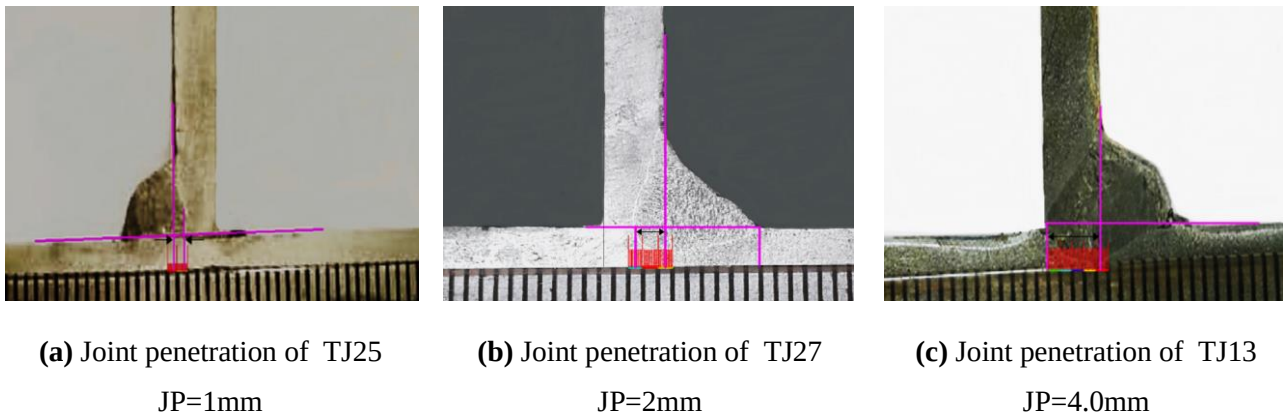
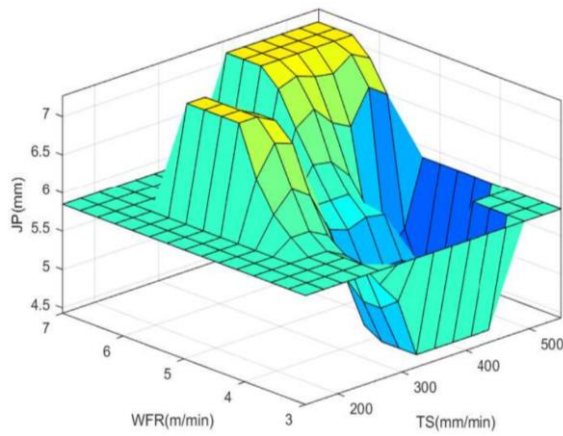


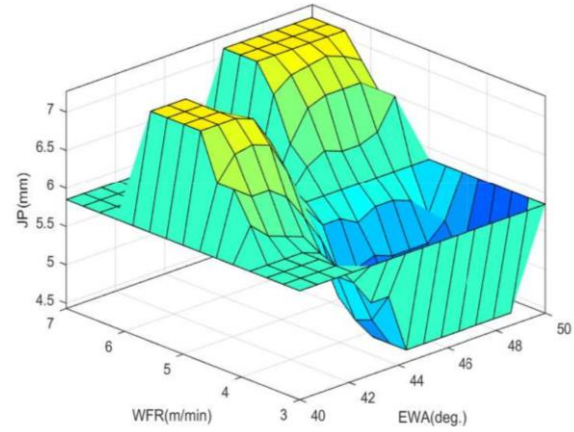
Figure 4.10: Welded samples for joint penetration measurement for 4mm plate

The rate of wire feed has a crucial effect on joint penetration. The maximum joint penetration of 8 mm has been observed at a WFR of 5-5.8m/min and TS of 230-260mm/min, and also at a WFR of 6.2-6.7m/min with TS of 380-520mm/min. The lesser value of joint penetration, 3.7mm, is noted at a WFR of 3.2-3.8m/min and TS of 350-420mm/min, as well as a WFR of 4.2-5m/min and TS of 490-525mm/min. Joint penetration is recorded above the average (5.85mm) at a WFR of 4-6.1m/min and TS of 210-350mm/min, as well as a WFR of 5.3-7m/min and TS of 350-550mm/min. Joint penetration is recorded below 5.85mm at a WFR of 3-5.5m/min and TS of 250-550mm/min (Fig. 4.11 (a)). WFR mostly determines the joint penetration; increasing the WFR increases the amount of heat input in the weld pool zone, increasing the joint penetration (Kamble and Rao, 2013; Adak, *et al.*, 2015).

The other set of combinations of parameters' effect in terms of WFR and EWA on joint penetration is observed as the maximum thickness of 8mm at a WFR of 5-5.8m/min and EWA of 40.6-42.1°; also at a WFR of 6.1-6.7m/min and EWA of 45.7-49.4°. The minimum penetration is at a WFR of 3.25-4.80m/min and EWA of 45-49.2°, measured as 3.7mm. The value of joint penetration was recorded above 5.85mm at a WFR of 3.8-6.1m/min and EWA of 40-45°, as well as a WFR of 5-7m/min and EWA of 45-50°. Joint penetration was recorded in the average range (5.85mm) at a WFR of 3-3.8m/min and EWA of 40-42.1° and a WFR of 6.1-7m/min and EWA of 40-45° (Fig. 4.11 (b)).



(a) WFR and TS effect

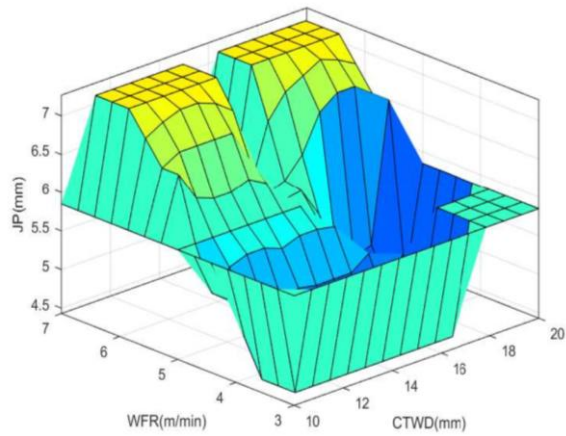


(b) WFR and EWA effect

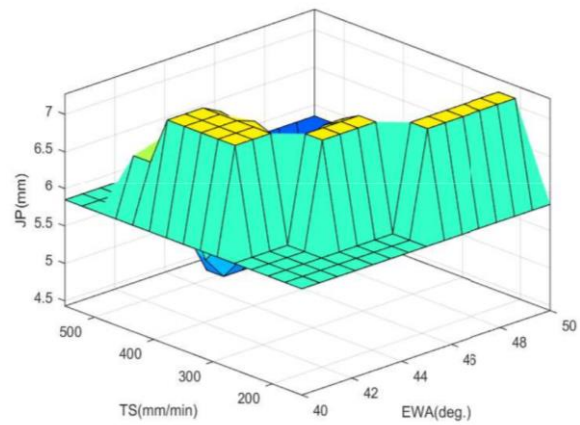
Figure 4.11: Surface plot of process parameters' effects on JP

In the combination of WFR and CTWD, the extent of joint penetration is above 5.85mm at a WFR of 5-7m/min and CTWD of 10-20mm. Joint penetration is recorded in the average range for the setting combination of a WFR of 3-3.8m/min and CTWD 17.9-20mm. Below 5.85mm of joint penetration has been recorded at a WFR of 3-5.5m/min and CTWD of 10-20mm (Fig. 4.12 (a)). There is an inverse relationship between CTWD and joint penetration, i.e., joint penetration decreases by increasing CTWD. At higher CTWD, the arc pressure reduction takes place, leading to increased resistance of current flow (Adak, *et al.*, 2015).

Joint penetration recorded a maximum value of 8mm at TS of 290-410mm/min and EWA of 40.7-42.2°; TS of 230-320mm/min and EWA of 42.9-45°; TS of 160-210mm/min and EWA of 45.7-49.4°. Recorded joint penetration is at an average of 5.85mm at a TS of 150-210mm/min and EWA of 40-45°; TS of 150-270mm/min and EWA of 40-42.1°; TS of 490-550mm/min and EWA of 40-42.1°. Joint penetration was recorded below the average of 5.85mm at TS of 350-550mm/min and EWA of 43-50° (Fig. 4.12 (b)). If the TS is increased, heat input per unit length of the weld decreases, and less filler metal is applied per unit length of the weld, resulting in shallow joint penetration. Joint penetration is affected more by TS than WFR. Conversely, too low TS provides excessive joint penetration, conferring to other related findings (Kim, *et al.*, 2003; Kamble and Rao, 2013; Gyasi, *et al.*, 2017).



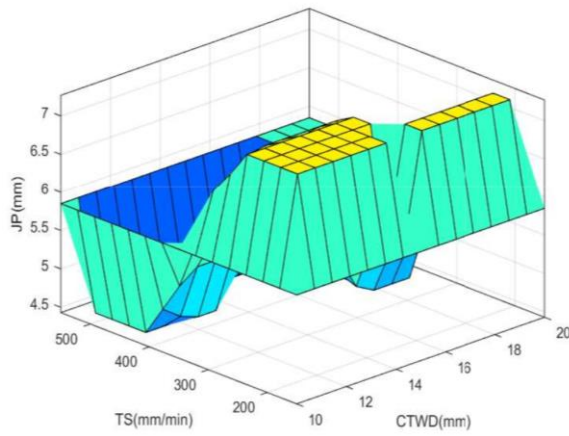
(a)WFR and CTWD effect



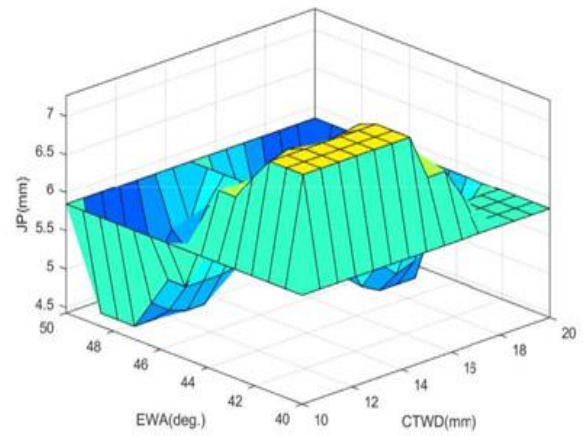
(b) TS and EWA effect

Figure 4.12: Surface plot of process parameters' effects on JP

The value of joint penetration is 8mm at TS of 180-230 and CTWD of 10.6-14.2mm; TS of 160-260 and CTWD of 15.7-19.3mm; TS of 180-210 and CTWD of 10.6-14.2mm. An average joint penetration (5.85mm) has been noted at a TS of 490-550mm/min and CTWD of 17.9-20mm. Joint penetration is below 5.85mm at a TS setting of 260-550mm/min, and CTWD of 10-20mm, and joint penetration is noted above average at a TS of 150-350mm/min and CTWD of 10-20mm. The recorded joint penetration reaches the minimum value (3.7mm) at a TS of 430-525mm/min and CTWD of 10.5-12mm; TS of 490-525mm/min and CTWD of 10.5-17; TS of 350-460mm/min and CTWD of 17.7-19.2mm (Fig. 4.13 (a)). At the combination of EWA and CTWD, the value of joint penetration is above 5.85mm at EWA of 40-45° and CTWD of 10-18mm. The noted joint penetration has been averaging at EWA 40-42.1° and CTWD 17.9-20mm. Joint penetration was registered below 5.85mm at EWA of 42-50° and CTWD of 10-15mm; EWA 45-50° and CTWD of 15-20mm. The extent of penetration has reached the maximum point at the combined setting of EWA 40.6-42.1° and CTWD 10.8-15mm. Conversely, the lower joint penetration (3.7mm) has been recorded at the setting of EWA 47.9-49.2° and CTWD 10.8-12.1mm; EWA 45-49.2° and CTWD 17.9-19.2mm (Fig. 4.13 (b)). EWA and CTWD influence the shape of the weld pool and joint penetration is relatively more influenced by EWA than CTWD. When the EWA is increased, the value of joint penetration is reduced and vice versa. CTWD also significantly affects joint penetration; when the CTWD is reduced, the amount of joint penetration is increased, and vice versa.



(a) TS and CTWD effect



(b) EWA and CTWD effect

Figure 4.13: Surface plot of process parameters' effects on JP

This investigation not only introduces an innovative approach to parameter selection through artificial intelligence but also emphasizes the importance of plate thickness and torch angle considerations for achieving and maintaining desired quality levels in robotic GMAW processes. These findings contribute significantly to advancing the state-of-the-art in welding technology, providing practical insights for improved manufacturing practices. The developed model is particularly suitable for emerging as a real-time automatic control system for the robotic gas metal arc welding process to produce products at desired weld quality levels of 'D', 'C', and 'B'. The parameters specific results are specific to the plate thickness and the material considered in this investigation. However, the developed approach is universal and can be applied to dissimilar plate thicknesses and dissimilar material combinations.

4.4 Process parameter optimization for joint strength and joint penetration

4.4.1 Performance of the joints

Mechanical break strength and joint penetration responses have been measured as per the experimental plan indicated in Table 4.7. The weldment failure pattern of break strength tests shows the weldment parts of the fracture are remaining in both plates (but more in the vertical plate which significantly determines the extent of joint penetration) at the specimen welded by 40° EWA. In the other specimens the weldment part of the fracture mainly remains in the horizontal plate for specimen are welded by 45° and 55° EWA. The break strength weldment failure pattern (fracture mode) and joint penetration measurement techniques through

macrostructures have been shown in Fig. 4.14 and 4.15 respectively. The results of break strength and joint penetrations of the welded joints are depicted in Table 4.7.



(a) Weldment failure pattern at TJ15

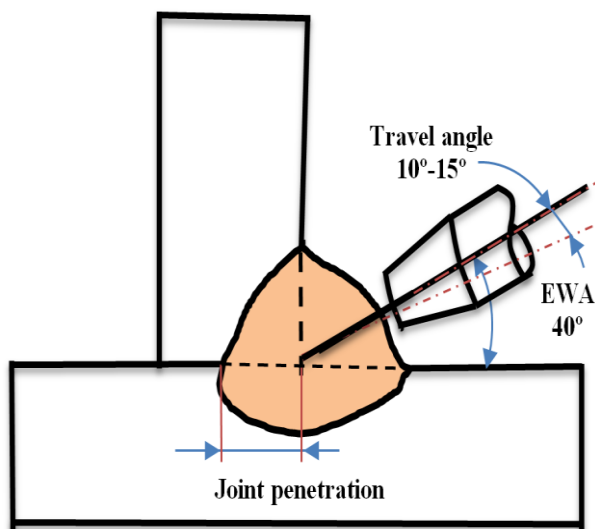


(b) Weldment failure pattern at TJ4

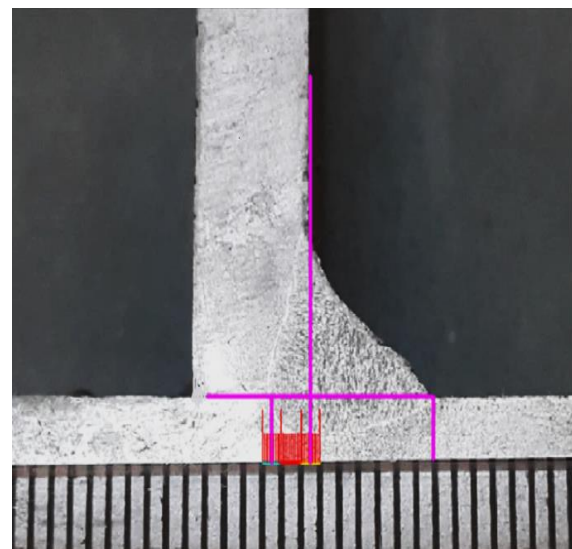


(c) Weldment failure pattern at TJ12

Figure 4.14: Infringement phenomenon of break strength



(a) Schematic diagram at 40°



(b) Test sample (OTJ6)=2.0mm

Figure 4.15: Joint penetration

Table 4.7 Responses of break strength and joint penetration

Sl. No.	Factors				Responses	
	WFR (m/min)	TS (mm/min)	EWA (deg.)	CTWD (mm)	BS (kN)	JP (mm)
OTJ1	7	350	45	20	49.3	3.1
OTJ2	5	250	45	15	47.02	3.5
OTJ3	7	250	40	10	66.25	3.7
OTJ4	9	250	45	10	65.46	3.9
OTJ5	9	450	40	20	51.06	2.4
OTJ6	7	450	50	15	38.7	2.0
OTJ7	3	350	40	10	32.51	2.7
OTJ8	3	150	45	15	43.2	3.4
OTJ9	5	450	50	10	31.56	1.6
OTJ10	7	150	45	10	75.3	4.6
OTJ11	5	350	40	15	46.8	3.4
OTJ12	9	350	50	20	50.33	3.3
OTJ13	5	150	50	20	46.51	4.1
OTJ14	3	250	50	10	35.4	2.3
OTJ15	9	150	40	15	72.3	5.2
OTJ16	3	450	45	20	18.49	1.5

BS; break strength, JP; joint penetration

- OTJ10 and OTJ15 are a higher WFR with lower TS; in real fabrication industry this setting do not applicable due to excessive deposition rate; wastage of filler materials and electric power.

4.4.2 Statistical analyses

The strengths and limitations of experimental design have been checked using the JMP evaluate design platform which determines the ability of design to detect the effects associated with meaningful changes in the responses, and address prediction variance and the precision of parameter estimates. The best fit from the developed models and adequacy has been determined by the analysis of variance (ANOVA) and the statistical significance has been evaluated. The full model has been presented in Table 4.8.

Table 4.8 Break strength parameter estimate full model

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	46.967445	0.0051	9209.0	<.0001*
WFR(m/min)(3,9)	12.905625	0.002212	5833.7	0.0001*
TS (mm/min)(150,450)	-15.03554	0.004173	-3603	0.0002*
EWA (deg.)(40,50)	-5.229697	0.002651	-1973	0.0003*
CTWD (mm)(10,20)	-1.426252	0.003013	-473.3	0.0013*
WFR(m/min)*WFR(m/min)	-7.485369	0.002785	-2687	0.0002*

Term	Estimate	Std Error	t Ratio	Prob> t
WFR(m/min)*TS (mm/min)	1.5582901	0.003502	444.92	0.0014*
TS (mm/min)*TS (mm/min)	0.0296995	0.00335	8.87	0.0715 Not significant
WFR(m/min)*EWA (deg.)	5.1011816	0.005552	918.84	0.0007*
TS (mm/min)*EWA (deg.)	2.2940614	0.004315	531.70	0.0012*
EWA (deg.)*EWA (deg.)	3.9823673	0.005673	701.99	0.0009*
WFR(m/min)*CTWD (mm)	-1.520964	0.003951	-385.0	0.0017*
TS (mm/min)*CTWD (mm)	4.1318994	0.002695	1533.3	0.0004*
EWA (deg.)*CTWD (mm)	-4.867357	0.005916	-822.8	0.0008*
CTWD (mm)*CTWD (mm)	4.2515426	0.005237	811.80	0.0008*

The full model shows that all parameters except TS (mm/min)*TS (mm/min) are significant at the 0.05 level. To get a better model non-significant factors and unimportant terms were removed. The final reduced mathematical models with significant coefficients are given in Table 4.9 for break strength and in Table 4.10 for joint penetration. The reduced models with significant coefficients were developed. It was found the reduced models were better than the full models because the reduced models have higher values of R^2 (adjusted) and lesser values of standard-error estimates than the full models.

Table 4.9 New fitted model or simplified model for break strength

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	46.963023	0.03202	1466.7	<.0001*
WFR(m/min)(3,9)	12.898669	0.013049	988.51	<.0001*
TS (mm/min)(150,450)	-15.05001	0.02423	-621.1	<.0001*
EWA (deg.)(40,50)	-5.236422	0.016023	-326.8	<.0001*
CTWD (mm)(10,20)	-1.412219	0.016176	-87.30	0.0001*
WFR(m/min)*WFR(m/min)	-7.484511	0.017561	-426.2	<.0001*
WFR(m/min)*TS (mm/min)	1.5684833	0.02087	75.15	0.0002*
WFR(m/min)*EWA (deg.)	5.114105	0.033794	151.33	<.0001*
TS (mm/min)*EWA (deg.)	2.3111059	0.024366	94.85	0.0001*
EWA (deg.)*EWA (deg.)	4.0039662	0.032319	123.89	<.0001*
WFR(m/min)*CTWD (mm)	-1.539046	0.021344	-72.11	0.0002*
TS (mm/min)*CTWD (mm)	4.131969	0.016999	243.07	<.0001*
EWA (deg.)*CTWD (mm)	-4.890372	0.033533	-145.8	<.0001*
CTWD (mm)*CTWD (mm)	4.268273	0.030819	138.49	<.0001*

Table 4.10 Joint penetration parametric estimate

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	3.3364525	0.016	208.52	<.0001*
WFR(m/min)(3,9)	0.5952085	0.00652	91.28	0.0001*
TS (mm/min)(150,450)	-1.318266	0.012108	-108.9	<.0001*
EWA (deg.)(40,50)	-0.267615	0.008007	-33.42	0.0009*
CTWD (mm)(10,20)	0.1704974	0.008083	21.09	0.0022*

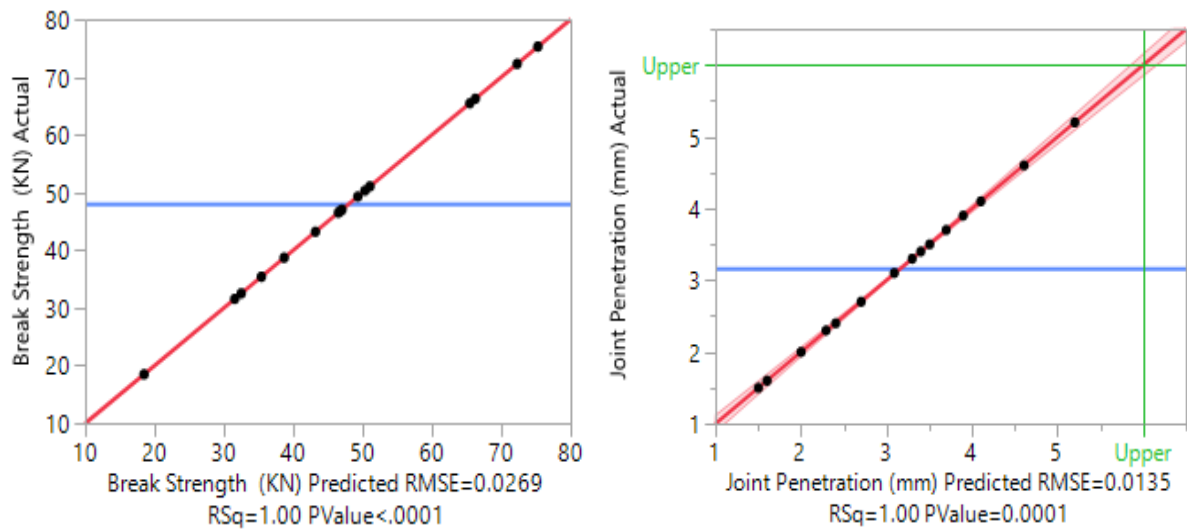
Term	Estimate	Std Error	t Ratio	Prob> t
WFR(m/min)*WFR(m/min)	-0.274837	0.008775	-31.32	0.0010*
WFR(m/min)*TS (mm/min)	-0.383984	0.010429	-36.82	0.0007*
WFR(m/min)*EWA (deg.)	0.4777258	0.016887	28.29	0.0012*
TS (mm/min)*EWA (deg.)	-0.152698	0.012176	-12.54	0.0063*
EWA (deg.)*EWA (deg.)	0.2044265	0.01615	12.66	0.0062*
WFR(m/min)*CTWD (mm)	0.0422155	0.010665	3.96	0.0583
TS (mm/min)*CTWD (mm)	-0.063208	0.008495	-7.44	0.0176*
EWA (deg.)*CTWD (mm)	-0.249961	0.016756	-14.92	0.0045*
CTWD (mm)*CTWD (mm)	-0.095287	0.0154	-6.19	0.0251*

Despite the reduction in run size in the actual design the relative standard errors for all parameters either exceed or equal to the standard errors for the intended design. All except (TS(mm/min)xCTWD(mm)) relative standard errors in the actual design are equal to the intended design Table 4.11.

Table 4.11 Estimation Efficiency Summaries, Actual design and intended design

Term	Actual design		Intended design	
	Fractional Increase in CI Length	Relative Std Error of Estimate	Fractional Increase in CI Length	Relative Std Error of Estimate
Intercept	3.781	1.195	3.758	1.189
WFR(m/min)	1.074	0.518	0.939	0.485
TS (mm/min)	2.912	0.978	2.6	0.9
EWA (deg.)	1.485	0.621	1.381	0.595
CTWD (mm)	1.825	0.706	1.404	0.601
WFR(m/min)*WFR(m/min)	1.611	0.653	1.609	0.652
WFR(m/min)*TS (mm/min)	2.283	0.821	2.101	0.775
TS (mm/min)*TS (mm/min)	2.14	0.785		
WFR(m/min)*EWA (deg.)	4.204	1.301	4.022	1.255
TS (mm/min)*EWA (deg.)	3.044	1.011	2.621	0.905
EWA (deg.)*EWA (deg.)	4.318	1.329	3.802	1.201
WFR(m/min)*CTWD (mm)	2.703	0.926	2.172	0.793
TS (mm/min)*CTWD (mm)	1.526	0.631	1.526	0.631
EWA (deg.)*CTWD (mm)	4.545	1.386	3.983	1.246
CTWD (mm)*CTWD (mm)	3.909	1.227	3.579	1.145

The actual by-predicted plot (Fig. 4.16) shows no evidence of a lack of fit. The model is significant. The notation $P < 0.0001$ for break strength, and $P = 0.0001$ for joint penetration gave the significance level of the overall model test. $R^2 = 1.00$ indicated that the data points fit a line or curve closely, and the square root of the mean square error (RMSE) is 0.0135 and 0.0269 for break strength and joint penetration respectively. Therefore the prediction models can be perceived as valid and accurate. The values of R^2 and standard error of estimates for both models are given in Table 4.12.



A. Break strength

b. Joint penetration

Figure 4.16: Effect summaries, actual by predicted plot

Table 4.12 Summary, Lack of fit

	Break strength	Joint penetration
RSquare	1	0.999978
RSquare Adj	0.999997	0.999833
Root Mean Square Error	0.026919	0.013452
Mean of Response	48.13688	3.16875
Observations (or Sum Wgts)	16	16

Figure 4.17 shows the prediction variance profile after maximizing desirability for the bounce input parameters; the largest value of the relative prediction variance is 1.414871, the values of the factors that gave the worst-case relative variance.

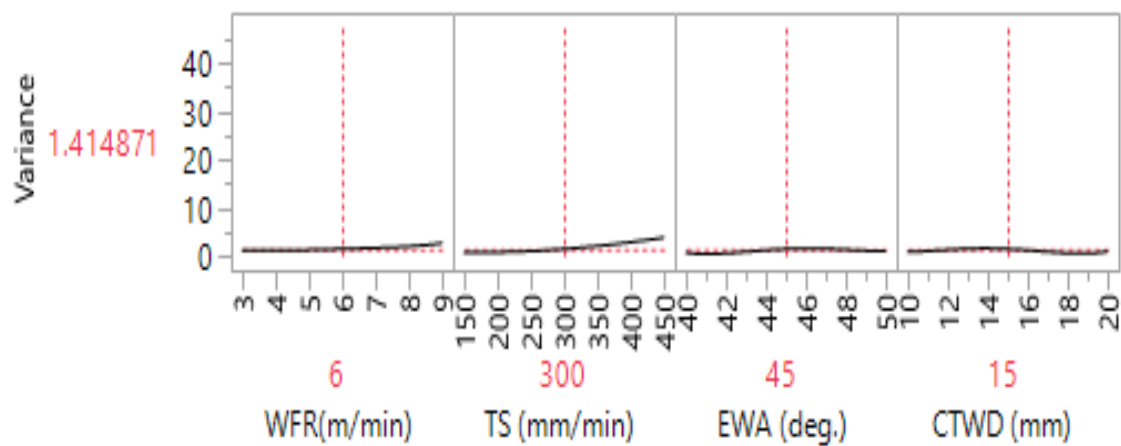


Figure 4.17: Prediction variance profile

Analysis of the variance report shows the sources of variations in Table 4.13, the model degrees of freedom (DF) are 13 and the Error DF is 2 for both responses. The recorded Error DF has shown that the difference between the Corrected Total (C. Total) DF and the Model DF is less. The C. Total DF is 15 for break strength and joint penetration which is one less than the number of total observations. Each mean square is the sum of squares divided by its corresponding DF. The mean square of the model is 280.295 and 1.25185 and the mean square of error is 0.000725 and 0.00018 for break strength and joint penetrations respectively. The small values of the mean square error indicate the data points are dispersed closely around its central moment as shown in Fig 4.16. The recorded value of Prob> F is 0.0001 and <0.0001 for break strength and joint penetration respectively, the p-value for the test indicated that the observed F Ratio is unlikely, and the model is significant.

Table 4.13 Analysis of variance

Source	DF	Break strength			Joint penetration		
		Sum Squares	of Mean Square	F Ratio	Sum Squares	of Mean Square	F Ratio
Model	13	3643.8397	280.295	386805.3	16.274013	1.25185	6918.415
Error	2	0.0014	0.000725	Prob > F	0.000362	0.00018	Prob > F
C. Total	15	3643.8411		<.0001*	16.274375		0.0001*

The canonical curvature report shows eigenvalues and eigenvectors of the effects. The positive eigenvalue 6.9721 of break strength and 0.3861 of joint penetration indicates positive curvature and the eigenvector values indicate that the curvature is primarily in the EWA direction. The large negative eigenvalue -8.0752 of break strength and -0.4355 of joint penetration indicates negative curvature and the eigenvector values indicate that the curvature is primarily in the WFR direction Table 4.14.

Table 4.14 Canonical curvature

A. Break strength

Eigenvalue	6.9721	3.4677	-1.5864	-8.0752
WFR(m/min)(3,9)	0.15286	0.14357	0.00732	0.97774
TS (mm/min)(150,450)	-0.08286	0.56168	0.81971	-0.07566
EWA (deg.)(40,50)	0.67911	0.60701	-0.36505	-0.19257
CTWD (mm)(10,20)	-0.71314	0.54355	-0.44131	0.03498

B. Joint penetration

Eigenvalue	0.3861	0.0435	-0.1556	-0.4355
WFR(m/min)(3,9)	0.39462	-0.25660	0.07373	0.87920
TS (mm/min)(150,450)	-0.32442	0.76354	0.44986	0.33074
EWA (deg.)(40,50)	0.83750	0.29807	0.33088	-0.31666
CTWD (mm)(10,20)	-0.19396	-0.51217	0.82626	-0.13172

4.4.3 Desirability profiling and optimization

The optimal setting of input parameters from the defined upper and lower level of welding parameters has been traced for the responses of break strength and joint penetration by using the axes of the prediction profiler. Prediction profiler for bounce data JMP with desirability maximized. The desirability function was used to identify one combination of factor-level settings (usually out of many possible combinations) by maximizing the desirability function. Figure 4.18 shows the settings as a wire feed rate (8.29m/min), travel speed (243mm/min), electrode to work angle (40°), and contact tip to work distance (10 mm) were predicted an estimated responses of break strength and joint penetration of 67.45kN and 3.71mm respectively, with the overall desirability measurement of 0.90, which is closed to 1 that indicates the responses positioned at the maximum and aligned at the most desirable responses. Table 4.15 shows predicted optimum combinations of input parameters.

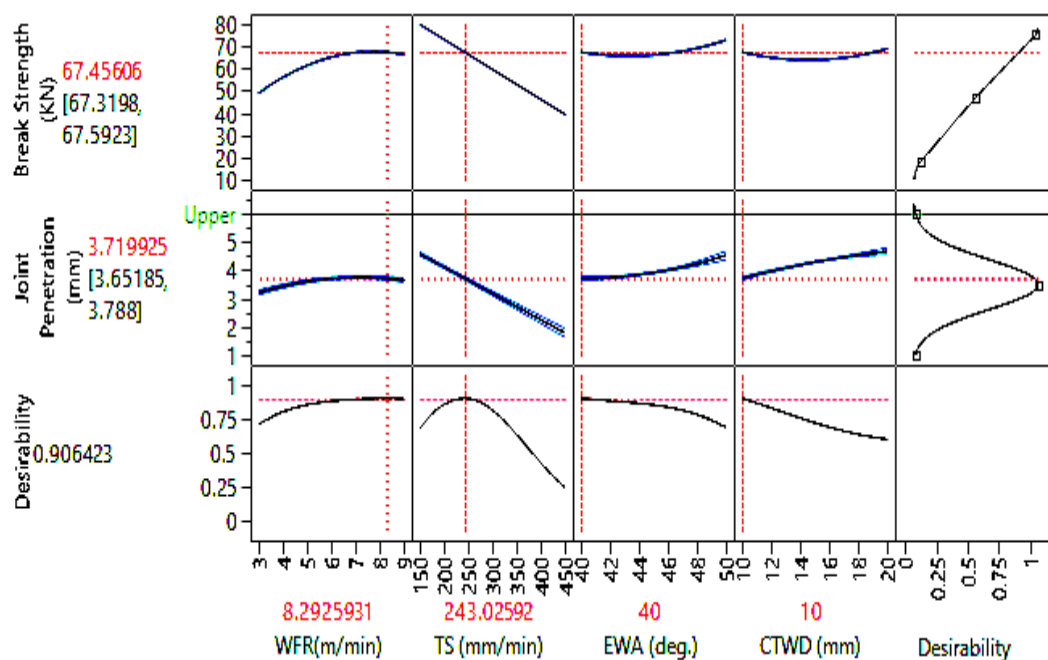


Figure 4.18: Prediction profiler plot with max. Desirability and optimum factor settings

Table 4.15 Predicted optimum combinations of input parameters

WFR m/min	TS (mm/min)	EWA (°)	CTWD (mm)	BS (kN)	JP (mm)	Desirability
8.29	243	40	10	67.45	3.71	0.90

4.4.4 Prediction and validation of the model

Prediction models were constructed for each response variable to find the optimum combination of input parameters on the break strength and joint penetration. The derived equations are built using standard least square regression+. The main effect, second interaction effects, and quadratic effect among the input variables were also taken into consideration. The optimal parameters values and regression model have been predicted by using prediction profilers, the prediction formula used to see predicted ratings for all the experiments. The prediction expression of break strength and joint penetration is given by prediction expression ‘A’ and ‘B’ respectively.

A, Prediction expression for break strength

$$\begin{aligned}
 BS = & 46.96 + 12.89 \left(\frac{(WFR(m/min) - 6)}{3} \right) - 15.05 \left(\frac{(TS(mm/min) - 300)}{150} \right) - \\
 & 5.23 \left(\frac{(EWA(deg.) - 45)}{5} \right) - 1.41 \left(\frac{(CTWD(mm) - 15)}{5} \right) + \\
 & \left(\frac{(WFR(m/min) - 6)}{3} \right) \cdot \left(\frac{(WFR(m/min) - 6)}{3} \right) \cdot -7.48 + \\
 & \left(\frac{(WFR(m/min) - 6)}{3} \right) \cdot \left(\frac{(TS(mm/min) - 300)}{150} \right) \cdot 1.57 + \\
 & \left(\frac{(WFR(m/min) - 6)}{3} \right) \cdot \left(\frac{(EWA(deg.) - 45)}{5} \right) \cdot 2.31 + \\
 & \left(\frac{(EWA(deg.) - 45)}{5} \right) \cdot \left(\frac{(EWA(deg.) - 45)}{5} \right) \cdot 4.0 + \\
 & \left(\frac{(WFR(m/min) - 6)}{3} \right) \cdot \left(\frac{(CTWD(mm) - 15)}{5} \right) \cdot -1.54 + \\
 & \left(\frac{(EWA(deg.) - 45)}{5} \right) \cdot \left(\frac{(CTWD(mm) - 15)}{5} \right) \cdot -4.89 + \\
 & \left(\frac{(CTWD(mm) - 15)}{5} \right) \cdot \left(\frac{(CTWD(mm) - 15)}{5} \right) \cdot 4.27
 \end{aligned}$$

B, Prediction expression for joint penetration

$$\begin{aligned} JP = & 3.33 + 0.59 \cdot \left(\frac{(WFR(m/min) - 6)}{3} \right) - 1.31 \left(\frac{(TS(mm/min) - 300)}{150} \right) - \\ & 0.27 \left(\frac{(EWA(deg.) - 45)}{5} \right) + 0.17 \left(\frac{(CTWD(mm) - 15)}{5} \right) + \\ & \left(\frac{(WFR(m/min) - 6)}{3} \right) \cdot \left(\left(\frac{(WFR(m/min) - 6)}{3} \right) \cdot -0.27 \right) + \\ & \left(\frac{(WFR(m/min) - 6)}{3} \right) \cdot \left(\left(\frac{(TS(mm/min) - 300)}{150} \right) \cdot -0.38 \right) + \\ & \left(\frac{(WFR(m/min) - 6)}{3} \right) \cdot \left(\left(\frac{(EWA(deg.) - 45)}{5} \right) \cdot 0.47 \right) + \\ & \left(\frac{(EWA(deg.) - 45)}{5} \right) \cdot \left(\left(\frac{(EWA(deg.) - 45)}{5} \right) \cdot 0.20 \right) + \\ & \left(\frac{(WFR(m/min) - 6)}{3} \right) \cdot \left(\left(\frac{(CTWD(mm) - 15)}{5} \right) \cdot -0.042 \right) + \\ & \left(\frac{(EWA(deg.) - 45)}{5} \right) \cdot \left(\left(\frac{(CTWD(mm) - 15)}{5} \right) \cdot -0.24 \right) + \\ & \left(\frac{(CTWD(mm) - 15)}{5} \right) \cdot \left(\left(\frac{(CTWD(mm) - 15)}{5} \right) \cdot -0.09 \right) \end{aligned}$$

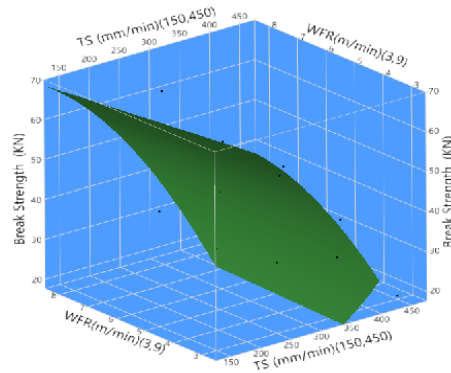
By using the optimal setting of input parameters which has been maximized by desirability functions conformity test runs were conducted. The responses of 65.13kN break strength and 3.63mm joint penetration have been recorded. The recorded results showed that the accuracy of the mathematical models is 96.56% and 97.84 (3.44 and 2.16% average error) of break strength and joint penetration respectively. It has been concluded that the percentage error obtained between the mathematical models and experimentally validated values is quite small and the predicted capacity is closer to test capacity.

4.4.5 Response for break strength

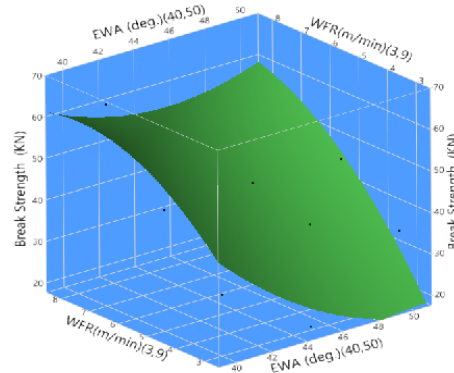
The weld quality characteristic of the Tee-joint has been determined by break strength and joint penetration of the weldment. WFR, TS, EWA, and CTWD are the main input process parameters that significantly affect the weld quality. The surface plots of process parameters WFR, TS, EWA, and CTWD combined effects on break strength are shown in Fig. 4.19, 4.20, and 4.21. The rate of wire feed has a crucial effect on the break strength and joint penetration (Srivastava and Garg, 2017). An increase in WFR results in increased joint

strength due to an increase in the level of welding current. If the wire feed speed is too high, the deposition of filler metals with amperage is increased and creates an excessive depth of penetration and bead geometry (Badheka, 2013; Kamble and Rao, 2013; Ramos-Jaime, *et al.*, 2013; Sathiya, *et al.*, 2013). If the WFR is too low, the amount of filler wire feeds to the weldment is very low resulting in a lack of penetration and insufficient weld reinforcement which is in agreement with (Kim, *et al.*, 2003; Kamble and Rao, 2013) findings.

Secondly, weld penetration is affected significantly by travel speed. Within limits, welding speed can be adjusted to control weld size and penetration. If the welding speed is increased, heat input of the weld is decreased and less filler metal is applied per unit length of the weld, resulting in weak joint strength. Excessive travel speed formed a lack of joint penetration and insufficient weld bead reinforcement due to the short time (Kamble and Rao, 2013). Too slow speed produces excessive depth penetration and may also in a large molten weld pool result in excessive joint penetration and waste of materials and electric energy in the process (Ramos-Jaime, *et al.*, 2013; Adak, *et al.*, 2015; Gyasi, *et al.*, 2017; Gupta, *et al.*, 2019).



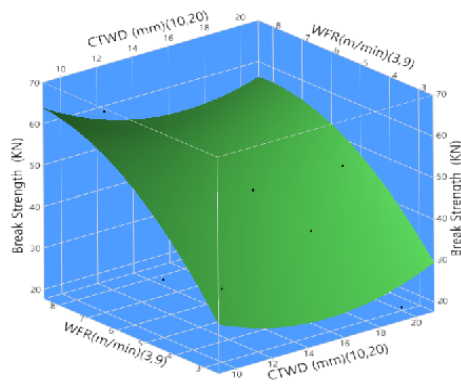
(a) WFR and TS effect



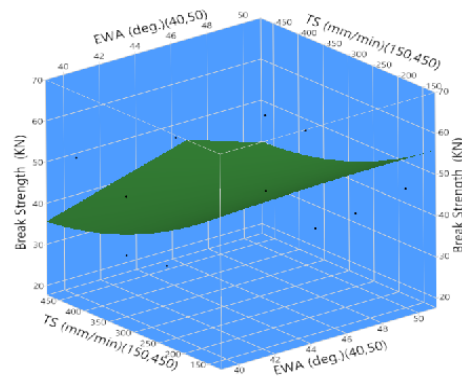
(b) WFR and EWA effect

Figure 4.19: Response surface plots of process paramters' effects on break streangth

The joint strength of the Tee-joints has been different in various EWA. At the decline electrode work angle, the extent of joint penetration has been increased due to the fusion of both plates taking place significantly and resulting in increased joint strength. With increasing EWA joint strength has been reduced significantly due to the arc impingement being focused near the corner of the two joints which determines the level of joint penetrations. When the EWA decreased the amount of joint strength has been increased significantly due to the arc impingement being focused above the corner of the two plates (focused considerably in the vertical plate) which enhances joint penetration (Lee and Rhee, 2000; Badheka, 2013).



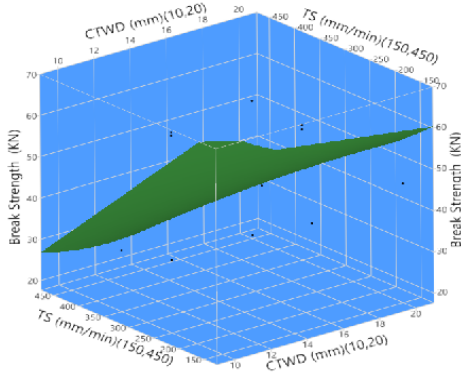
(a) WFR and CTWD effect



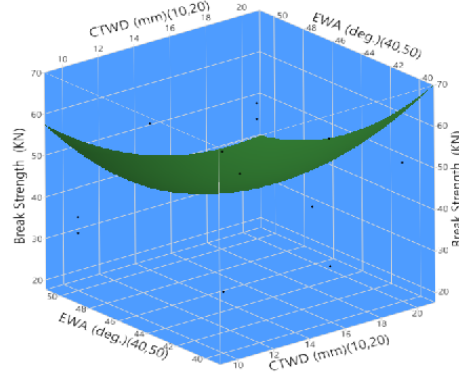
(b) TS and EWA effect

Figure 4.20: Response surface plots of process paramters' effects on break streangth

CTWD is another welding input parameter that significantly determines the level of break strength and joint penetrations; the CTWD has been settled properly to achieve the desired weld quality characteristics. When the contact tip-to-work distance increases joint strength has been decreased because creating a lack of the arc force due to the distance between the tip of the wire and the parent metals (Kim, *et al.*, 2003). On the other side when CTWD decreases the joint strength has been also reduced because the shorten art length creates less arc force which cannot penetrate the welded metals (Badheka, 2013).



(a) TS and CTWD effect



(b) EWA and CTWD effect

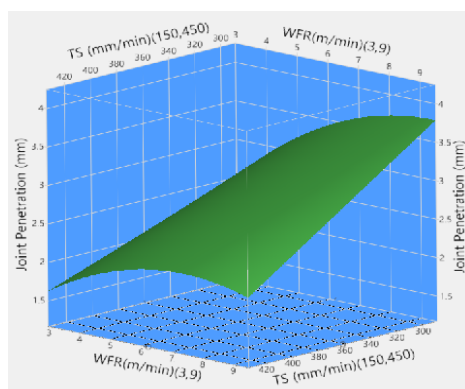
Figure 4.21: Response surface plots of process' paramters effects on break streangth

4.4.6 Response for joint penetration

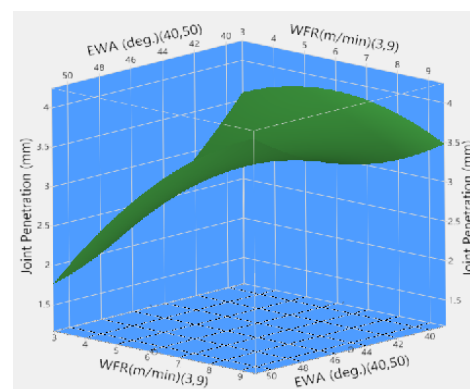
Joint penetration is the maximum distance between the corner of the two plates (vertical and horizontal) and the depth to which the fusion has taken place on both common plates (Fig.

4.15 (a)). It is observed that the penetration is influenced by WFR, TS, CTWD, and EWA. Joint penetration was directly proportional to WFR and inversely proportional to TS. The surface plots of process parameters WFR, TS, EWA, and CTWD combined effects on joint penetration are shown in Fig. 4.22, 4.23, and 4.24. Wire feed rate affects the extent of depth of joint penetration significantly. The deposition rate and level of current are mostly determined by the wire feed rate. Increasing WFR increases the deposition of filler wire which is considerably more molten metals and increases the joint penetration. In line with this, an increase in WFR increases the level of current (heat input) resulting in more joint penetration. Setting the wire feed rate too high leads to excessive joint penetration, wide weld bead, and burn-through. Conversely, too low WFR creates low joint penetration due to the supply of insufficient amperage and lack of filler metals to fill the joint (Kim, *et al.*, 2003; Kamble and Rao, 2013).

Weld joint penetration decreases when the travel speed increases due to decreases in the time it takes the arc force to penetrate the surface of the parent material including the volume of material deposited decreases. When the travel speed is too slow the amount of heat input increases resulting in higher joint penetration. When traveling at a high speed, the arc forces, arc heat, and droplet impingement are not concentrating on the molten weld pool; the amount of fused both plates is smaller, and the quantity of molten weld pool that established the common weldment is relatively small in agreement to related findings (Kamble and Rao, 2013; Adak, *et al.*, 2015; Gyasi, *et al.*, 2017).



(a) WFR and TS effect

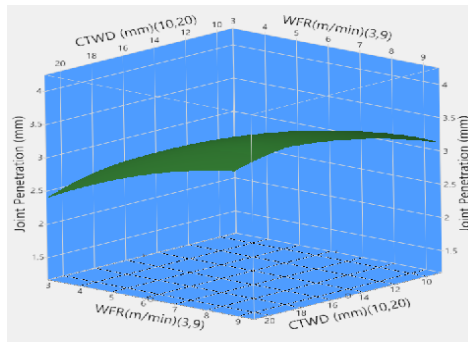


(b) WFR and EWA effect

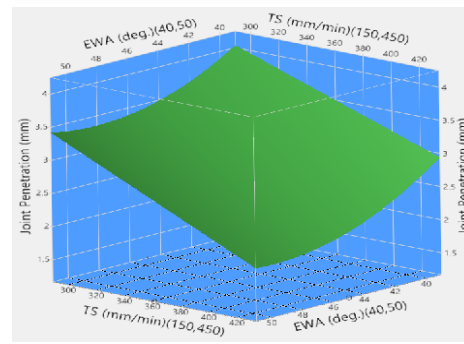
Figure 4.22: Response surface plots of process paramters' effects on break streangth

EWA plays a crucial role in the amount of joint penetration. Mostly in the vertical structure component of the fillet welds torch angle inconsistencies result in insufficient fusion and lack

of joint penetration. The decrease in the EWA means an increase in the chance of melting the vertical plate of the joint, at a low level of EWA the effect of gravity has been low and surface tension force supports the mode of metal transfers on the vertical plate. These significantly determine the level of joint penetrations. When EWA increased the molten metal was more deposited on the horizontal plate due to relatively the electrode being sited on vertical positions (Lee and Rhee, 2000; Badheka, 2013).



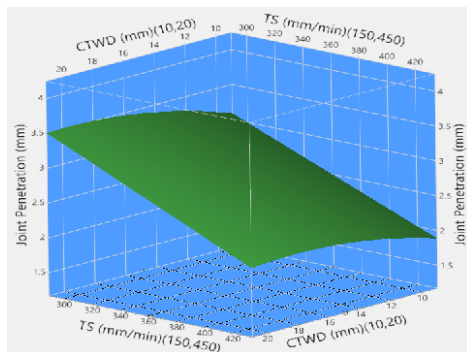
(a) WFR and CTWD effect



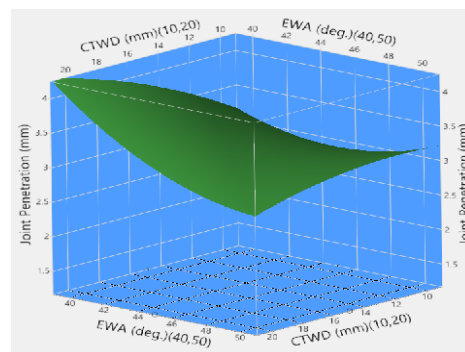
(b) TS and EWA effect

Figure 4.23: Response surface plots of process paramters' effects on break streangth

CTWD is one of the welding input parameters that determine the level of joint penetration. The decrease in CTWD increases the level of joint penetration due to the high heat input that occurs between the electrode and the parent metals. Too short CTWD creates an unstable arc and poor joints. The increase in the CTWD means an increase energized length of the electrode before the fusion of the electrode occurs, due to more resistance in the conductor (the Joule effect). Higher CTWD reduces the arc pressure and decreases joint penetration; because, when CTWD increases the length of electrode extension increases, and an increase in resistance to the flow of current consequences in a decreasing welding current resulting in arc pressure (Kim, *et al.*, 2003).



(a) TS and CTWD effect



(b) EWA and CTWD effect

Figure 4.24: response surface plots of process paramters effects on break streangth

4.5 Optimization of welding parameters for a set of EWA

Based on the experimental design, the welds have been made, tested, and measured at a set of torch angles such as 35°, 45°, 50°, and 55°. The schematic diagram of joint penetration at different EWAs has been presented in Fig. 4.25.

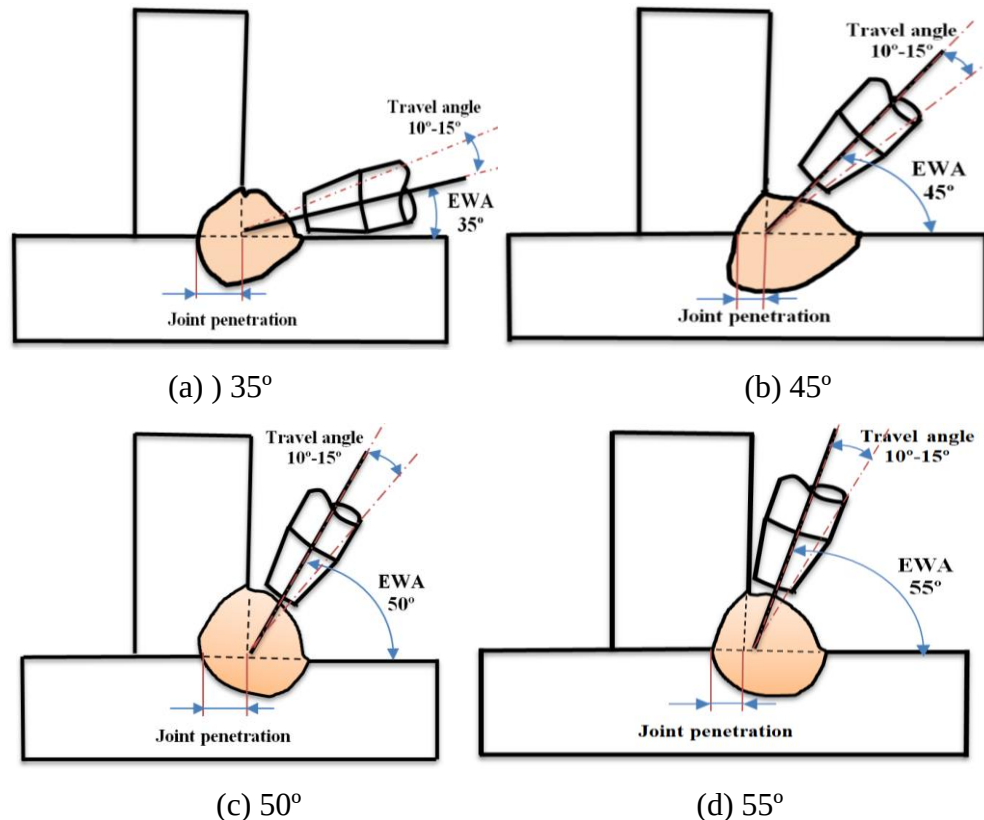


Figure 4.25: Schematic diagram of JP at different EWA with CTWD is 15mm

The strength and penetration of joints have been determined by the level of both plates that have been fused and joined together. The weld bead geometry and joint strength are determined by the amount of heat input (flow of welding current), forces acting in the metal transfer process, and molten metal droplet formation on both plates (vertical and horizontal) together. Welding current takes the path of least resistance, therefore, the arc and resulting weld will go where the electrode tip is nearby; this significantly affects the extent of joint penetration. During welding, different forces are applied to the tip of the electrode, on the arc, and weld pool area which influences the mode of metal transfer, metal disposition efficiencies, and the detachment of molten metal drop hanging at the electrode tip which is leading to the variation of weld penetration. Weld metal transfer is detachment and movement of molten metal drops from the tip of the electrode to the weld pool in the workpiece. The effect of surface tension force, pinch force (an electromagnetic force), and

gravitational force are mainly dependent on the position of EWA, and are discussed in the following section;

A. Surface tension force

Drop of the liquid metal hanging at the tip of electrode due to surface tension effect. Magnitude of the surface tension force (Eq. 4.5) is influenced by the electrode radius and surface tension coefficient. This force tends to resist the detachment of molten metal drop from electrode tip and usually acts against gravitational force. In case of elevated EWA, high surface tension force helps in placing the molten weld metal at vertical plate by reducing tendency of falling down of molten weld metal. Surface tension tends to retain the molten droplet at the tip of the electrode and its magnitude is given by the expression (Uddin, *et al.*, 2019):

$$F_s = 2\pi\alpha\gamma.....(4.5)$$

Where;

γ = surface tension of the liquid metals

α = radius of the electrode

- Experimental results showed that; when the EWA is extremely tilt (55°) with higher CTWD (20mm) the effect of surface tension force is increased on the VP. And when the EWA is extremely flatten (35°) with higher CTWD (20mm) the effect of surface tension force is increased on the HP.

B. Pinch force

The pinch force reduces the cross section for molten metal drop near the tip of the electrode and thus helps in detachment of the droplet from the electrode tip. Small electromagnetic force is repulsive force and at large enough electromagnetic force; current line diverge, pinch force is positive, and become to detaching force (Eq. 4.6). Pinch force is referred to as Lorentz force or electromagnetic pinch force is given by the expression (Kim and Eagar, 1993; Uddin, *et al.*, 2019):

$$F_p = \frac{\mu_0 I^2}{4\pi} f_2.....(4.6)$$

Where,

μ_o = Magnetic permeability of metals

I= Welding current flowing through the arc gap

f_2 = the function of the conduction zone angle (electromagnetic force)

- Experimental investigation showed that; when the EWA is extremely tilt (55°) with closed CTWD (10mm) the effect of pinch force is increased on the HP. And When the EWA is extremely flatten (35°) with closed CTWD (10mm) the effect of pinch force is increased on the VP.

C. Gravitational force

Gravitational force depends on the volume of the drop and density of metal (Eq. 4.7). In case of welding at elevated EWA, gravitational force helps in detachment/transfer of molten metal drop from electrode tip. Given by the expression (Kim and Eagar, 1993; Uddin, *et al.*, 2019):

$$F_g = \frac{4}{3} \pi R^3 \rho_d g \dots \dots \dots (4.7)$$

Where,

R = droplet radius

ρ = density of the drop

g = gravitational constant

- Based on the experimental results, when the EWA is extremely tilt (55°) with closed CTWD (10mm) the effect of gravitational force is increased on the HP. And When the EWA is extremely flatten (35°) with closed CTWD (10mm) the effect of gravitational force is increased on the VP.

Selection of higher WFR and lower TS with low CTWD (10 mm) in all set angles may electrode stuck to the contact tube due to insufficient arc length. Higher CTWD (20mm) has been recommended. For welding of extreme EWA (35° and 55°) with too low WFR and closed CTWD the arc has been terminated and not ignited; welding with higher CTWD (20mm) has been recommended. Investigated the extreme setting of EWA and CTWD parameters and their consequence on the process have been discussed in the following cases:-

Case 1: at EWA is 35° and CTWD 10mm with a medium WFR and TS the current flows more in the vertical plate due to very closing CTWD to the vertical plate and the fusion occurs only in the vertical plate; not at all joint penetration has been achieved and surface tension effect is less in the horizontal plate because the tip of the electrode is very close to the VP.

Case 2: at EWA 55° and CTWD 10mm with a medium WFR and TS the current flows more in the horizontal plate due to very closing CTWD; easy for the molten metals to contact the surface of the weld pool on a horizontal plate and molten column pinches off to detach the filler wire mostly on horizontal plate and gravitational force significantly helps in detachment/transfer of molten metal drop from electrode tip and The thermal energy from the arc is efficiently carried downward HP. The deeper weld pool was created only in a horizontal plate and joint penetration has not been achieved.

Case 3: at EWA 35° and CTWD 20mm, current flows more in the horizontal plate due to the least resistance to flow to HP than VP (especially from the side of the electrode). Surface tension force, and gravitational forces (detaching force of the molten metal to fuse down) are also significant to the horizontal plate; current fairly flowing to the plate due to increasing the resistance (the distance between the tip of electrode and welded metals) resulting fair joint penetration has been achieved.

Case 4: at EWA 55° and CTWD 20mm current flows more in the vertical plate due to the least resistance to flow of current to the VP. In this case, the maximum surface tension occurs near the vertical plate, resulting in a reduction in the tendency of falling of molten weld metal to the horizontal plate (acts against gravitational force) resulting in significant joint penetration has been achieved.

4.5.1 Joint strength

The strength of welded joints is the main quality requirement for all welded products to determine the functional requirements of the product. The break strength of 'T' joints depends on the amount of joint penetration; the level of joint penetration is significantly affected by EWA. The weldment failure pattern of break strength OSTJ1 (WFR=7, TS=250, and CTWD=15) at different torch angles is presented in Fig. 4.26.

The fracture result of the specimen welded by 35° EWA Fig. 4.26(a) shows that the weldment parts remain in the vertical plate. This indicates the amount of depth of penetration and the fusion of the electrode wire has taken place in the vertical plate rather than a horizontal plate. The fracture result of the specimen welded by 45° EWA Fig. 4.26(b) shows that the weldment parts are fairly proportionally in both plates. This indicates the amount of depth of penetration and the fusion of the electrode wire has taken place in both plates uniformly.

The fracture result of the specimen welded by 50° EWA Fig. 4.26(c) shows that large amounts of weldment parts remain in the horizontal plate; indicating the amount of depth of penetration and the fusion of the electrode wire has taken place more in the horizontal plate.

The fracture result of the specimen welded by 55° EWA Fig. 4.26(d) shows that the weldment parts remain in the horizontal plate. This indicates the amount of depth of penetration and the fusion of the electrode wire has taken place in the horizontal plate rather than the vertical plate.



a) Weldment failure pattern at 35°



b) Weldment failure pattern at 45°



c) Weldment failure pattern at 50°



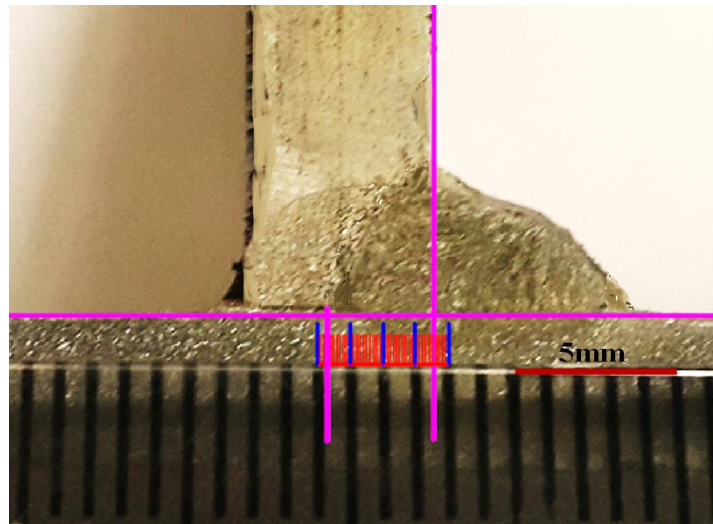
d) weldment failure pattern at 55°

Figure 4.26: Infringement phenomenon of break strength OSTJ1

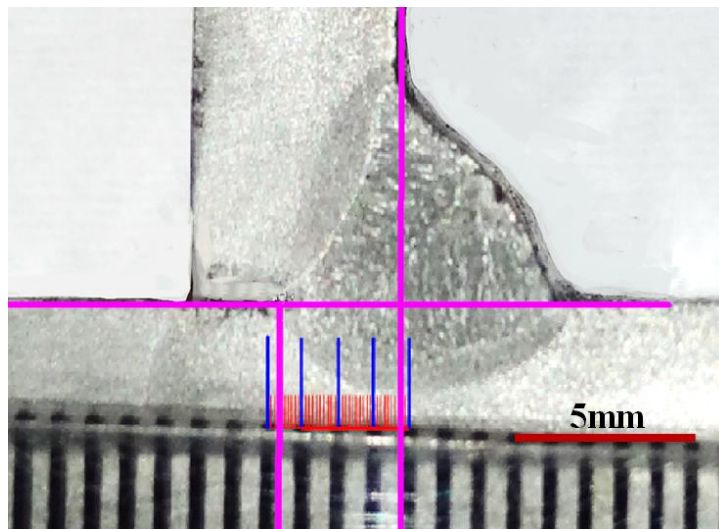
4.5.2 Joint penetration

For joint penetration tests, the welded specimens were prepared from the weldment of the test specimen. And polished by metallurgical polishing methods and etched with 2% Nital. Joint penetration has been measured from the imported macrostructure image of Tee-joint weldment. For measuring joint penetration, two lines (horizontal and vertical) along with the faying surfaces of the plates have been drawn. The joint penetration is taken where these two lines meet at a point, then the image of each mm was scaled into 10 divisions by AutoCAD.

Fillet weld joint measurement OSTJ1 (WFR=7m/min, TS=250mm/min, and CTWD=15mm) at 35° and 55° EWA are presented in Fig. 4.27 (a) and (b) respectively.



a) EWA 35°, joint penetration=3.2mm



b) EWA 55°, joint penetration=3.5mm

Figure 4.27: Joint penetration measurement of OSTJ1

OSTJ2 and OSTJ8 have higher WFR with lower TS; in the real fabrication industry, this setting is not applied because of an excessive deposition rate, resulting in the wastage of filler materials and electric power. For OSTJ4, OSTJ8, OSTJ14, and OSTJ16 the CTWD for 35° and 55° not be welded because of closed CTWD; filler wire is stuck to the contact tube, in the experimental work for 35° and 55° EWA it has been used the higher CTWD which had corrected in the DoE and analyzed based on the experimental setting Table 4.16. In general, the CTWD for higher WFR and lower travel speed should be greater than 15mm for welding

of 35° and 55°, for lower WFR and higher travel speed the recommended CTWD is less than 15mm for welding of 35° and 55°. The profiler and maximized desirability functions have been used to find optimal factor settings of input parameters (WFR, TS, and CTWD). The experimental results have been analyzed and optimized by using a prediction profiler and desirability functions as shown in Fig. 4.28. The predicted optimum combinations of input parameters for a set of torch angles are presented in Table 4.17.

Table 4.16 Responses of break strength and joint penetration

S/No	WFR (m/min)	TS (mm/min)	CTWD (mm)		BS for different EWA (kN)				JP for different EWA (mm)			
			35° and 55°	45° and 50°	35°	45°	50°	55°	35°	45°	50°	55°
OSTJ1	7	250	15	15	56.11	67.58	61.32	63.48	3.2	3.7	3.4	3.5
OSTJ2	7	150	20	20	57.39	68.73	64.35	63.76	4.2	4.2	3.9	4.3
OSTJ3	5	450	20	20	29.96	34.25	31.40	30.89	1.0	1.5	1.2	1.4
OSTJ4	7	450	15	10	55.37	60.65	56.42	53.80	2.1	2.2	2.2	1.9
OSTJ5	3	150	20	20	44.16	63.05	57.55	53.87	2.6	3.3	3.3	3.1
OSTJ6	5	350	10	10	43.83	47.02	46.13	40.65	3.1	3.2	2.9	2.7
OSTJ7	5	150	15	15	52.11	62.85	56.91	59.25	3.7	4.3	4.1	4.2
OSTJ8	9	150	20	10	70.71	73.29	71.98	67.15	4.3	4.8	4.2	4.1
OSTJ9	9	350	20	20	46.57	59.41	50.33	49.90	2.6	3.4	3.3	3.1
OSTJ10	5	250	15	15	48.44	47.02	55.93	58.14	3.0	3.5	3.3	3.5
OSTJ11	9	250	20	20	59.95	68.81	62.62	65.06	3.1	3.9	3.4	3.4
OSTJ12	3	450	10	10	27.12	29.88	28.30	25.70	1.2	1.3	1.2	1.1
OSTJ13	3	250	10	10	38.84	47.50	35.40	35.56	2.4	2.6	2.3	2.3
OSTJ14	9	450	20	15	59.09	63.82	62.63	62.21	2.9	3.3	3.1	3.2
OSTJ15	3	350	15	15	33.68	36.74	31.46	34.18	2.1	2.6	2.6	2.3
OSTJ16	7	350	20	10	51.53	62.03	58.33	43.20	2.9	3.3	3.1	2.5

BS; break strength, JP; joint penetration

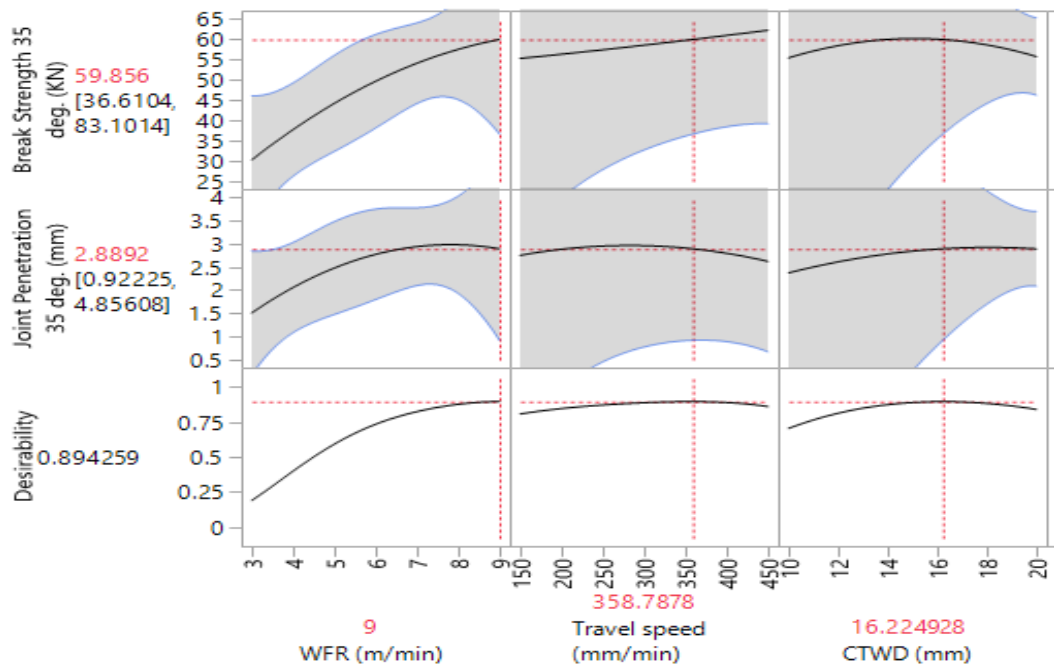


Figure 4.28: Prediction profiler with desirability maximized at 35° EWA

The predicted optimum combination of welding parameters for 35° EWA is a wire feed rate of 9m/min, travel speed of 358.78mm/min, and contact tip to work distance of 16.22mm. The prediction results show that when EWA decreases the WFR should increase with medium travel speed at modest CTWD; at this angle, the effect of surface tension force is high at the VP which significantly determines the amount of joint penetration.

The predicted optimum combination of welding parameters for 45° EWA is a wire feed rate of 7m/min, travel speed of 418.98mm/min, and contact tip to work distance of 10mm, The prediction results show that high response achieved at moderate WFR, high travel speed with closed CTWD; the effect of pinch force is low in the tip of the electrode that determines the formation of the droplet in the weld zone. If the tip of the electrode is much closer to the base metal the level of heat input increases and the joint penetration has been increased.

The predicted optimum combination of welding parameters for 50° EWA is a wire feed rate of 7.40m/min, travel speed of 159.26mm/min, and contact tip to work distance of 16.63mm, the prediction results show that when EWA at 50° the WFR should increase with slow travel speed at the moderate CTWD; the effect of surface tension force and gravitational force is

significant on VP and HP respectively, the weld bead formation is relatively higher in the horizontal plate, the level of joint strength and joint penetration is high.

The predicted optimum combination of welding parameters for 55° EWA is a wire feed rate of 7.26m/min, travel speed of 281.31mm/min, and contact tip-to-work distance of 14.38mm, with a high desirability function (1). The prediction results show that WFR should be moderate with moderate travel speed at moderate CTWD; the effect of gravitational force is significant on the horizontal plate by promoting surface tension force in the vertical plate due to moderate CTWD, which significantly determines the amount of joint penetration.

Table 4.17 Predicted optimum combinations of input parametres for different EWA

EWA (°)	WFR m/min	TS (mm/min)	CTWD (mm)	BS (kN)	JP mm)	Desirability
35	9	358.78	16.22	59.85	2.89	0.89
45	7	418.98	10	59.87	2.7	0.86
50	7.40	159.26	16.63	67.25	3.87	0.89
55	7.26	281.31	14.38	65.00	3.50	1.00

4.5.3 Prediction formula

Prediction models were constructed for each response variable to find the optimum combination of input parameters. The derived equations are built using standard least square regression. The main effect, second interaction effects, and quadratic effect among the input variables were also taken into consideration. The optimal parameters values and regression model have been predicted by using prediction profilers, the prediction formula used to see predicted ratings for all the experiments. The prediction expression of break strength and joint penetration of 35° of EWA is given by equations ‘A’ and ‘B’ respectively.

A, Prediction expression for break strength for 35° EWA

$$\begin{aligned} BS = & 51.80 + 11.02 \left(\frac{(WFR(m/min) - 6)}{3} \right) - \\ & 3.43 \left(\frac{(TS(mm/min) - 300)}{150} \right) - 0.77 \left(\frac{(CTWD(mm) - 15)}{5} \right) + \\ & \left(\frac{(WFR(m/min) - 6)}{3} \right) \cdot \left(\left(\frac{(WFR(m/min) - 6)}{3} \right) - 4.54 \right) + \\ & \left(\frac{(WFR(m/min) - 6)}{3} \right) \cdot \left(\left(\frac{(TS(mm/min) - 300)}{150} \right) \cdot 7.96 \right) + \\ & \left(\frac{(TS(mm/min) - 300)}{150} \right) \cdot \left(\frac{(TS(mm/min) - 300)}{150} \cdot 0.20 \right) + \\ & \left(\frac{(WFR(m/min) - 6)}{3} \right) \cdot \left(\left(\frac{(CTWD(mm) - 15)}{5} \right) \cdot 2.6 \right) + \\ & \left(\frac{(TS(mm/min) - 300)}{150} \right) \cdot \left(\left(\frac{(CTWD(mm) - 15)}{5} \right) - 4.33 \right) + \\ & \left(\frac{(CTWD(mm) - 15)}{5} \right) \cdot \left(\left(\frac{(CTWD(mm) - 15)}{5} \right) - 4.58 \right) \end{aligned}$$

B, Prediction expression for joint penetration for 35° EWA

$$\begin{aligned} JP = & 3.10 + 0.34 \left(\frac{(WFR(m/min) - 6)}{3} \right) - \\ & 0.60 \left(\frac{(TS(mm/min) - 300)}{150} \right) - 0.06 \left(\frac{(CTWD(mm) - 15)}{5} \right) + \\ & \left(\frac{(WFR(m/min) - 6)}{3} \right) \cdot \left(\left(\frac{(WFR(m/min) - 6)}{3} \right) - 0.56 \right) + \\ & \left(\frac{(WFR(m/min) - 6)}{3} \right) \cdot \left(\left(\frac{(TS(mm/min) - 300)}{150} \right) \cdot 0.60 \right) + \\ & \left(\frac{(TS(mm/min) - 300)}{150} \right) \cdot \left(\frac{(TS(mm/min) - 300)}{150} - 0.27 \right) + \\ & \left(\frac{(WFR(m/min) - 6)}{3} \right) \cdot \left(\left(\frac{(CTWD(mm) - 15)}{5} \right) \cdot 0.42 \right) + \\ & \left(\frac{(TS(mm/min) - 300)}{150} \right) \cdot \left(\left(\frac{(CTWD(mm) - 15)}{5} \right) - 0.24 \right) + \\ & \left(\frac{(CTWD(mm) - 15)}{5} \right) \cdot \left(\left(\frac{(CTWD(mm) - 15)}{5} \right) - 0.20 \right) \end{aligned}$$

4.5.4 Efficiency checking of developed model

The analysis of variance (ANOVA) test was performed to evaluate the statistical significance of the fitted models and factors involved there for responses break strength and joint penetration. All the fitted models are found to be significant. For all the responses, the probability of F (Prob.>F) is observed to be less than 0.05. In addition to this, the goodness of fit of the fitted model was also evaluated through the lack of fit test. As a result, the developed model for every response is found to be adequate concerning the 95% confidence level. The values of R² and standard error of estimates for both models are given in Table 4.18.

Table 4.18 Summary of fit for 35° EWA

Description	Break strength	Joint penetration
RSquare	0.909323	0.873287
RSquare Adj	0.7053	0.588184
Root Mean Square Error	5.742133	0.48587
Mean of Response	46.19714	2.564286
Observations (or Sum Wgts)	14	14

4.5.5 Validation of model

To test the accuracy of the optimized parameters in real applications, conformity test runs were conducted. The break strength and joint penetration were tested and measured. The recorded results showed that the average accuracy of the mathematical models for the four different angles is 96.01% and 99.94 (3.99 and 0.06 % average error) of break strength and joint penetration respectively as presented in Table 4.19. The percentage error has been calculated as Eq. 4.8. The average percentage error for the models is less than 5%. It has been concluded that the average percentage error obtained between the mathematical models and experimentally validated values is insignificant and the predicted capacity is closer to test capacity.

$$Error (\%) = \frac{Measured\ value - Predicted\ value}{Predicted\ value} \times 100 \dots\dots\dots(4.8)$$

Table 4.19 Predicted and experimental values with percentage error

Angle	Break Strength			Joint Penetration		
	PV (kN)	EV (kN)	ER (%)	PV (mm)	EV (mm)	ER (%)
35°	59.83	63.21	-3.97	2.89	2.7	-0.06
45°	59.87	61.74	3.12	2.70	2.9	0.07
50°	67.25	64.25	-4.46	3.87	3.5	-0.09
55°	65.00	62.13	-4.41	3.50	3.3	-0.05
Ave. error (%)			3.99	Ave. error (%)		0.06
Predicted accuracy (%)			96.01	Predicted accuracy (%)		99.94

PV; predicted value EV; experimental value, ER; error

4.6 Automatic generation of optimal combination of welding parameters

The optimum combination of welding parameters has been investigated and presented for optimum combination of welding parameters and optimum combination of welding parameters for different electrode work angles in Tables 4.15 and 4.17 respectively.

The optimum welding parameters for optimal EWA (40°) and optimum welding parameters for other torch angles (35°, 45°, 50°, and 55°) have been interpolated as [35°-37.5°], [37.6°-42.5°], [42.6°-47.5°], [47.6°-52.5°], and [52.6°-55°] EWA which are divided into five ranges. The optimized welding parameters for a range of EWA are presented in Table 4.20.

Table 4.20 Optimized welding parameters for range of EWA

Welding parameters			EWA ranges (deg.)
WFR (m/min)	TS (mm/min)	CTWD (mm)	
9	358.78	16.22	[35° – 37.5°]
8.29	243	10	[37.6° ≥ 42.5°]
7	418.98	10	[42.6° ≥ 47.5°]
7.40	159.26	16.63	[47.6° ≥ 52.5°]
7.26	281.31	14.38	[52.6° ≥ 55°]

4.6.1 Algorithm for optimal parameters

1. Enter Input: n data points: $(x_0, y_0), (x_1, y_1), \dots, (x_{n-1}, y_{n-1})$, where $x_0 < x_1 < \dots < x_{n-1}$.

2. Compute Differences: Compute the differences between consecutive x values and y values:

$$h_i = x_{i+1} - x_i \text{ for } i=0,1,\dots,n-2$$

$$a_i = y_{i+1} - y_i \text{ for } i=0,1,\dots,n-2$$

3. Apply Tridiagonal System: Set up a tridiagonal system of equations

$$u_i = 2(h_{i-1} + h_i)$$

$$v_i = 6(a_i/h_i - a_{i-1}/h_{i-1}) \text{ For } i=1,2,\dots,n-2.$$

4. Solve the tridiagonal system to obtain the second derivatives $z_0, z_1, \dots, z_{n-1}$. Thomas algorithm.
5. Calculate Coefficients: Compute the coefficients of the cubic polynomials for each interval $[x_i, x_{i+1}]$:

$$S_i(x) = (z_{i-1}/6h_i)(x_{i+1}-x)^3 + (z_i/6h_i)(x-x_i)^3 + (y_{i+1}/h_i)(x-x_i) + (y_i/h_i)(x_{i+1}-x)$$

$$\text{For } i=0, 1, \dots, n-2.$$

6. Output: The interpolating cubic spline is the piecewise function $S(x)$ formed by combining the cubic polynomials for each interval. This algorithm assumes a natural spline, meaning that the second derivatives at the endpoints are set to zero.

4.6.2 The interpolated optimum combination of welding parameters

An interpolated optimum combination of welding parameters for a set of torch angles (35°-55°) at a theta (EWA) division of 1. Appendix-V.

EWA	WFR	TS	CTWD	EWA	WFR	TS	CTWD
35.0000	9.0000	358.7800	16.2200	47.0000	7.0629	327.5679	13.1075
36.0000	9.0109	363.4010	16.3751	48.0000	7.1863	255.8402	14.7213
37.0000	8.9369	335.6656	15.3992	49.0000	7.3128	193.3262	15.9843
38.0000	8.7880	294.0189	13.7313	50.0000	7.3976	159.8189	16.6197
39.0000	8.5739	256.9062	11.8099	51.0000	7.4078	169.1818	16.4473
40.0000	8.3047	242.7726	10.0741	52.0000	7.3634	207.7152	15.7370
41.0000	7.9940	264.8118	8.8945	53.0000	7.3002	253.7166	14.8888
42.0000	7.6727	311.8075	8.3269	54.0000	7.2538	285.4826	14.3031
43.0000	7.3766	365.4558	8.3352	55.0000	7.2600	281.3100	14.3800
44.0000	7.1416	407.4524	8.8831				
45.0000	7.0037	419.4927	9.9348				
46.0000	6.9872	388.7162	11.4198				

An interpolated optimum combination of welding parameters for different torch angles (35°-55°) at a theta division of 0.1

EWA	WFR	TS	CTWD	EWA	WFR	TS	CTWD
35.0000	9.0000	358.7800	16.2200	39.3000	8.4985	249.4141	11.2497
35.1000	9.0052	361.2238	16.2989	39.4000	8.4723	247.4624	11.0688
35.2000	9.0095	363.1781	16.3626	39.5000	8.4456	245.8142	10.8914
35.3000	9.0128	364.6612	16.4114	39.6000	8.4184	244.4881	10.7181
35.4000	9.0152	365.6916	16.4458	39.7000	8.3907	243.5024	10.5492
35.5000	9.0167	366.2878	16.4663	39.8000	8.3625	242.8757	10.3853
35.6000	9.0173	366.4683	16.4733	39.9000	8.3338	242.6262	10.2268
35.7000	9.0170	366.2513	16.4673	40.0000	8.3047	242.7726	10.0741
35.8000	9.0158	365.6555	16.4486	40.1000	8.2752	243.3325	9.9276
35.9000	9.0138	364.6992	16.4177	40.2000	8.2452	244.3059	9.7875
36.0000	9.0109	363.4010	16.3751	40.3000	8.2148	245.6753	9.6538
36.1000	9.0072	361.7791	16.3211	40.4000	8.1840	247.4224	9.5265
36.2000	9.0026	359.8521	16.2563	40.5000	8.1530	249.5289	9.4056
36.3000	8.9972	357.6385	16.1811	40.6000	8.1216	251.9765	9.2909
36.4000	8.9910	355.1566	16.0959	40.7000	8.0900	254.7469	9.1825
36.5000	8.9839	352.4250	16.0011	40.8000	8.0582	257.8218	9.0803
36.6000	8.9761	349.4620	15.8972	40.9000	8.0262	261.1829	8.9844
36.7000	8.9675	346.2861	15.7846	41.0000	7.9940	264.8118	8.8945
36.8000	8.9581	342.9158	15.6638	41.1000	7.9618	268.6903	8.8108
36.9000	8.9479	339.3694	15.5352	41.2000	7.9295	272.8001	8.7332
37.0000	8.9369	335.6656	15.3992	41.3000	7.8971	277.1229	8.6617
37.1000	8.9252	331.8226	15.2563	41.4000	7.8648	281.6403	8.5961
37.2000	8.9128	327.8589	15.1070	41.5000	7.8324	286.3340	8.5365
37.3000	8.8997	323.7930	14.9516	41.6000	7.8002	291.1858	8.4829
37.4000	8.8858	319.6433	14.7905	41.7000	7.7681	296.1774	8.4351
37.5000	8.8712	315.4283	14.6243	41.8000	7.7361	301.2904	8.3932
37.6000	8.8559	311.1664	14.4534	41.9000	7.7043	306.5065	8.3572
37.7000	8.8399	306.8761	14.2782	42.0000	7.6727	311.8075	8.3269
37.8000	8.8233	302.5758	14.0992	42.1000	7.6414	317.1750	8.3024
37.9000	8.8059	298.2839	13.9167	42.2000	7.6103	322.5907	8.2837
38.0000	8.7880	294.0189	13.7313	42.3000	7.5796	328.0363	8.2706
38.1000	8.7693	289.7993	13.5433	42.4000	7.5492	333.4935	8.2631
38.2000	8.7500	285.6434	13.3532	42.5000	7.5193	338.9441	8.2613
38.3000	8.7301	281.5698	13.1615	42.6000	7.4897	344.3697	8.2651
38.4000	8.7096	277.5969	12.9686	42.7000	7.4606	349.7519	8.2744
38.5000	8.6885	273.7430	12.7748	42.8000	7.4321	355.0726	8.2892
38.6000	8.6667	270.0268	12.5808	42.9000	7.4041	360.3133	8.3095
38.7000	8.6444	266.4665	12.3868	43.0000	7.3766	365.4558	8.3352
38.8000	8.6215	263.0807	12.1934	43.1000	7.3498	370.4818	8.3663
38.9000	8.5980	259.8878	12.0010	43.2000	7.3236	375.3730	8.4027
39.0000	8.5739	256.9062	11.8099	43.3000	7.2981	380.1111	8.4445
39.1000	8.5493	254.1545	11.6208	43.4000	7.2733	384.6777	8.4916
39.2000	8.5242	251.6510	11.4339	43.5000	7.2492	389.0546	8.5439

43.6000	7.2260	393.2235	8.6015	48.5000	7.2520	222.1944	15.4140
43.7000	7.2036	397.1660	8.6642	48.6000	7.2647	215.9594	15.5389
43.8000	7.1820	400.8638	8.7321	48.7000	7.2772	209.9353	15.6587
43.9000	7.1614	404.2987	8.8051	48.8000	7.2894	204.1418	15.7731
44.0000	7.1416	407.4524	8.8831	48.9000	7.3013	198.5989	15.8817
44.1000	7.1229	410.3065	8.9662	49.0000	7.3128	193.3262	15.9843
44.2000	7.1052	412.8427	9.0543	49.1000	7.3239	188.3436	16.0807
44.3000	7.0884	415.0427	9.1474	49.2000	7.3345	183.6708	16.1704
44.4000	7.0728	416.8883	9.2454	49.3000	7.3446	179.3277	16.2534
44.5000	7.0583	418.3611	9.3483	49.4000	7.3542	175.3340	16.3293
44.6000	7.0449	419.4428	9.4560	49.5000	7.3632	171.7096	16.3977
44.7000	7.0328	420.1151	9.5686	49.6000	7.3715	168.4742	16.4586
44.8000	7.0218	420.3597	9.6859	49.7000	7.3792	165.6477	16.5114
44.9000	7.0121	420.1584	9.8080	49.8000	7.3861	163.2497	16.5561
45.0000	7.0037	419.4927	9.9348	49.9000	7.3923	161.3002	16.5923
45.1000	6.9966	418.3452	10.0663	50.0000	7.3976	159.8189	16.6197
45.2000	6.9909	416.7166	10.2023	50.1000	7.4021	158.8247	16.6380
45.3000	6.9864	414.6260	10.3426	50.2000	7.4057	158.3167	16.6475
45.4000	6.9832	412.0931	10.4868	50.3000	7.4085	158.2740	16.6483
45.5000	6.9811	409.1377	10.6346	50.4000	7.4105	158.6750	16.6409
45.6000	6.9802	405.7796	10.7860	50.5000	7.4118	159.4979	16.6258
45.7000	6.9804	402.0386	10.9404	50.6000	7.4123	160.7210	16.6032
45.8000	6.9817	397.9345	11.0977	50.7000	7.4121	162.3227	16.5737
45.9000	6.9839	393.4871	11.2576	50.8000	7.4113	164.2812	16.5377
46.0000	6.9872	388.7162	11.4198	50.9000	7.4098	166.5748	16.4954
46.1000	6.9913	383.6415	11.5840	51.0000	7.4078	169.1818	16.4473
46.2000	6.9964	378.2830	11.7499	51.1000	7.4052	172.0805	16.3939
46.3000	7.0022	372.6602	11.9174	51.2000	7.4021	175.2493	16.3355
46.4000	7.0089	366.7932	12.0860	51.3000	7.3986	178.6663	16.2725
46.5000	7.0163	360.7016	12.2556	51.4000	7.3946	182.3100	16.2053
46.6000	7.0244	354.4052	12.4258	51.5000	7.3902	186.1585	16.1344
46.7000	7.0331	347.9238	12.5964	51.6000	7.3854	190.1903	16.0601
46.8000	7.0425	341.2773	12.7670	51.7000	7.3803	194.3835	15.9828
46.9000	7.0525	334.4854	12.9375	51.8000	7.3749	198.7166	15.9029
47.0000	7.0629	327.5679	13.1075	51.9000	7.3693	203.1677	15.8208
47.1000	7.0738	320.5446	13.2768	52.0000	7.3634	207.7152	15.7370
47.2000	7.0852	313.4354	13.4451	52.1000	7.3573	212.3374	15.6518
47.3000	7.0970	306.2599	13.6120	52.2000	7.3511	217.0125	15.5656
47.4000	7.1091	299.0380	13.7774	52.3000	7.3448	221.7190	15.4788
47.5000	7.1214	291.7894	13.9410	52.4000	7.3384	226.4350	15.3918
47.6000	7.1341	284.5341	14.1024	52.5000	7.3319	231.1388	15.3051
47.7000	7.1469	277.2917	14.2614	52.6000	7.3254	235.8089	15.2190
47.8000	7.1600	270.0821	14.4178	52.7000	7.3190	240.4234	15.1339
47.9000	7.1731	262.9250	14.5712	52.8000	7.3126	244.9606	15.0502
48.0000	7.1863	255.8402	14.7213	52.9000	7.3063	249.3989	14.9684
48.1000	7.1996	248.8476	14.8680	53.0000	7.3002	253.7166	14.8888
48.2000	7.2128	241.9669	15.0108	53.1000	7.2942	257.8919	14.8118
48.3000	7.2260	235.2180	15.1496	53.2000	7.2884	261.9031	14.7378
48.4000	7.2390	228.6206	15.2841	53.3000	7.2828	265.7286	14.6673

53.4000	7.2776	269.3466	14.6006	54.3000	7.2485	288.9919	14.2383
53.5000	7.2726	272.7355	14.5381	54.4000	7.2480	289.3416	14.2319
53.6000	7.2680	275.8735	14.4802	54.5000	7.2481	289.2451	14.2337
53.7000	7.2638	278.7389	14.4274	54.6000	7.2489	288.6807	14.2441
53.8000	7.2600	281.3100	14.3800	54.7000	7.2505	287.6267	14.2635
53.9000	7.2567	283.5652	14.3384	54.8000	7.2528	286.0614	14.2924
54.0000	7.2538	285.4826	14.3031	54.9000	7.2560	283.9630	14.3311
54.1000	7.2515	287.0407	14.2743	55.0000	7.2600	281.3100	14.3800
54.2000	7.2497	288.2177	14.2526				

4.6.3 Optimal welding parameters for different EWA

The optimum combinations of welding parameters for different torch angles were generated by employing cubic spline interpolation. This cubic spline interpolation method is an effective method for grasping the optimum combination of input parameters for the robotic GMAW process. The major welding input parameters, including WFR, TS, EWA, and CTWD, were included to weld *AISI SAE 4130* alloy steel of a 6mm thickness plate. The optimal setting and interaction effect of each parameter have been discussed in the following sections.

4.6.3.1 Optimal WFR at different EWAs

The weld quality characteristics are significantly affected by welding input parameters. The weld quality is decided based on the combinations of WFR and EWA, mainly by (Cruz, et al., 2015, Srivastava and Garg 2017). The interpolated results of this investigation showed that when EWA increases 35-35.6°, the WFR increases with a small range of 9-9.0173m/min. In the case of 35.7-45.6° EWA, WFR has been decreased from 9.0170-6.9802m/min correspondingly. In other ranges of EWA such as EWA, 45.7-50.6°: WFR has increased 6.9804-7.4123m/min, 50.7-54.4°: WFR decreased from 7.4121-7.2480m/min, 54.5-55 °: WFR has been increased 7.2481- 7.26m/min. This optimum setting of WFR at different EWAs is shown in Fig. 4.29. Figure 4.29 shows the WFR and EWA and how they are connected at every point of combinations for the quality welds.

The optimal combinations correlations of three parameters (WFR, TS, and EWA) show that when EWA increases from 35-35.6°, both WFR and TS have been increased together. In the case of EWA 35.7-35.9°, WFR and TS decreased. In other series of EWA such as 40-44.8°: WFR decreased, and TS has increased 44.9-45.6°; both WFR and TS decreased, 45.7-50.3°: WFR increased, and TS decreased 50.4-50.6°: both WFR and TS increased, 50.7-54.4°: WFR decreased and TS increased, 54.5-55°: WFR increased and TS decreased.

Additionally, Fig. 4.30 shows three parameters (WFR, TS, and EWA) and optimal combinations of correlations. Even though Fig. 4.30 has been plotted with the heat map concept, it doesn't mean that effective parameters only. Under all these three parameter combinations, the best weld quality will be seen.

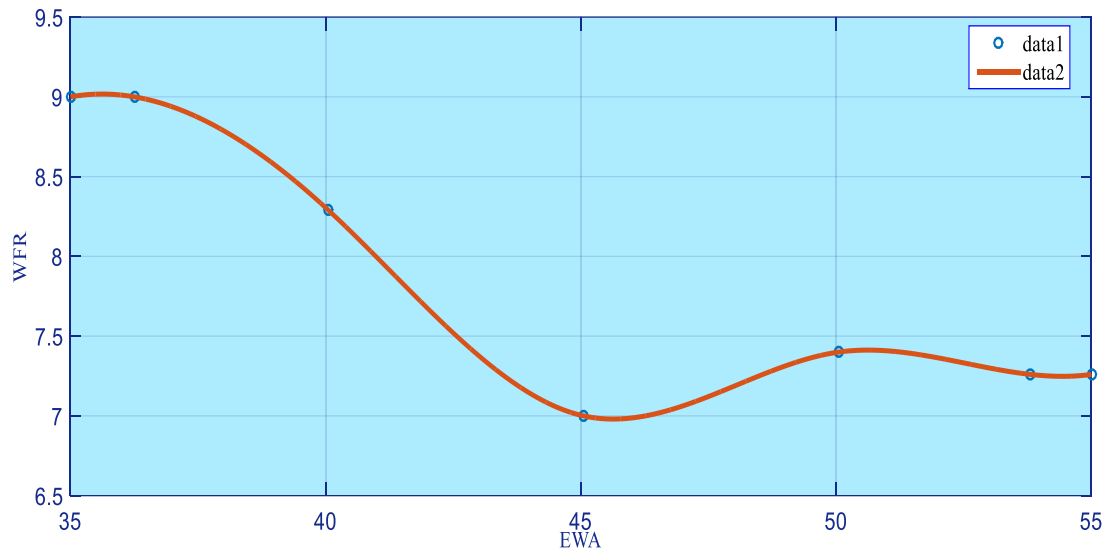


Figure 4.29: Optimal setting of WFR at different EWA

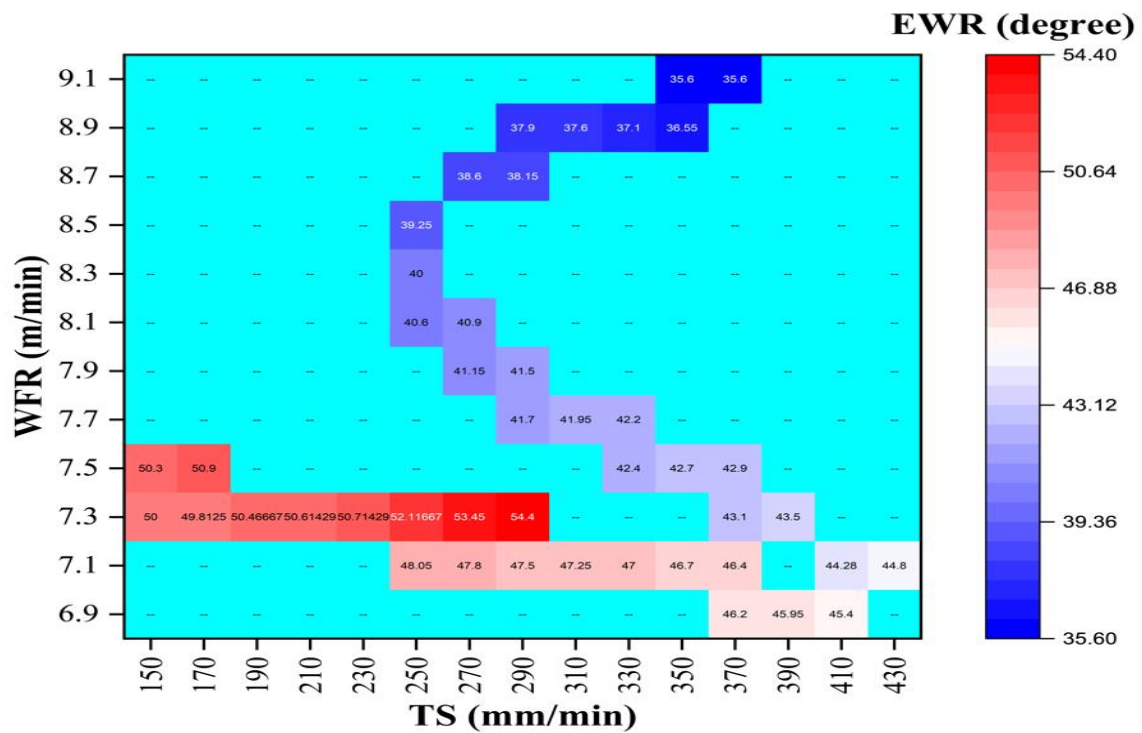


Figure 4.30: The heat map of WFR and TS at different EWA

4.6.3.2 Optimal TS at different EWAs

The travel speed is among the most challenging variables to anticipate the quality of weldment (Gyasi, *et al.*, 2017). To achieve the optimum welding quality, the correct choice of travel speed related to the dynamic torch angle is essential. The interpolated result shows that TS and EWA are very sensitive to weld quality characteristics. When EWA increased from 35-35.6°, TS has been increased from 358.78-366.4683mm/min correspondingly. In the case of EWA, increased 35.7-39.9° TS decreased 366.2513-242.6262mm/min. In other ranges of EWA such as 40-44.8°: TS increased 242.7726-420.3597mm/min, 44.9-50.3°: TS decreased from 420.1584-158.2740mm/min, 50.4-54.4° TS has been increased from 158.6750-289.3416mm/min correspondingly, 50.5-55°: TS has been increased from 289.2451-281.31mm/min. This optimum setting of TS at different EWAs is shown in Fig. 4.31. Figure 4.32 shows that TS and EWA are connected at every point of combination for the quality welds.

The three parameters (TS, CTWD, and EWA) optimal combinations correlations show an increase in EWA from 35-35.6° TS, and CTWD has been increasing at the same time. In the case of EWA 35.7-39.9°, both TS and CTWD decreased together. In the other range of EWA, such as 40-42.5°: TS increased, and CTWD decreased 42.6-44.8°: both TS and CTWD increased simultaneously, 44.9-50.3°: TS decreased, and CTWD increased 50.4-54.4°: TS increased, and CTWD decreased 54.5-55°: TS decreased and CTWD have been increased. Figure 4.32 shows three parameters (TS, CTWD, and EWA) optimal combinations correlations.

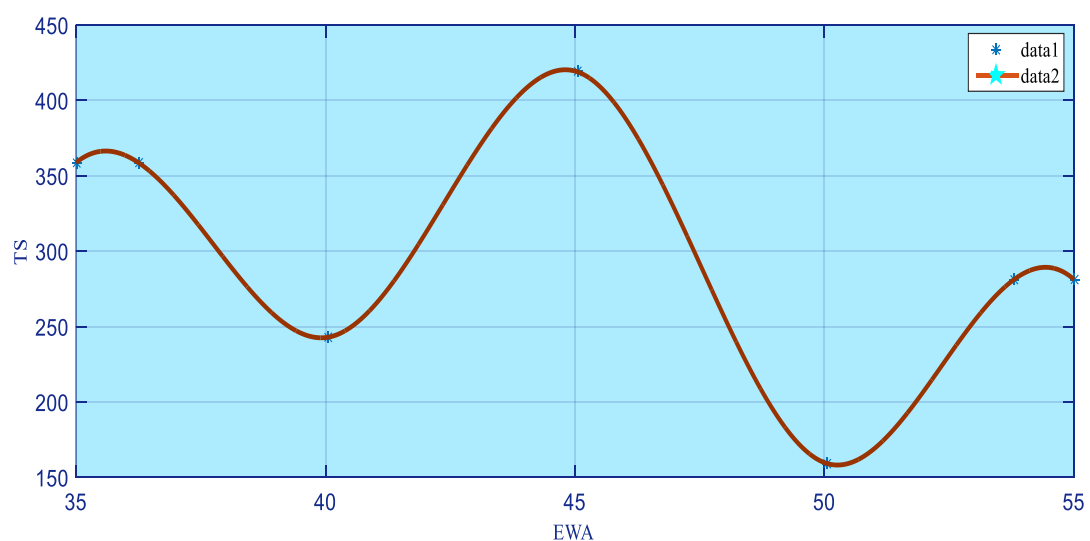


Figure 4.31: Optimal setting of TS at different EWA

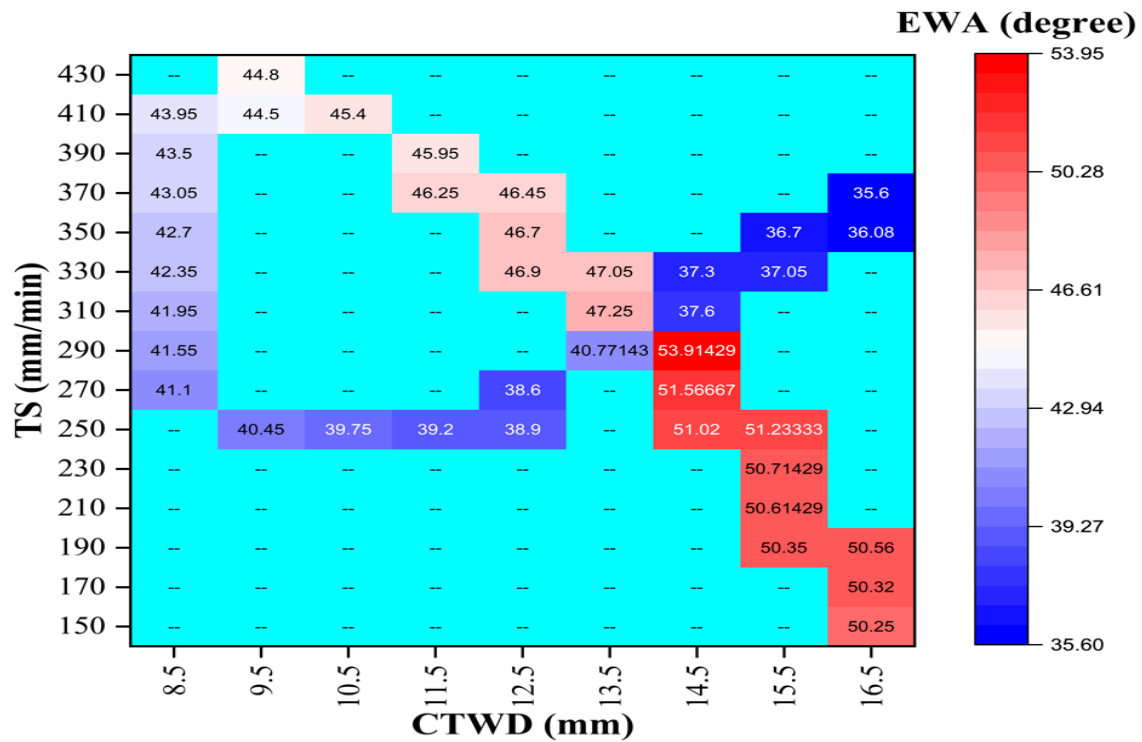


Figure 4.32: The heat map of TS and CTWD at different EWA

4.6.3.3. Optimal CTWD at different EWAs

To control the weld quality characteristics at the dynamic EWA of fillet weld; the amount of CTWD is very important because CTWD is determined by the level of heat input and the deposition amount of filler wire in horizontal and vertical plates separately (Filho and Ferraresi, 2010; Sterjovski, 2010; Gyasi, *et al.*, 2017). The generated optimal CTWD at different EWA shows; When EWA increase from 35-35.6° CTWD increases from 16.22-16.4733mm. In the case of EWA increased from 35.7-42.4° CTWD decreased from 16.4673-8.2613mm correspondingly. In other series of EWA such as EWA, 42.6-50.3°: CTWD increased 8.2651-16.6483mm, 50.4-54.4°: CTWD decreased 16.6409-14.2319mm consistently, 54.5-55°: CTWD has been increased from 14.2337-14.38mm in the same manner. This optimum setting of CTWD at different EWA is shown in Fig. 4.33. Figure 4.34 shows the CTWD and EWA and how they are connected at each EWA to achieve optimum weld quality.

The three parameters (WFR, CTWD and EWA) optimal combinations correlations show; when the level of EWA increase from 35-35.6° both WFR and CTWD have been increased at the same time. In the case of EWA 35.7-42.5° both WFR and CTWD were decreased

simultaneously. In other positions of EWA such as EWA, 42.6-45.6°: WFR has been reduced and CTWD increased, 45.7-50.3° both WFR and CTWD have been increased, 50.7-54.4°: both WFR and CTWD have been decreased, 54.5-55°: both WFR and CTWD have been increased in the same manner. Figure 4.34 shows three parameters (WFR, CTWD and EWA) optimal combinations correlations.

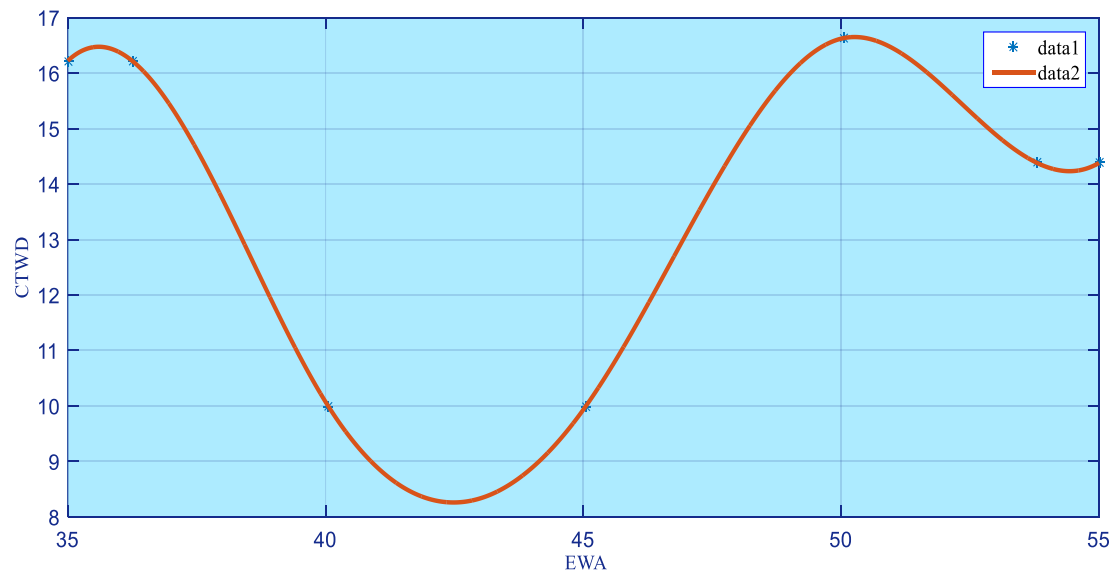


Figure 4.33: Optimal setting of CTWD at different EWA

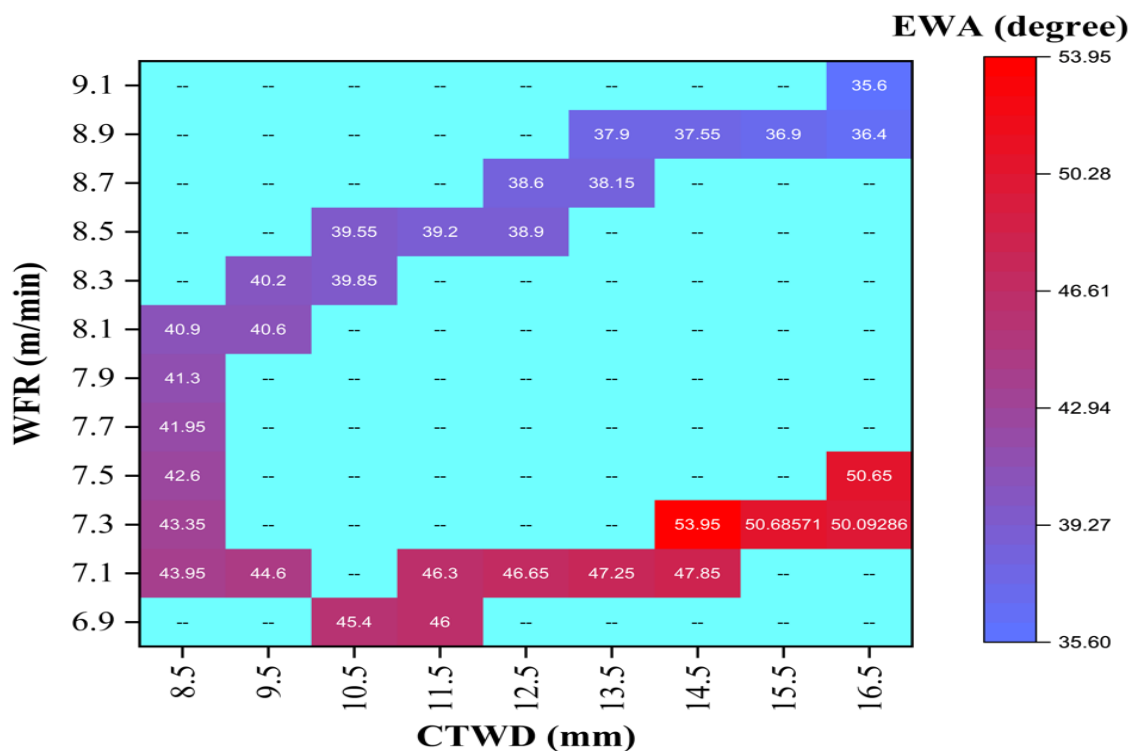


Figure 4.34: The heat map of WFR and CTWD at different EWA

4.7. Mechanical and microstructural characterization influence of EWAs

The assessment of weld quality is contingent upon the microstructure, HAZ, and mechanical properties of the weldment. This paper delves into an exploration of the primary welding conditions and the impacts of input process parameters on the micro-structure, extent of HAZ, and micro-hardness. The pivotal determinants influencing the mechanical properties and microstructure of weldments encompass the composition of the prior base metal, filler metal, heat input, and the cooling rate within the weld zone (Chaveriat, *et al.*, 1987; Gery, *et al.*, 2005). WFR holds a direct proportional relationship to heat input, as an increase in WFR leads to a corresponding rise in amperage. In contrast, TS exhibits an inverse proportionality to heat input, as more heat is introduced without altering the cooling rate (Chaveriat, *et al.*, 1987). The microstructure, HAZ, and micro-hardness of welded components are predominantly influenced by three primary factors: the initial composition of the base metal, the composition of the filler metal, and the balance between heat input and cooling rate during the welding process.

4.7.1 Microstructure analysis

The inhomogeneity of microstructure significantly influences the physical and mechanical properties of materials, including toughness, strength, hardness, ductility, corrosion resistance, and wear resistance (Gery, *et al.*, 2005; Rahul and Arya, 2013). Microstructure analysis has unveiled that a lower WFR combined with higher TS results in reduced heat input and a faster cooling rate, yielding a fine-grain structure. Conversely, a higher WFR with lower TS leads to higher heat input and a slower cooling rate, resulting in a coarse grain structure, aligning with findings by (Rahul and Arya, 2013). The level of CTWD also influences the microstructure of the weld zone, where a reduced CTWD increases the cooling effect of shielding gas, contributing to the formation of a fine-grain structure. The microstructure of the BM, HAZ, and FZ is elaborated in the following sections.

4.7.1.1 Microstructure of the BM

Microscopic analysis revealed that the microstructure of the base metal consists of a ferrite grain structure formed during the solidification of molten material (Fig. 4.35). The ferrite microstructure in the parent metal exhibits relatively coarse grain size and low levels of internal stress, aligning with observations by (Zamora, *et al.*, 2023).

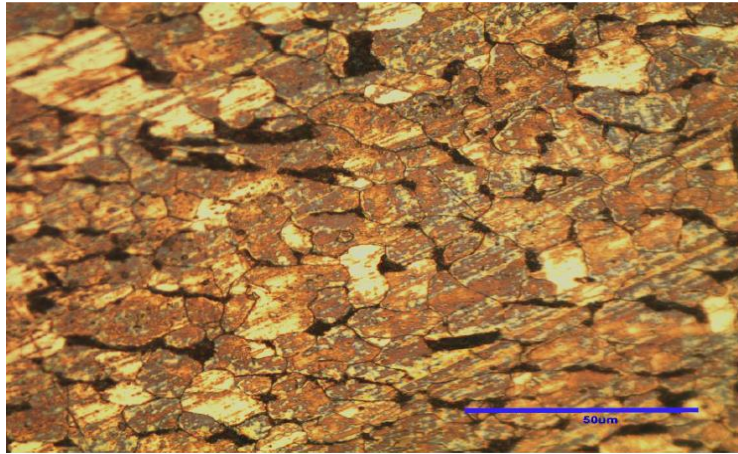
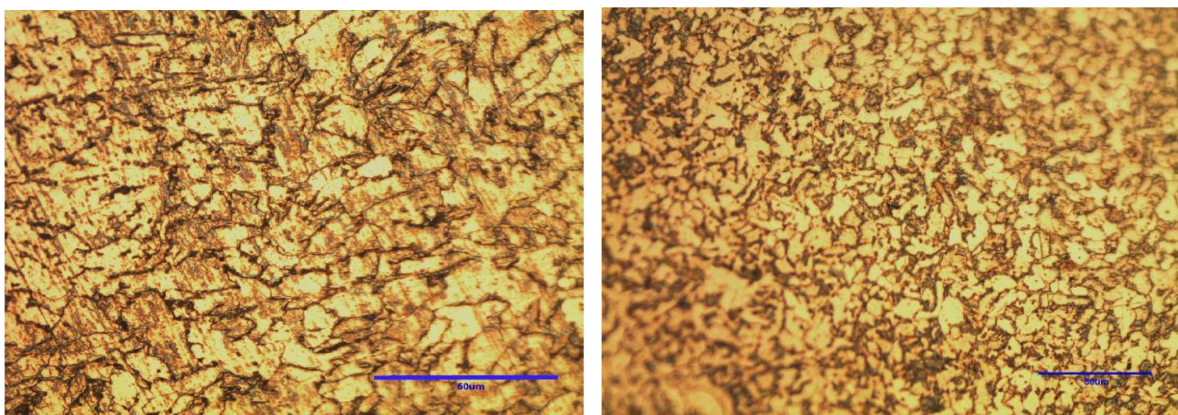


Figure 4.35: BM optical microstructure evaluation of AISI SAE 4130 alloy steel at 50X

4.7.1.2 Microstructure of HAZ

The HAZ serves as the transitional region between the fusion zone and the parent metal, yet its mechanical properties and microstructure undergo alterations due to the applied heat. The microstructure of the HAZ is primarily influenced by the magnitude of heat input and the cooling rate during welding. Reduced heat input and a faster cooling rate result in the formation of a fine-grain structure. Grains produced with a higher cooling rate exhibit significantly finer characteristics compared to those formed under a slower cooling rate. Microstructural observations were conducted on all T-joints fabricated using the parameters outlined in Table 3.9, with Fig. 4.36 (a) and (b) selected for illustrative purposes among other joints. From the microstructural analysis depicted in Fig.4.36 (a) and (b), it becomes evident that the HAZ exhibits coarse and elongated grains in comparison to the fusion zone (Zamora, *et al.*, 2023). This observed microstructure is consistent with similar patterns and behavior identified in previous studies.



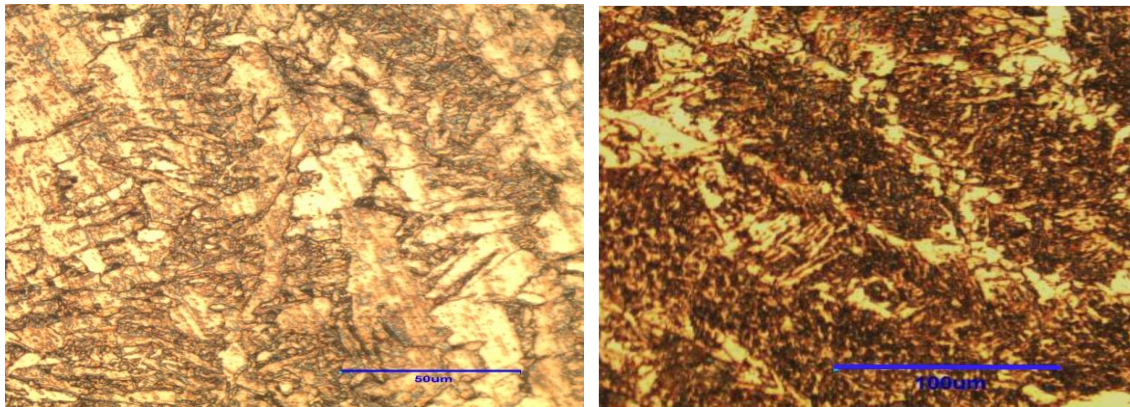
a) MTJ2

b) MTJ11

Figure 4.36: HAZ optical microstructure of AISI SAE 4130 alloy steel at 50X

4.7.1.3 Microstructure of FZ

Similarly, the microstructure of the FZ has been systematically observed and documented across all joints. Notably, the microstructure of the FZ is significantly influenced by the chemical composition of the filler materials. Dendritic microstructures and fine grains are evident in the weld FZ, as illustrated in Fig. 4.37 (a) and (b). Generally, a lower heat input leads to a higher cooling rate, resulting in the formation of fine grains in the FZ, aligning with findings by (Kornookar, *et al.*, 2022). In the FZ, a combination of ferrite and austenite grains was identified, corroborating observations by (Zamora, *et al.*, 2023).



a) MTJ2

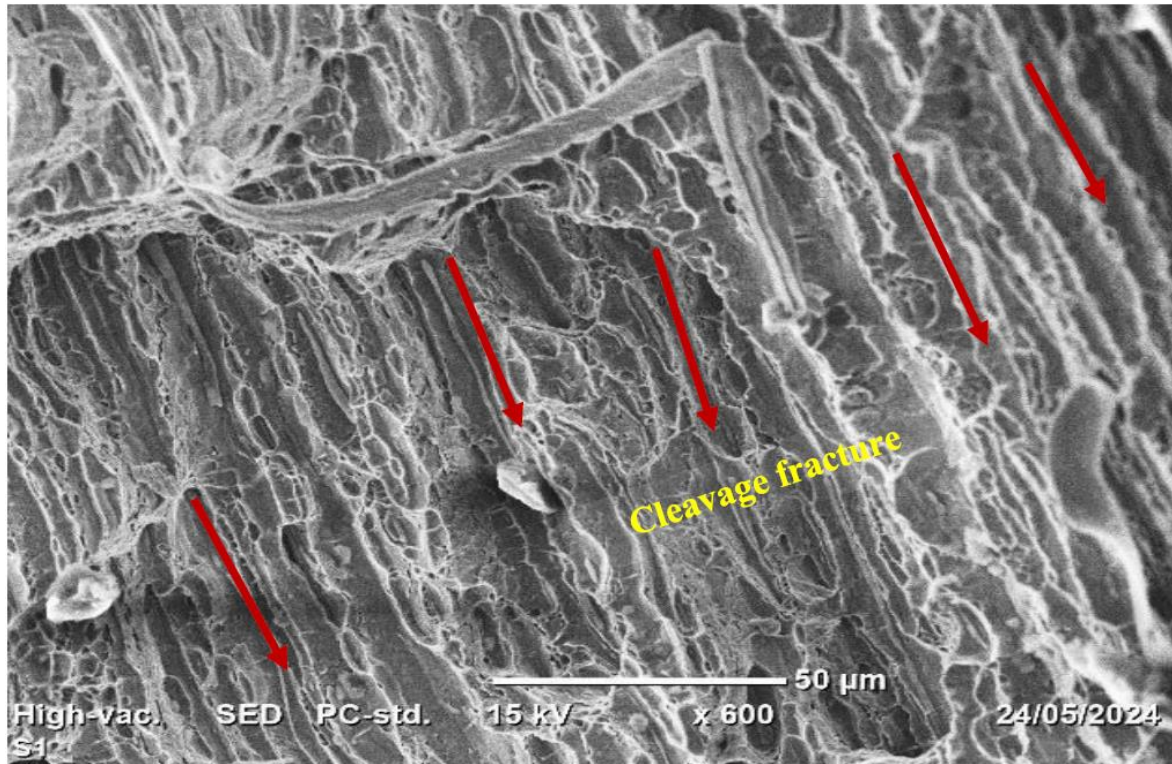
b) MTJ11

Figure 4.37: FZ optical microstructure of *AISI* SAE 4130 alloy steel at 50X

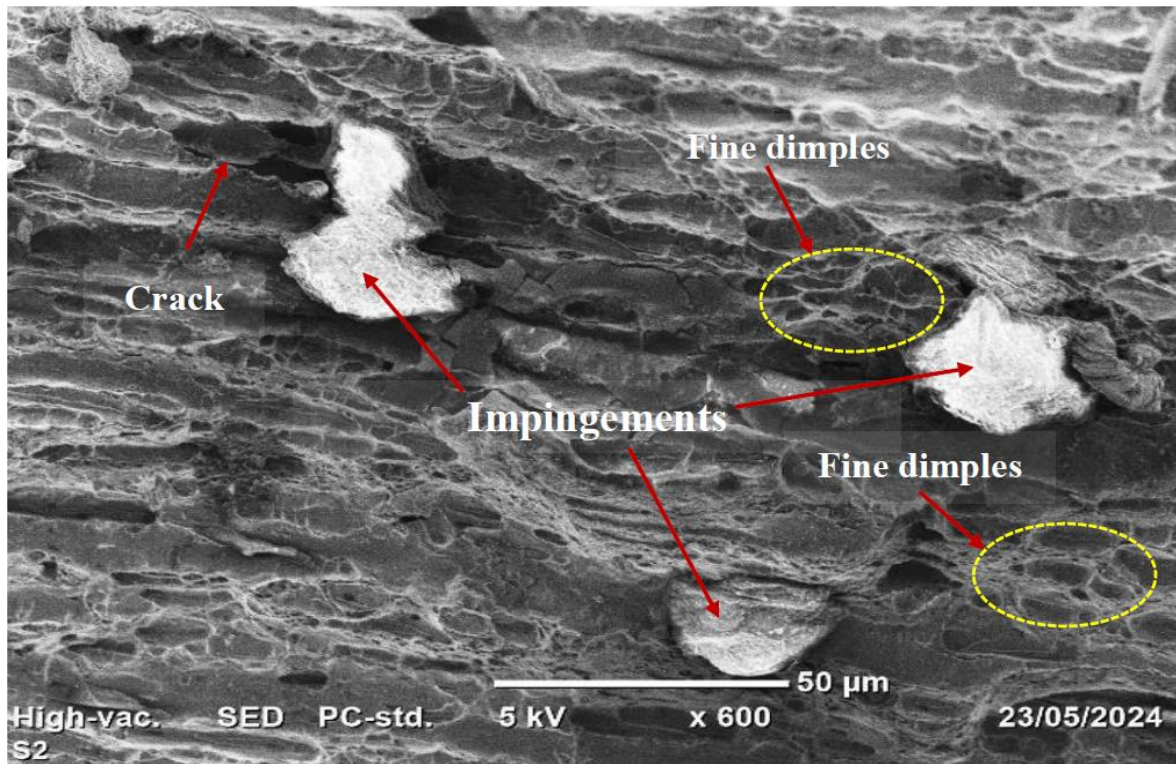
4.7.2 SEM fracture surface analysis

SEM fracture surface analysis is a method of failure analysis for studying the fracture surface of welded samples. Most of the welded spacemen failed at the faying surface of the horizontal and vertical plates. Fracture surface morphologies of *AISI* SAE 4130 alloy steel show a cleavage fracture in welded fracture; cleavage occurs along grain boundaries it appears with an exposed metal grain with a flat river pattern as indicated in Fig. 438 (a). The smooth fracture surface was observed on the weldment fracture of TJ4, as shown in Fig 438 (c). The higher the WFR inserts the higher the heat input in the weldment adhering to the fracture surface shown in Fig. 438 (b) is found to be more brittle compared to the low level of WFR (Fig. 438 (c)). Another important observation is the effect of micro-cracks that cause sudden failure. Fine dimples and cracking were noticed at TJ2 (Fig. 438 (b)) at higher WFR (9 m min⁻¹) which is a complement to a higher level of welding current provided higher heat input. The metallographic analysis showed that the fracture location was near the fusion line

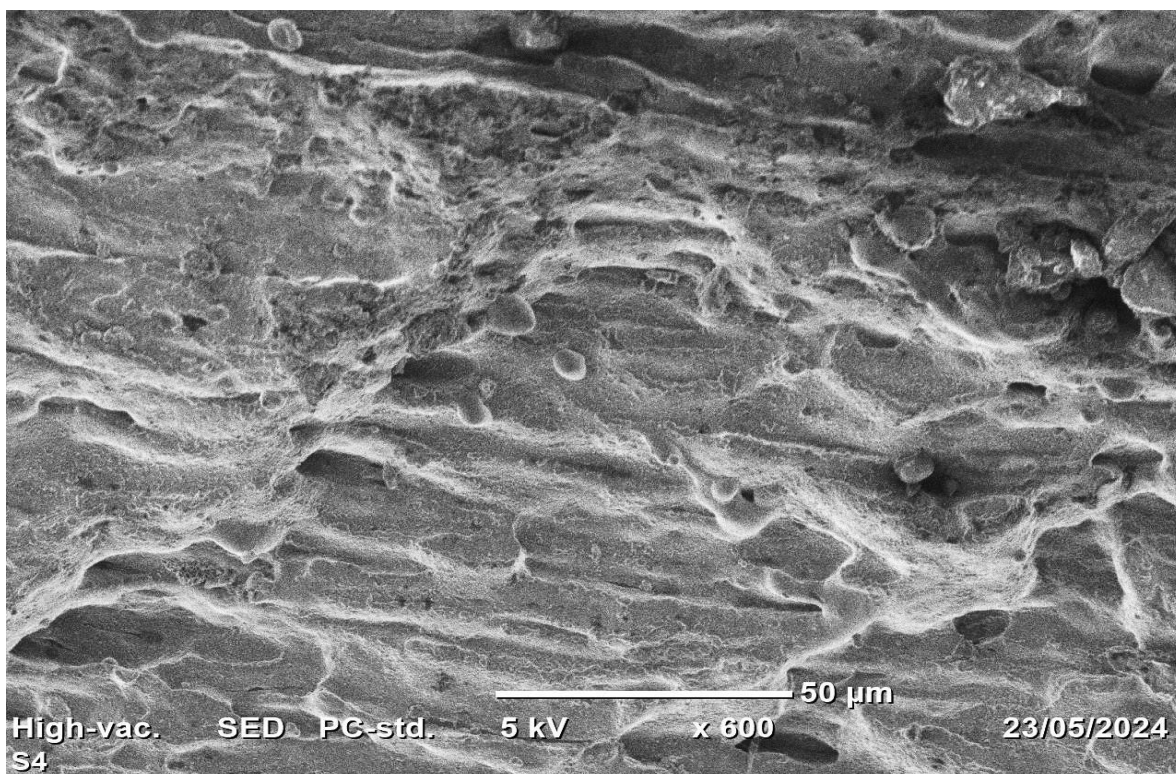
of the weldment and observed fractured surfaces exhibited fine dimples together with some impingements in the fusion zone (Fig. 438 (b)). In dimple fractures, the increase in voids size accounts for the degradation of the material stiffness. The inter-dendritic fracture surface identified in Fig.438 (c), the inter-dendritic fracture surface has a serrated appearance with precipitates of different shapes and sizes.



a) SEM micrographs of the welded surface TJ1



b) SEM micrographs of the welded surface TJ2

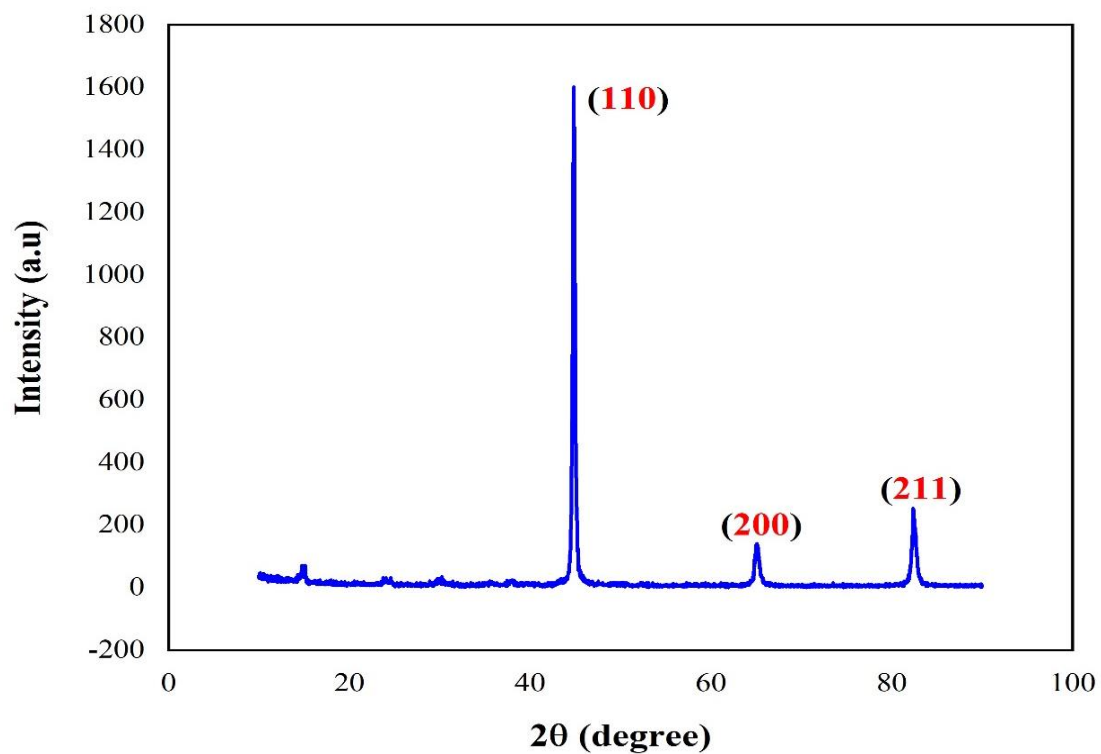


c) SEM micrographs of the welded surface TJ4

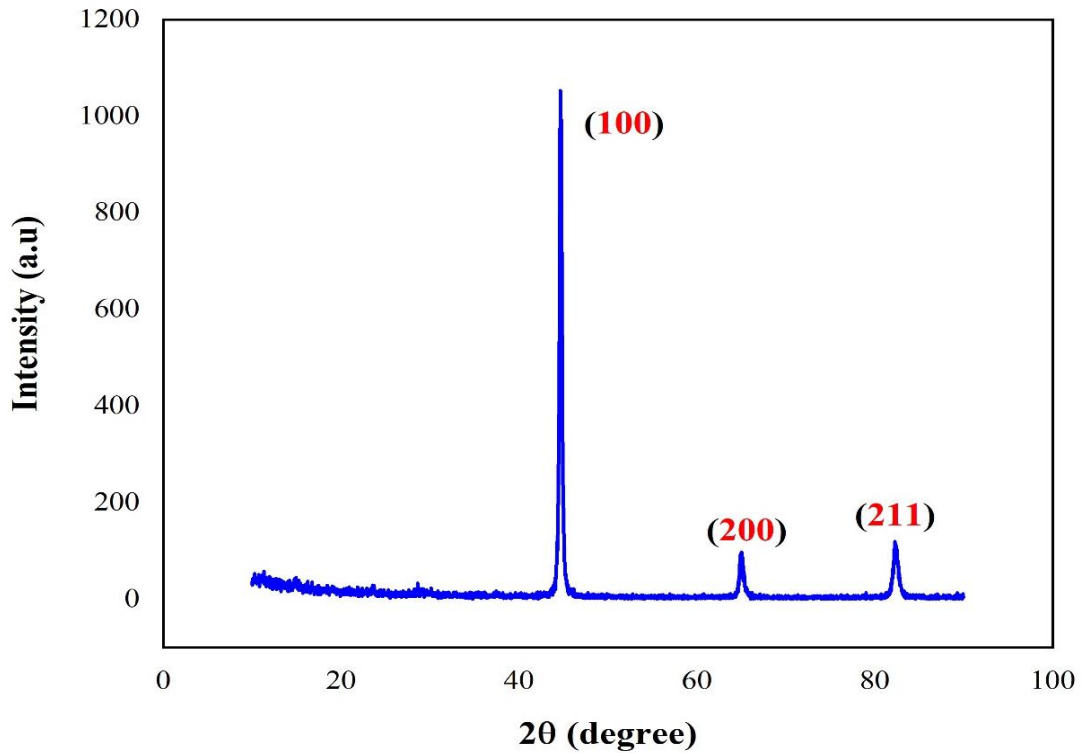
Figure 4.38: SEM micrographs of the welded surface of AISI SAE 4130 alloy steel

4.7.3. X-ray diffraction (XRD) analysis

XRD measurements were performed for the base material and the fusion zone of the weldment to study the crystal structure. X-ray diffraction pattern of AISI SAE 4130 alloy steel for base metal and fusion zone has been shown in Fig. 439 (a) and (b) respectively. From the XRD data, the level of intensity for the base materials was higher compared to that of the fusion zone. Different peak intensities indicate the difference not only in grain size but also in orientation distribution between them. The average crystallite size of the base metal and fusion zone is 25.75 nm and 24.51 nm respectively. Appendix-VI.



a) Base material



b) Fusion zone of weldment

Figure 4.39: XRD pattern of AISI SAE alloy steel

4.7.4 Extent of HAZ

The extent of the HAZ is contingent upon factors such as the quantity of heat input, the duration of exposure to heat, and the composition and mechanical properties of the parent material. Additionally, the HAZ is influenced by input parameters, including WFR, TS, EWA, and CTWD, as noted in studies by (Lermen, *et al.*, 2018), (Ghazvinloo and Raouf, 2022). A broader extent of the HAZ correlates with heightened variations in material properties. An escalation in WFR and CTWD increases the level of heat input, consequently expanding the extent of the HAZ. Conversely, higher travel speeds reduce the inoculated heat input, resulting in an increased extent of constitutional supercooling and, consequently, a reduced extent of the HAZ, as observed by (Chaveriat, *et al.*, 1987). Furthermore, the independent extents of the HAZ on the vertical and horizontal plates are determined by the EWA. The results of the extent of the HAZ and micro-hardness tests are detailed in Table 4.21.

4.7.4.1 Extent of HAZ on the vertical plate

During welding with higher EWA and CTWD, the electrode tip approaches the vertical plate, leading to the current flowing along the path of least resistance and resulting in higher heat

input. Consequently, this leads to an increased extent of the HAZ on the vertical plate. Moreover, a greater quantity of filler metals is deposited in the vertical plane during welding. To illustrate, the greatest extent of the HAZ was recorded at MTJ3 (3m/min WFR, 150mm/min TS, 55° EWA, 20mm CTWD) and MTJ10 (9m/min WFR, 350mm/min TS, 55° EWA, 20mm CTWD) on the vertical plate, measuring 956.08 μ m and 717.91 μ m, respectively, as depicted in Fig. 4.40 (a) and (b).

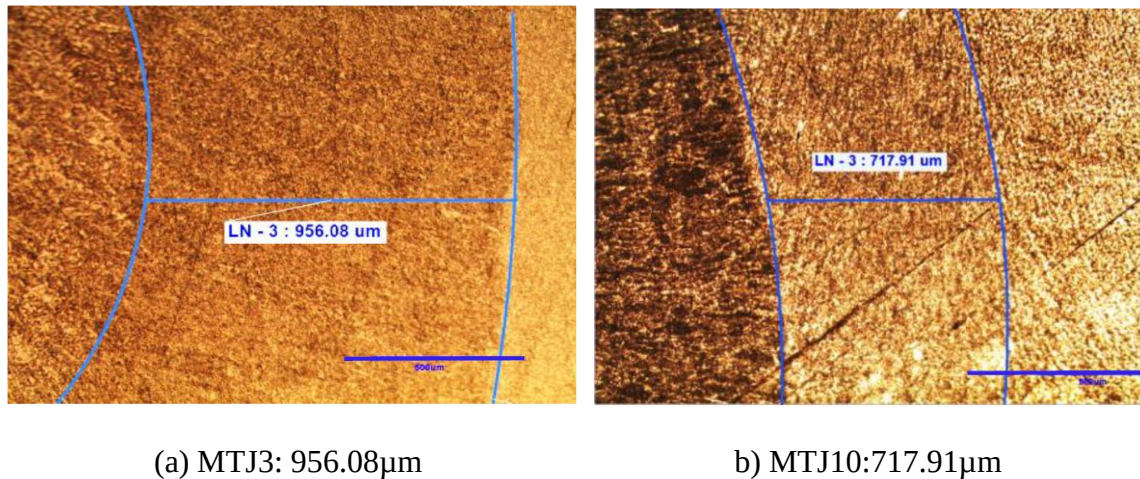
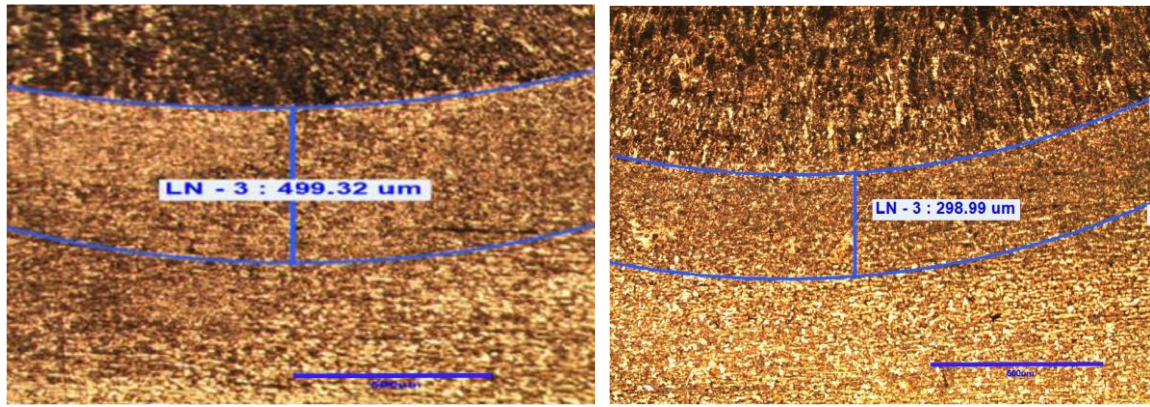


Figure 4.40: Maximum extents of HAZ on the vertical plate, 5X

4.7.4.2 Extent of HAZ on the horizontal plate

Welding with a lower EWA and higher CTWD setting directs more amperage towards the horizontal plate, resulting in increased heat input on the horizontal plate and, consequently, an expanded extent of the HAZ on the horizontal plate. Conversely, at a higher EWA and a closed CTWD, the extent of the HAZ is larger on the horizontal plate due to the reduced gap between the tip of the electrode and the horizontal plate. In particular, the highest extent of HAZ on the horizontal plate was observed at MTJ4 (5m/min WFR, 150mm/min TS, 35° EWA, 20mm CTWD), recorded as 499.32 μ m. Conversely, the lowest extent of HAZ on the horizontal plate, measuring 298.99 μ m, was recorded at MTJ11 (7m/min WFR, 350mm/min TS, 35° EWA, 15mm CTWD), as illustrated in Fig. 4.41 (a) and (b).

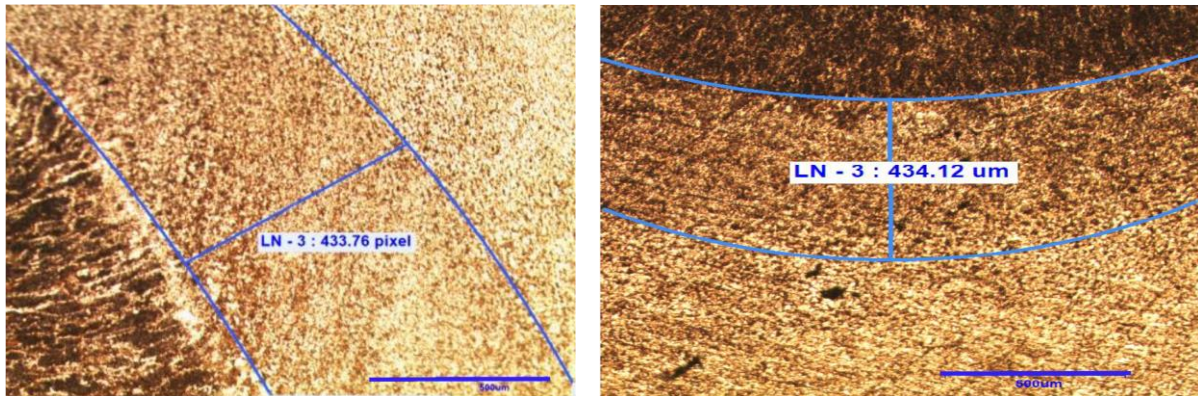


(a) MTJ4: highest (499.32 μ m) (b) MTJ11: lowest (298.99 μ m)

Figure 4.41: The extent of HAZ on the horizontal plate, 5X

4.7.4.3 Equal extent of HAZ on vertical and horizontal plate

Welding with a setting of moderate EWA and CTWD creates a scenario where the provided heat input is distributed relatively equally between the vertical and horizontal plates. For instance, in the case of MTJ2, the recorded extent of the HAZ on the vertical plate (433.76 μ m) and the horizontal plate (434.12 μ m) is approximately equal. This equality in the extent of HAZ on both plates can be attributed to the intermediate setting of EWA (45°) and CTWD (15mm), indicating that the amperage and heat input are evenly diffused for both plates. This observation is depicted in Fig. 4.42 (a) and (b).



a) MTJ2: 433.76 μ m, vertical plate

(b) MTJ2: 434.12 μ m, horizontal plate

Figure 4.42: MTJ2: Equal extent of HAZ on vertical and horizontal plate, 5×

Table 4.21 Extent of HAZ measurements and micro-hardness tests results

Run	Extent of HAZ (μm)		Micro-hardness (VHN)									
	Vertical plate	Horizontal Plate	Fusion zone					Heat affected zone				
			Replication 1	Replication 2	Replication 3	Average	SD	Replication 1	Replication 2	Replication 3	Average	SD
MTJ1	464.55	376.32	435.7	435.8	434.9	435.4	0.49	305.4	304.6	304.9	304.9	0.40
MTJ2	433.76	434.12	405.6	405.7	405.4	405.5	0.15	313.5	313.8	313.7	313.6	0.15
MTJ3	956.08	446.98	432.9	433.6	432.7	433.0	0.47	312.5	311.7	312.3	312.1	0.41
MTJ4	453.63	499.32	428.7	428.7	428.3	428.5	0.23	325.5	324.9	325.2	325.2	0.30
MTJ5	578.86	434.69	409.5	409.4	409.2	409.3	0.15	313.4	313.4	313.6	313.4	0.11
MTJ6	448.92	344.60	573.2	573	572.4	572.8	0.41	360.9	361.8	362	361.5	0.58
MTJ7	453.76	463.12	414.6	414.7	414.1	414.4	0.32	315.4	314.7	315.4	315.1	0.40
MTJ8	500.03	451.01	401.4	401.2	401.2	401.2	0.11	331.3	330.2	330.5	330.6	0.56
MTJ9	493.00	403.12	394.9	395.2	394.5	394.8	0.35	309.3	309.1	309.4	309.2	0.15
MTJ10	717.91	434.12	463.6	463.5	463.3	463.4	0.15	319.8	319.6	319.6	319.6	0.11
MTJ11	657.10	298.99	416.6	416.7	416.5	416.6	0.10	313.6	313.4	314	313.6	0.30

SD: standard deviation

4.7.5 Micro-hardness

Micro-hardness has been determined by the formation of metal oxides, proper fusion of filler metal with base metal, and the effect of input process parameters (Kamble and Rao, 2013; Raman Kumar, *et al.*, 2020). The micro-hardness result shows a significant difference in micro-hardness value between the BM, HAZ, and FZ, as shown in Fig. 4.43, in agreement with (Xue, Y. *et al.*, 2005; Xue, J. *et al.*, 2021). The intensity of this difference depends on the grain structure (size) which has been formed during the weld. The grain size and grain structure determine the level of microhardness in the welding zones. The microstructure of HAZ has been coarse and elongated grains than FZ. The microstructure of HAZ is relatively finer than the BM. agreement with (Zamora, *et al.*, 2023). On average, the higher hardness has been recorded on FZ, followed by HAZ and BM, due to the relatively finest grain structure that has been formed on FZ, HAZ, and BM, respectively, in agreement with (Kamble and Rao, 2013). The microstructure of different welding zones has been shown in Fig. 4.43 (a) and (b). The micro-hardness of BM, HAZ, and FZ have been explained in the following sections.

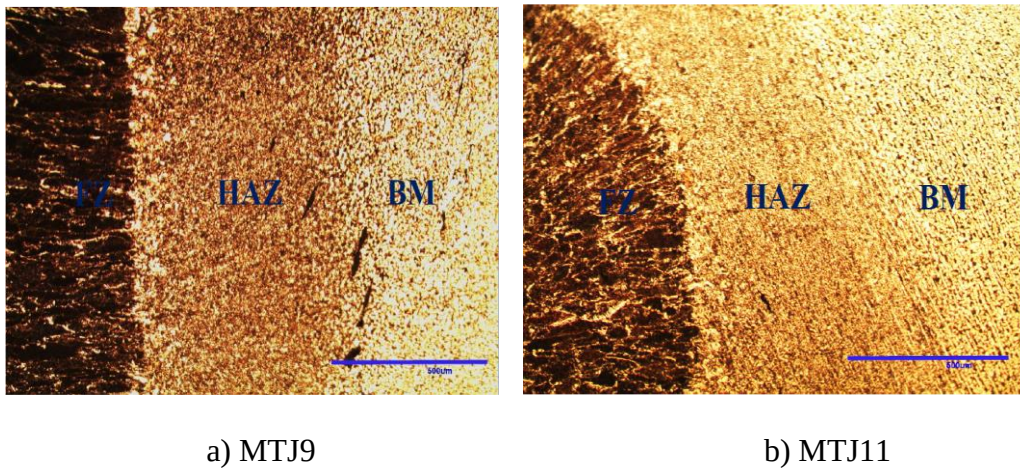


Figure 4.43: Weld macrographs in different weld zones; 20X

4.7.5.1 Base metal

The parent metal ferrite grains exhibit the lowest hardness (228HV) because of the relatively low level of internal stress and coarse grain microstructure associated with the highest transformation temperature of the austenite decomposition products (Senol and Cam, 2020).

4.7.5.2 Heat-affected zone

HAZ is the most critical region in the welded joint. The micro-hardness of HAZ is majorly determined by the amount of WFR (determine the level of heat input) and TS (determine the level of cooling rate) (Oyetunji, et al., 2013). When WFR increases, the level of heat input increases; higher heat input forms a coarse grain structure, resulting in a decline in microhardness. The average grain size in HAZ increases with heat input (Li, *et al.*, 2013). When TS increases, the level of a cooling rate increases; a higher cooling rate forms a fine grain structure, increasing microhardness in agreement with (Poelt, *et al.*, 2006; Yeshwanth, *et al.*, 2012). Microhardness measurements are shown in Table 4.21. For comparison, the joints made using low heat input exhibit higher microhardness values than those welded with medium and high heat input. The joints made by using a higher cooling rate exhibit higher microhardness values than those welded with medium and lower cooling rates, which is in agreement with (Wan Muda, et al., 2015; Xue, Y. *et al.*, 2005; Xue, J. *et al.*, 2021). For instance, micro-hardness values are much higher (361.5HV) MTJ6 (WFR of 3m/min, TS of 450mm/min, EWA of 35°, and CTWD of 15mm) and (330.6 HV) MTJ8 (WFR of 5m/min, TS of 450mm/min, EWA of 45° and CTWD of 10mm) than another set of parameters Fig. 4.44. The level of CTWD are significantly affected the level of micro-hardness on HAZ, at closed CTWD shielding gas cooling rate effect has been increased, results higher micro-hardness.

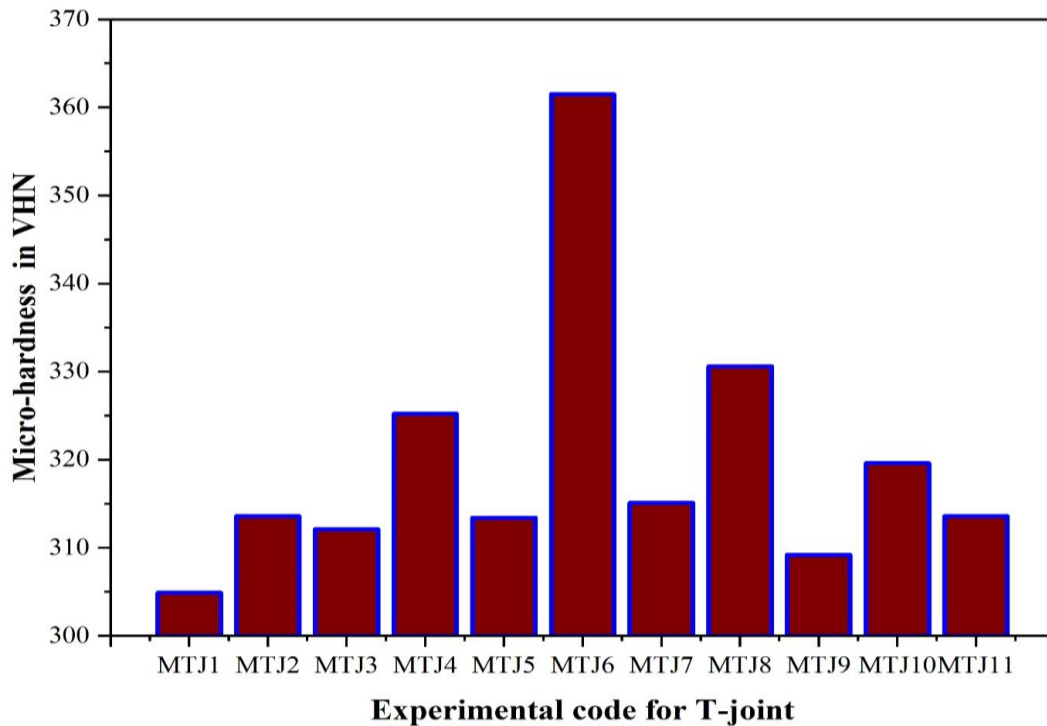


Figure 4.44: Micro-hardness on HAZ

4.7.5.3 Fusion zone

The micro-hardness of the FZ is primarily influenced by the chemical composition of filler metals and the heat input during welding. The chemical composition of filler materials plays a crucial role in the precipitation and solid solution process, directly affecting the micro-hardness of the FZ. Additionally, the levels of WFR and TS determine the amount of filler metal deposition in the weldment. Higher WFR and lower TS result in increased filler metal deposition, leading to a higher amount of precipitation, increased micro-hardness, and the formation of fine, dark-colored grain structures in the FZ (Figure. 4.43). The mechanical investigation results indicate that joints created with lower heat input exhibit higher micro-hardness values compared to those welded with medium and high heat input. For instance, the maximum micro-hardness of 572.8HV is recorded at MTJ6 (WFR of 3m/min, TS of 450mm/min, EWA of 35°, and CTWD of 15mm). The next higher micro-hardness values of 463.4HV and 435.4HV are recorded at MTJ10 (WFR of 9m/min, TS of 350mm/min, EWA of 55°, and CTWD of 20mm) and MTJ1 (WFR of 7m/min, TS of 250mm/min, EWA of 55°, and CTWD of 15mm), respectively. The lowest micro hardness of 394.8HV is recorded at MTJ9 (WFR of 7m/min, TS of 350mm/min, EWA of 45°, and CTWD of 20mm) (Fig. 4.45).

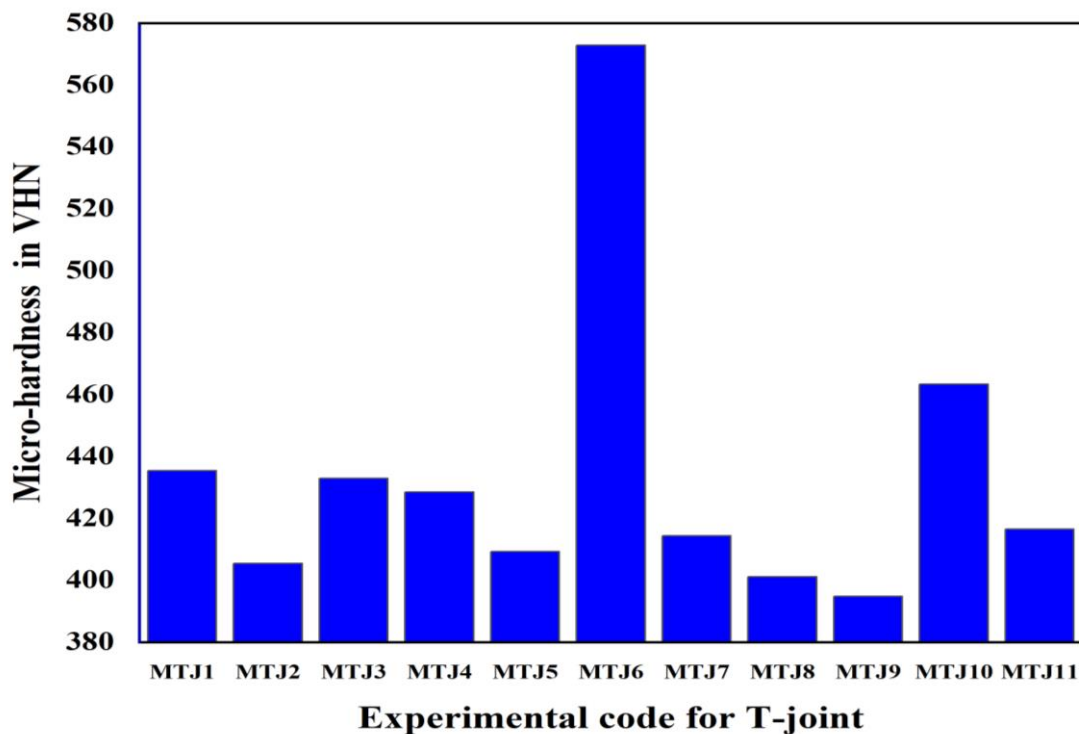


Figure 4.45: Micro-hardness on FZ

These observations suggest that at higher WFR and lower TS, more filler metals are deposited in the weldment, significantly contributing to the micro-hardness, in agreement with (Feng, *et al.*, 2016; Prajapati and Badheka, 2017). Higher heat input can lead to an expansion of the microstructure's grain size, resulting in lower micro-hardness values (Yeshwanth, *et al.*, 2012). Overall, the micro-hardness results recorded on the FZ were higher than those observed in the HAZ, aligning with the findings of (Sankar, *et al.*, 2021).

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

Form the entire research work on robotic GMAW of *AISI SAE 4130* alloy steel at three different thickness (2, 4 and 6mm), the following conclusion have been drawn.

5.1.1 Quality level-based prediction of welding parameters

This dissertation focuses on the quality level-based selection of robotic Gas Metal Arc Welding (GMAW) input process parameters (WFR, TS, CTWD, and EWA) for 4130 steel plates with thicknesses of 2mm, 4mm, and 6mm. The exploration of an artificial intelligence system aimed to determine acceptable input process parameters for quality levels 'D', 'C', and 'B' opens up diverse opportunities for the manufacturing industry to tailor their production to different quality standards. This investigation introduces a method to ensure quality levels during the selection of process parameters, a departure from the conventional practice of using predefined single sets of welding parameters and assessing quality post-deposition. Key conclusions drawn from this dissertation are as follows:

- The conventional approach of seeking near-optimal or optimal process conditions based on specific objectives is replaced by an artificial intelligence method, enabling the identification of acceptable process conditions that ensure the desired quality levels.
- In contrast to the conventional practice of confining operations to a single set of parameters, the present approach provides a set of process parameters that ensure higher productivity without compromising quality levels. Similarly, reducing the waste of filler materials and electric power at the same quality level can be achieved by choosing a low-level wire feed rate.
- The investigation reveals that quality level selection is dependent on the thickness of the plate. This crucial aspect should be taken into account during the process design phase, offering a more effective approach to achieving desired quality standards.
- A noteworthy contribution of this investigation is the consideration of torch angle for achieving acceptable quality levels in T-welds. This insight enhances the understanding of critical factors influencing weld quality, providing valuable guidance for practitioners in the field.

5.1.2 Process parameter optimization on AISI SAE 4130 alloy steel

A total of sixteen Tee-joint weld runs were carried out of AISI SAE 4130 alloy steel plates of 6 mm thickness using a robotic gas metal arc welding process. The experiments were done based on the central composite design technique and data has been recorded to find an optimal setting of input parameters to achieve the desirable weld strength with an adequate level of joint penetration. Mathematical models are developed for break strength and joint penetration. The statistical significance of the fitted models and variables involved as the response parameters are tested by ANOVA. In addition, the lack-of-fit test is used and F-ratios are compared with the tabulated values. ANOVA and lack-of-fit test shows that the developed models are reasonably accurate. It can be concluded that;-

- DOE, response surface methodology with a central composite design technique is a powerful tool for optimization of robotic arc welding input parameters.
- As RSM analyzes the significance of process parameters, wire feed rate followed by travel speed, electrode to work angle has been found as the sequence of effective parameters among all used in this investigation. Contact tip to work distance is the least effective parameter.
- The optimal break strength of 67.45kN and joint penetration of 3.71mm have been predicted in the optimal setting of the wire feed rate of 8.29m/min, travel speed is 243 mm/min, electrode to work angle is 40° and contact tip to work distance is 10mm with an overall desirability measurement of 0.90.
- Conformity tests were conducted with the same experimental setup to validate the accuracy of the optimized results. The responses of 65.13kN break strength and 3.63mm joint penetration have been recorded. The recorded results showed that the accuracy of the mathematical models is 96.56% and 97.84 (3.44 and 2.16% average error) of break strength and joint penetration respectively. The predicted capacity is closer to the test capacity.

5.1.3 Optimization of welding parameters for a set of electrode work angles

In this dissertation, optimum combinations of welding parameters for different torch angles are investigated. DoE has been used to acquire the optimum combination of welding parameters for non-optimal torch angles. Response surface methodology with central composite design can be employed for developing mathematical models and predicting optimum combination input process parameters for different torch angles. A

prediction profiler with desirability function has been used to predict optimal setting for EWA including 35° (WRR=9m/min, TS=358.78mm/min, and CTWD=16.22mm), 45° (WER=7m/min, TS=418.98mm/min, and CTWD=10mm), 50° (WFR=7.40m/min, TS=159.26mm/min and CTWD=16.63mm) and 55° (WFR=7.26m/min, TS=281.31mm/min and CTWD=14.38mm) for optimal responses of break strength and joint penetration. Conformity tests were conducted to validate the accuracy of the optimized results. The average accuracy of the mathematical models of the four different torch angles is 96.01% and 99.94 (or 3.99 and 0.06% average error) of break strength and joint penetration respectively. The recorded results showed that the predicted capacity is closer to the test capacity and the optimized process parameters for different torch angles have made a significant contribution to the quality of weldment and enhanced productivity by reducing parameters setting time and efforts.

5.1.4 Automatic generation of optimal combination of welding parameters

For high-volume welding fabrication and manufacturing processes, the robotic GMAW process plays a great role. The optimum combination of welding parameters for 6mm thickness *AISI SAE 4130* alloy steel has been investigated by design of experiment method; the investigated result for five (5) torch angles (35°, 40°, 45°, 50°, and 55°) has been used and interpolated for all accessible (35°-55°) torch angles by cubic spline interpolation method. Finally, the system generates optimum combinations of welding parameters, including WFR, TS, and CTWD, for all optimal and non-optimal torch angles. The generated optimal setting of welding parameters can be employed for the robotic GMAW process to increase the programmable efficiency of the welding robot and reduce parameter setting time and effort during welding. In addition to this, it increases the quality of the products and productivity of the industry.

5.1.5 Mechanical and microstructural characterization of 4130 alloy steel

In this dissertation, a comprehensive investigation into the microstructural analysis, extent of HAZ, and micro-hardness of 'T' joints in *AISI SAE 4130* alloy steel welded at different torch angles has been conducted. The following conclusions have been drawn:

- The XRD analysis results indicated that the average crystallite size of the base metal and fusion zone is 25.75nm and 24.51nm respectively.

- Fracture surface morphologies of AISI SAE 4130 alloy steel show a cleavage fracture in welded fracture. As per the scanning electron microscope (SEM) image observations, the higher wire feed rate yields to brittle fracture surface. Fine dimples and cracking were noticed at TJ2 at higher WFR (9 m/min) which is a complement to a higher level of welding current provided higher heat input.
- Microstructure, HAZ extent, and micro-hardness in the weld zone are primarily governed by three key factors: the composition of the base metal, the composition of the filler metal, and the heat input and cooling rate during welding.
- The base metal composition influences the microstructure and micro-hardness of the base metal. Meanwhile, the HAZ microstructure, extent of HAZ, and micro-hardness are primarily determined by heat input and cooling rate. The FZ microstructure, extent of HAZ, and micro-hardness are mainly influenced by filler metal composition and the shielding gas effect.
- Microstructural examination reveals that lower WFR (3m/min) with higher TS (450 mm/min) leads to lower heat input and a faster cooling rate, resulting in a fine-grain structure. Conversely, higher WFR (9m/min) with lower TS (150mm/min) produces higher heat input and a slower cooling rate, resulting in a coarse grain structure.
- WFR and CTWD are the main input parameters affecting the extent of HAZ; higher WFR (9m/min) with a closed CTWD (10mm) leads to a greater extent of HAZ. EWA is another factor affecting the extent of HAZ, with higher EWA (55°) and CTWD (20mm) resulting in a higher extent of HAZ on the vertical plate. Similarly, lower EWA (35°) with higher CTWD (20mm) results in a higher extent of HAZ on the horizontal plate.
- Welding with lower EWA (35°) and closed CTWD (10mm) results in a high extent of HAZ recorded on the vertical plate, while welding with higher EWA (55°) and closed CTWD (10mm) results in a higher extent of HAZ recorded on horizontal plates.
- Welding with higher WFR (9m/min) and lower TS (150mm/min) results in more filler metals deposited in the weldment, supplying high welding amperage in the weld zone; the lower cooling rate leads to the formation of coarse grain structure and lower micro-hardness.
- Welding with lower WFR (3m/min) and higher TS (450mm/min) creates a rapid cooling rate in the weld zone, producing a fine grain structure and resulting in a higher micro-hardness value.

- At higher WFR (9m/min) and lower TS (150mm/min), the deposition amount of filler metals is very high, leading to an increased contribution of filler metal composition and significantly affecting the micro-hardness level in the FZ. In general, the average higher hardness is recorded in the FZ, followed by HAZ and the BM, due to the relatively finest grain structure formed in the FZ, HAZ, and BM, respectively.

5.2 Recommendations

In the future, the following research aspects may be considered in the fields of robotic arc welding process:-

- Determine the optimal welding sequence and welding parameters sets for a given objective function that trade off various criteria, such as quality, collision free motion and time.
- The optimization of different combination of welding variables have not been done yet for obtaining required quality characteristics in terms of weld quality, cost and welding time.
- Extract relevant geometric, material and production information from the computer aided drawing and computer aided manufacturing.
- Online quality monitoring of robot welding processes
- It needs further investigation to define the optimal welding sequence and parameters for different welding materials type of joint and welding position.
- Application of different artificial intelligence techniques for welding process control and monitoring of weld quality.
- The quality characteristics of weld like weld strength, weld bead shape and size, weld reinforcement, weld penetration shape factors, weld reinforcement shape factors, presence of porosity and cracks etc. need to be explored in research work.
- Research work on advanced soft computing or hybrid optimization technique needs to be more discover to obtain better weld quality.

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LIST OF PUBLICATIONS

7.1 Journals (Papers Published)

During the course of this project, a number of public presentations and articles have been made which are based on the work presented in this thesis. They are listed here for reference.

- [1] Wordofa, T.N., Perumalla, J.R. & Sharma, A. An artificial intelligence system for quality level-based prediction of welding parameters for robotic gas metal arc welding. *Int J Adv Manuf Technol* (2024).
- [2] Wordofa, T.N., Perumalla, J.R. & Sharma, A. Mechanical and microstructural characterization of AISI SAE 4130 steel welded joints made by robotic gas metal arc welding process: influence of electrode work angle in 'T' welded joints. *Mater. Res. Express* (2024).
- [3] Wordofa, T. N., & Ramulu, P. J. (2023). Gas metal arc welding input parameters impacts on weld quality characteristics of steel materials a comprehensive exploration. *Manufacturing Technology*, 23(3), 366-379.

7.2 Conference

- [1] Tesfaye Negash Wordofa, Perumalla Janaki Ramulu, Robotic Arc welding process parameters optimization of different welded joints: Review, 2nd Silk Road Symposium on Advanced Manufacturing (SAM 2019), November 3-5, 2019, Adama, Ethiopia.

7.3 Papers under Review

- [1] Process parameter optimization of robot gas metal arc welding process on *AISI SAE* 4130 steel plate - Part I.
- [2] Process Parameter Optimization for a Set of Torch Angles for 'T'-joints Produced by Robotic Gas Metal Arc Welding Process - Part II.
- [3] Automatic generation of optimal combination welding parameters for robotic gas metal arc welding process - Part III.
- [4] Optimization, prediction and programming of input parameters for robot gas metal arc welding process: a review

APPENDICES

APPENDIX-I

Fuzzy rule weightage for each parameter (from pilot Experimentation)

A. Objective function (prediction formula) for throat thickness

$$\begin{aligned}
 TT = & 19.77 + 0.1636(CTWD) + 0.08008(EWA) + 0.301091(TS) + 0.28154(WFR) \\
 & - 0.0085(CTWD)^2 + 0.0094(EWA)^2 + 0.000029(TS)^2 - 0.0634(WFR)^2 \\
 & - 0.0098(CTWD)(EWA) + 0.00010(CTWD)(TS) + 0.025(CTWD)(WFR) \\
 & - 0.00028(EWA)(TS) + 0.021(EWA)(WFR) - 0.00094(TS)(WFR)
 \end{aligned}$$

Impact (Effect) level for JP	WFR	TS	EWA	CTWD
Main effect	0.28154	0.301091	0.08008	0.1636
Quadratic effect	-0.0634	0.000029	0.0094	-0.0085
Two-factor interaction effect of EWA and CTWD			-0.0098	-0.0098
Two-factor interaction effect of TS and CTWD		0.00010		0.00010
Two-factor interaction effect of WFR and CTWD	0.025			0.025
Two-factor interaction effect of TS and EWA		-0.00028	-0.00028	
Two-factor interaction effect of WFR and EWA	0.021		0.021	
Two-factor interaction effect of WFR and TS	-0.00094	-0.00094		
Sum of impact levels	0.39	0.30	0.12	0.19

$$Input\ parameters\ impact\ on\ TT = 0.39WFR + 0.30TS + 0.12EWA + 0.19CTWD$$

B. Objective function (prediction formula) for joint penetration

$$\begin{aligned}
 JP = & 19.47 + 0.18178(CTWD) + 0.20919(EWA) + 0.3011106(TS) + 0.34654(WFR) \\
 & - 0.004(CTWD)^2 + 0.009(EWA)^2 - 0.0000006(TS)^2 - 0.003(WFR)^2 \\
 & - 0.010(CTWD)(EWA) - 0.00008(CTWD)(TS) + 0.0023(CTWD)(WFR) \\
 & - 0.00019(EWA)(TS) + 0.032(EWA)(WFR) - 0.00084(TS)(WFR)
 \end{aligned}$$

Impact (Effect) level for JP	WFR	TS	EWA	CTWD
Main effect	0.34654	0.3011106	0.20919	0.18178
Quadratic effect	-0.003	-0.0000006	0.009	-0.004
Two-factor interaction effect of EWA and CTWD			-0.010	-0.010
Two-factor interaction effect of TS and CTWD		-0.00008		-0.00008
Two-factor interaction effect of WFR and CTWD	0.0023			0.0023
Two-factor interaction effect of TS and EWA		-0.00019	-0.00019	
Two-factor interaction effect of WFR and EWA	0.032		0.032	
Two-factor interaction effect of WFR and TS	-0.00084	-0.00084		
Sum of impact levels	0.36	0.28	0.21	0.15

$$Input\ parameters\ impact\ on\ JP = 0.36WFR + 0.28TS + 0.21EWA + 0.15CTWD$$

APPENDIX-II

Table 1. Parameters level, weightage and membership functions for Throat Thickness

Rule No	Parameter Levels				Assigned Values for each level				Sum	Weightage	TT
	WFR	TS	EWA	CTWD	WFR	TS	EWA	CTWD			
1	L1	VL2	L3	L4	13	30	12	6.33	61.33	0.007025563	EXC
2	L1	VL2	L3	M4	13	30	12	19	74	0.008476955	EXC
3	L1	VL2	L3	H4	13	30	12	12.66	67.66	0.007750686	INT
4	L1	VL2	M3	L4	13	30	8	6.33	57.33	0.006567349	INS
5	L1	VL2	M3	M4	13	30	8	19	70	0.008018741	EXC
6	L1	VL2	M3	H4	13	30	8	12.66	63.66	0.007292472	INT
7	L1	VL2	H3	L4	13	30	4	6.33	53.33	0.006109135	INS
8	L1	VL2	H3	M4	13	30	4	19	66	0.007560527	INT
9	L1	VL2	H3	H4	13	30	4	12.66	59.66	0.006834258	INS
10	L1	L2	L3	L4	13	24	12	6.33	55.33	0.006338242	INS
11	L1	L2	L3	M4	13	24	12	19	68	0.007789634	INT
12	L1	L2	L3	H4	13	24	12	12.66	61.66	0.007063365	INT
13	L1	L2	M3	L4	13	24	8	6.33	51.33	0.005880028	INS
14	L1	L2	M3	M4	13	24	8	19	64	0.00733142	INT
15	L1	L2	M3	H4	13	24	8	12.66	57.66	0.006605151	INS
16	L1	L2	H3	L4	13	24	4	6.33	47.33	0.005421814	UN-INS
17	L1	L2	H3	M4	13	24	4	19	60	0.006873207	INT
18	L1	L2	H3	H4	13	24	4	12.66	53.66	0.006146938	INS
19	L1	M2	L3	L4	13	18	12	6.33	49.33	0.005650921	UN-INS
20	L1	M2	L3	M4	13	18	12	19	62	0.007102313	INT
21	L1	M2	L3	H4	13	18	12	12.66	55.66	0.006376045	INS
22	L1	M2	M3	L4	13	18	8	6.33	45.33	0.005192708	UN-INS
23	L1	M2	M3	M4	13	18	8	19	58	0.0066441	INS
24	L1	M2	M3	H4	13	18	8	12.66	51.66	0.005917831	INS

25	L1	M2	H3	L4	13	18	4	6.33	41.33	0.004734494	UN-INS
26	L1	M2	H3	M4	13	18	4	19	54	0.006185886	INS
27	L1	M2	H3	H4	13	18	4	12.66	47.66	0.005459617	UN-INS
28	L1	H2	L3	L4	13	12	12	6.33	43.33	0.004963601	UN-INS
29	L1	H2	L3	M4	13	12	12	19	56	0.006414993	INS
30	L1	H2	L3	H4	13	12	12	12.66	49.66	0.005688724	UN-INS
31	L1	H2	M3	L4	13	12	8	6.33	39.33	0.004505387	UN-INS
32	L1	H2	M3	M4	13	12	8	19	52	0.005956779	INS
33	L1	H2	M3	H4	13	12	8	12.66	45.66	0.00523051	UN-INS
34	L1	H2	H3	L4	13	12	4	6.33	35.33	0.004047173	UN-INS
35	L1	H2	H3	M4	13	12	4	19	48	0.005498565	UN-INS
36	L1	H2	H3	H4	13	12	4	12.66	41.66	0.004772296	UN-INS
37	L1	VH2	L3	L4	13	6	12	6.33	37.33	0.00427628	UN-INS
38	L1	VH2	L3	M4	13	6	12	19	50	0.005727672	INS
39	L1	VH2	L3	H4	13	6	12	12.66	43.66	0.005001403	UN-INS
40	L1	VH2	M3	L4	13	6	8	6.33	33.33	0.003818066	UN-INS
41	L1	VH2	M3	M4	13	6	8	19	46	0.005269458	UN-INS
42	L1	VH2	M3	H4	13	6	8	12.66	39.66	0.00454319	UN-INS
43	L1	VH2	H3	L4	13	6	4	6.33	29.33	0.003359852	UN-INS
44	L1	VH2	H3	M4	13	6	4	19	42	0.004811245	UN-INS
45	L1	VH2	H3	H4	13	6	4	12.66	35.66	0.004084976	UN-INS
46	M1	VL2	L3	L4	26	30	12	6.33	74.33	0.008514757	EXC
47	M1	VL2	L3	M4	26	30	12	19	87	0.009966149	UN-EXC
48	M1	VL2	L3	H4	26	30	12	12.66	80.66	0.009239881	UN-EXC
49	M1	VL2	M3	L4	26	30	8	6.33	70.33	0.008056544	EXC
50	M1	VL2	M3	M4	26	30	8	19	83	0.009507936	UN-EXC
51	M1	VL2	M3	H4	26	30	8	12.66	76.66	0.008781667	EXC
52	M1	VL2	H3	L4	26	30	4	6.33	66.33	0.00759833	INT

53	M1	VL2	H3	M4	26	30	4	19	79	0.009049722	EXC
54	M1	VL2	H3	H4	26	30	4	12.66	72.66	0.008323453	EXC
55	M1	L2	L3	L4	26	24	12	6.33	68.33	0.007827437	INT
56	M1	L2	L3	M4	26	24	12	19	81	0.009278829	UN-EXC
57	M1	L2	L3	H4	26	24	12	12.66	74.66	0.00855256	EXC
58	M1	L2	M3	L4	26	24	8	6.33	64.33	0.007369223	INT
59	M1	L2	M3	M4	26	24	8	19	77	0.008820615	EXC
60	M1	L2	M3	H4	26	24	8	12.66	70.66	0.008094346	EXC
61	M1	L2	H3	L4	26	24	4	6.33	60.33	0.006911009	INT
62	M1	L2	H3	M4	26	24	4	19	73	0.008362401	EXC
63	M1	L2	H3	H4	26	24	4	12.66	66.66	0.007636132	INT
64	M1	M2	L3	L4	26	18	12	6.33	62.33	0.007140116	INT
65	M1	M2	L3	M4	26	18	12	19	75	0.008591508	EXC
66	M1	M2	L3	H4	26	18	12	12.66	68.66	0.007865239	INT
67	M1	M2	M3	L4	26	18	8	6.33	58.33	0.006681902	INS
68	M1	M2	M3	M4	26	18	8	19	71	0.008133294	EXC
69	M1	M2	M3	H4	26	18	8	12.66	64.66	0.007407026	INT
70	M1	M2	H3	L4	26	18	4	6.33	54.33	0.006223689	INS
71	M1	M2	H3	M4	26	18	4	19	67	0.007675081	INT
72	M1	M2	H3	H4	26	18	4	12.66	60.66	0.006948812	INT
73	M1	H2	L3	L4	26	12	12	6.33	56.33	0.006452795	INS
74	M1	H2	L3	M4	26	12	12	19	69	0.007904188	INT
75	M1	H2	L3	H4	26	12	12	12.66	62.66	0.007177919	INT
76	M1	H2	M3	L4	26	12	8	6.33	52.33	0.005994582	INS
77	M1	H2	M3	M4	26	12	8	19	65	0.007445974	INT
78	M1	H2	M3	H4	26	12	8	12.66	58.66	0.006719705	INS
79	M1	H2	H3	L4	26	12	4	6.33	48.33	0.005536368	UN-INS
80	M1	H2	H3	M4	26	12	4	19	61	0.00698776	INT

81	M1	H2	H3	H4	26	12	4	12.66	54.66	0.006261491	INS
82	M1	VH2	L3	L4	26	6	12	6.33	50.33	0.005765475	INS
83	M1	VH2	L3	M4	26	6	12	19	63	0.007216867	INT
84	M1	VH2	L3	H4	26	6	12	12.66	56.66	0.006490598	INS
85	M1	VH2	M3	L4	26	6	8	6.33	46.33	0.005307261	UN-INS
86	M1	VH2	M3	M4	26	6	8	19	59	0.006758653	INS
87	M1	VH2	M3	H4	26	6	8	12.66	52.66	0.006032384	INS
88	M1	VH2	H3	L4	26	6	4	6.33	42.33	0.004849047	UN-INS
89	M1	VH2	H3	M4	26	6	4	19	55	0.006300439	INS
90	M1	VH2	H3	H4	26	6	4	12.66	48.66	0.00557417	UN-INS
91	H1	VL2	L3	L4	39	30	12	6.33	87.33	0.010003952	UN-EXC
92	H1	VL2	L3	M4	39	30	12	19	100	0.011455344	UN-EXC
93	H1	VL2	L3	H4	39	30	12	12.66	93.66	0.010729075	UN-EXC
94	H1	VL2	M3	L4	39	30	8	6.33	83.33	0.009545738	UN-EXC
95	H1	VL2	M3	M4	39	30	8	19	96	0.01099713	UN-EXC
96	H1	VL2	M3	H4	39	30	8	12.66	89.66	0.010270862	UN-EXC
97	H1	VL2	H3	L4	39	30	4	6.33	79.33	0.009087525	EXC
98	H1	VL2	H3	M4	39	30	4	19	92	0.010538917	UN-EXC
99	H1	VL2	H3	H4	39	30	4	12.66	85.66	0.009812648	UN-EXC
100	H1	L2	L3	L4	39	24	12	6.33	81.33	0.009316631	UN-EXC
101	H1	L2	L3	M4	39	24	12	19	94	0.010768024	UN-EXC
102	H1	L2	L3	H4	39	24	12	12.66	87.66	0.010041755	UN-EXC
103	H1	L2	M3	L4	39	24	8	6.33	77.33	0.008858418	EXC
104	H1	L2	M3	M4	39	24	8	19	90	0.01030981	UN-EXC
105	H1	L2	M3	H4	39	24	8	12.66	83.66	0.009583541	UN-EXC
106	H1	L2	H3	L4	39	24	4	6.33	73.33	0.008400204	EXC
107	H1	L2	H3	M4	39	24	4	19	86	0.009851596	UN-EXC
108	H1	L2	H3	H4	39	24	4	12.66	79.66	0.009125327	EXC

109	H1	M2	L3	L4	39	18	12	6.33	75.33	0.008629311	EXC
110	H1	M2	L3	M4	39	18	12	19	88	0.010080703	UN-EXC
111	H1	M2	L3	H4	39	18	12	12.66	81.66	0.009354434	UN-EXC
112	H1	M2	M3	L4	39	18	8	6.33	71.33	0.008171097	EXC
113	H1	M2	M3	M4	39	18	8	19	84	0.009622489	UN-EXC
114	H1	M2	M3	H4	39	18	8	12.66	77.66	0.00889622	EXC
115	H1	M2	H3	L4	39	18	4	6.33	67.33	0.007712883	INT
116	H1	M2	H3	M4	39	18	4	19	80	0.009164275	UN-EXC
117	H1	M2	H3	H4	39	18	4	12.66	73.66	0.008438007	EXC
118	H1	H2	L3	L4	39	12	12	6.33	69.33	0.00794199	INT
119	H1	H2	L3	M4	39	12	12	19	82	0.009393382	UN-EXC
120	H1	H2	L3	H4	39	12	12	12.66	75.66	0.008667113	EXC
121	H1	H2	M3	L4	39	12	8	6.33	65.33	0.007483776	INT
122	H1	H2	M3	M4	39	12	8	19	78	0.008935168	EXC
123	H1	H2	M3	H4	39	12	8	12.66	71.66	0.0082089	EXC
124	H1	H2	H3	L4	39	12	4	6.33	61.33	0.007025563	INT
125	H1	H2	H3	M4	39	12	4	19	74	0.008476955	EXC
126	H1	H2	H3	H4	39	12	4	12.66	67.66	0.007750686	INT
127	H1	VH2	L3	L4	39	6	12	6.33	63.33	0.007254669	INT
128	H1	VH2	L3	M4	39	6	12	19	76	0.008706062	EXC
129	H1	VH2	L3	H4	39	6	12	12.66	69.66	0.007979793	INT
130	H1	VH2	M3	L4	39	6	8	6.33	59.33	0.006796456	INS
131	H1	VH2	M3	M4	39	6	8	19	72	0.008247848	EXC
132	H1	VH2	M3	H4	39	6	8	12.66	65.66	0.007521579	INT
133	H1	VH2	H3	L4	39	6	4	6.33	55.33	0.006338242	INS
134	H1	VH2	H3	M4	39	6	4	19	68	0.007789634	INT
135	H1	VH2	H3	H4	39	6	4	12.66	61.66	0.007063365	INT
Sum									8729.55	1	

Table 2. Parameters level, weightage and membership functions for Joint Penetration

Rule No	Parameter Levels				Assigned Value for Each level				Sum	Weightage	TT
	WFR	TS	EWA	CTWD	WFR	TS	EWA	CTWD			
1	L1	VL2	L3	L4	12	28	21	10	71	0.008116141	EXC
2	L1	VL2	L3	M4	12	28	21	15	76	0.0086877	EXC
3	L1	VL2	L3	H4	12	28	21	5	66	0.007544582	INT
4	L1	VL2	M3	L4	12	28	14	10	64	0.007315958	INT
5	L1	VL2	M3	M4	12	28	14	15	69	0.007887517	INT
6	L1	VL2	M3	H4	12	28	14	5	59	0.006744399	LAK
7	L1	VL2	H3	L4	12	28	7	10	57	0.006515775	LAK
8	L1	VL2	H3	M4	12	28	7	15	62	0.007087334	INT
9	L1	VL2	H3	H4	12	28	7	5	52	0.005944216	LAK
10	L1	L2	L3	L4	12	22.4	21	10	65.4	0.007475995	INT
11	L1	L2	L3	M4	12	22.4	21	15	70.4	0.008047554	EXC
12	L1	L2	L3	H4	12	22.4	21	5	60.4	0.006904435	INT
13	L1	L2	M3	L4	12	22.4	14	10	58.4	0.006675812	LAK
14	L1	L2	M3	M4	12	22.4	14	15	63.4	0.007247371	INT
15	L1	L2	M3	H4	12	22.4	14	5	53.4	0.006104252	LAK
16	L1	L2	H3	L4	12	22.4	7	10	51.4	0.005875629	LAK
17	L1	L2	H3	M4	12	22.4	7	15	56.4	0.006447188	LAK
18	L1	L2	H3	H4	12	22.4	7	5	46.4	0.00530407	UN-LAK
19	L1	M2	L3	L4	12	16.8	21	10	59.8	0.006835848	LAK
20	L1	M2	L3	M4	12	16.8	21	15	64.8	0.007407407	INT
21	L1	M2	L3	H4	12	16.8	21	5	54.8	0.006264289	LAK
22	L1	M2	M3	L4	12	16.8	14	10	52.8	0.006035665	LAK
23	L1	M2	M3	M4	12	16.8	14	15	57.8	0.006607225	LAK
24	L1	M2	M3	H4	12	16.8	14	5	47.8	0.005464106	UN-LAK

25	L1	M2	H3	L4	12	16.8	7	10	45.8	0.005235482	UN-LAK
26	L1	M2	H3	M4	12	16.8	7	15	50.8	0.005807042	LAK
27	L1	M2	H3	H4	12	16.8	7	5	40.8	0.004663923	UN-LAK
28	L1	H2	L3	L4	12	11.2	21	10	54.2	0.006195702	LAK
29	L1	H2	L3	M4	12	11.2	21	15	59.2	0.006767261	LAK
30	L1	H2	L3	H4	12	11.2	21	5	49.2	0.005624143	UN-LAK
31	L1	H2	M3	L4	12	11.2	14	10	47.2	0.005395519	UN-LAK
32	L1	H2	M3	M4	12	11.2	14	15	52.2	0.005967078	LAK
33	L1	H2	M3	H4	12	11.2	14	5	42.2	0.00482396	UN-LAK
34	L1	H2	H3	L4	12	11.2	7	10	40.2	0.004595336	UN-LAK
35	L1	H2	H3	M4	12	11.2	7	15	45.2	0.005166895	UN-LAK
36	L1	H2	H3	H4	12	11.2	7	5	35.2	0.004023777	UN-LAK
37	L1	VH2	L3	L4	12	5.6	21	10	48.6	0.005555556	UN-LAK
38	L1	VH2	L3	M4	12	5.6	21	15	53.6	0.006127115	LAK
39	L1	VH2	L3	H4	12	5.6	21	5	43.6	0.004983996	UN-LAK
40	L1	VH2	M3	L4	12	5.6	14	10	41.6	0.004755373	UN-LAK
41	L1	VH2	M3	M4	12	5.6	14	15	46.6	0.005326932	UN-LAK
42	L1	VH2	M3	H4	12	5.6	14	5	36.6	0.004183813	UN-LAK
43	L1	VH2	H3	L4	12	5.6	7	10	34.6	0.00395519	UN-LAK
44	L1	VH2	H3	M4	12	5.6	7	15	39.6	0.004526749	UN-LAK
45	L1	VH2	H3	H4	12	5.6	7	5	29.6	0.003383631	UN-LAK
46	M1	VL2	L3	L4	24	28	21	10	83	0.009487883	UN-EXC
47	M1	VL2	L3	M4	24	28	21	15	88	0.010059442	UN-EXC
48	M1	VL2	L3	H4	24	28	21	5	78	0.008916324	EXC
49	M1	VL2	M3	L4	24	28	14	10	76	0.0086877	EXC
50	M1	VL2	M3	M4	24	28	14	15	81	0.009259259	UN-EXC
51	M1	VL2	M3	H4	24	28	14	5	71	0.008116141	EXC
52	M1	VL2	H3	L4	24	28	7	10	69	0.007887517	INT

53	M1	VL2	H3	M4	24	28	7	15	74	0.008459076	EXC
54	M1	VL2	H3	H4	24	28	7	5	64	0.007315958	INT
55	M1	L2	L3	L4	24	22.4	21	10	77.4	0.008847737	EXC
56	M1	L2	L3	M4	24	22.4	21	15	82.4	0.009419296	UN-EXC
57	M1	L2	L3	H4	24	22.4	21	5	72.4	0.008276177	EXC
58	M1	L2	M3	L4	24	22.4	14	10	70.4	0.008047554	EXC
59	M1	L2	M3	M4	24	22.4	14	15	75.4	0.008619113	EXC
60	M1	L2	M3	H4	24	22.4	14	5	65.4	0.007475995	INT
61	M1	L2	H3	L4	24	22.4	7	10	63.4	0.007247371	INT
62	M1	L2	H3	M4	24	22.4	7	15	68.4	0.00781893	INT
63	M1	L2	H3	H4	24	22.4	7	5	58.4	0.006675812	LAK
64	M1	M2	L3	L4	24	16.8	21	10	71.8	0.00820759	EXC
65	M1	M2	L3	M4	24	16.8	21	15	76.8	0.00877915	EXC
66	M1	M2	L3	H4	24	16.8	21	5	66.8	0.007636031	INT
67	M1	M2	M3	L4	24	16.8	14	10	64.8	0.007407407	INT
68	M1	M2	M3	M4	24	16.8	14	15	69.8	0.007978967	INT
69	M1	M2	M3	H4	24	16.8	14	5	59.8	0.006835848	LAK
70	M1	M2	H3	L4	24	16.8	7	10	57.8	0.006607225	LAK
71	M1	M2	H3	M4	24	16.8	7	15	62.8	0.007178784	INT
72	M1	M2	H3	H4	24	16.8	7	5	52.8	0.006035665	LAK
73	M1	H2	L3	L4	24	11.2	21	10	66.2	0.007567444	INT
74	M1	H2	L3	M4	24	11.2	21	15	71.2	0.008139003	EXC
75	M1	H2	L3	H4	24	11.2	21	5	61.2	0.006995885	INT
76	M1	H2	M3	L4	24	11.2	14	10	59.2	0.006767261	LAK
77	M1	H2	M3	M4	24	11.2	14	15	64.2	0.00733882	INT
78	M1	H2	M3	H4	24	11.2	14	5	54.2	0.006195702	LAK
79	M1	H2	H3	L4	24	11.2	7	10	52.2	0.005967078	LAK
80	M1	H2	H3	M4	24	11.2	7	15	57.2	0.006538637	LAK

81	M1	H2	H3	H4	24	11.2	7	5	47.2	0.005395519	UN-LAK
82	M1	VH2	L3	L4	24	5.6	21	10	60.6	0.006927298	INT
83	M1	VH2	L3	M4	24	5.6	21	15	65.6	0.007498857	INT
84	M1	VH2	L3	H4	24	5.6	21	5	55.6	0.006355738	LAK
85	M1	VH2	M3	L4	24	5.6	14	10	53.6	0.006127115	LAK
86	M1	VH2	M3	M4	24	5.6	14	15	58.6	0.006698674	LAK
87	M1	VH2	M3	H4	24	5.6	14	5	48.6	0.005555556	UN-LAK
88	M1	VH2	H3	L4	24	5.6	7	10	46.6	0.005326932	UN-LAK
89	M1	VH2	H3	M4	24	5.6	7	15	51.6	0.005898491	LAK
90	M1	VH2	H3	H4	24	5.6	7	5	41.6	0.004755373	UN-LAK
91	H1	VL2	L3	L4	36	28	21	10	95	0.010859625	UN-EXC
92	H1	VL2	L3	M4	36	28	21	15	100	0.011431184	UN-EXC
93	H1	VL2	L3	H4	36	28	21	5	90	0.010288066	UN-EXC
94	H1	VL2	M3	L4	36	28	14	10	88	0.010059442	UN-EXC
95	H1	VL2	M3	M4	36	28	14	15	93	0.010631001	UN-EXC
96	H1	VL2	M3	H4	36	28	14	5	83	0.009487883	UN-EXC
97	H1	VL2	H3	L4	36	28	7	10	81	0.009259259	UN-EXC
98	H1	VL2	H3	M4	36	28	7	15	86	0.009830818	UN-EXC
99	H1	VL2	H3	H4	36	28	7	5	76	0.0086877	EXC
100	H1	L2	L3	L4	36	22.4	21	10	89.4	0.010219479	UN-EXC
101	H1	L2	L3	M4	36	22.4	21	15	94.4	0.010791038	UN-EXC
102	H1	L2	L3	H4	36	22.4	21	5	84.4	0.00964792	UN-EXC
103	H1	L2	M3	L4	36	22.4	14	10	82.4	0.009419296	UN-EXC
104	H1	L2	M3	M4	36	22.4	14	15	87.4	0.009990855	UN-EXC
105	H1	L2	M3	H4	36	22.4	14	5	77.4	0.008847737	EXC
106	H1	L2	H3	L4	36	22.4	7	10	75.4	0.008619113	EXC
107	H1	L2	H3	M4	36	22.4	7	15	80.4	0.009190672	UN-EXC
108	H1	L2	H3	H4	36	22.4	7	5	70.4	0.008047554	EXC

109	H1	M2	L3	L4	36	16.8	21	10	83.8	0.009579332	UN-EXC
110	H1	M2	L3	M4	36	16.8	21	15	88.8	0.010150892	UN-EXC
111	H1	M2	L3	H4	36	16.8	21	5	78.8	0.009007773	EXC
112	H1	M2	M3	L4	36	16.8	14	10	76.8	0.00877915	EXC
113	H1	M2	M3	M4	36	16.8	14	15	81.8	0.009350709	UN-EXC
114	H1	M2	M3	H4	36	16.8	14	5	71.8	0.00820759	EXC
115	H1	M2	H3	L4	36	16.8	7	10	69.8	0.007978967	INT
116	H1	M2	H3	M4	36	16.8	7	15	74.8	0.008550526	EXC
117	H1	M2	H3	H4	36	16.8	7	5	64.8	0.007407407	INT
118	H1	H2	L3	L4	36	11.2	21	10	78.2	0.008939186	EXC
119	H1	H2	L3	M4	36	11.2	21	15	83.2	0.009510745	UN-EXC
120	H1	H2	L3	H4	36	11.2	21	5	73.2	0.008367627	EXC
121	H1	H2	M3	L4	36	11.2	14	10	71.2	0.008139003	EXC
122	H1	H2	M3	M4	36	11.2	14	15	76.2	0.008710562	EXC
123	H1	H2	M3	H4	36	11.2	14	5	66.2	0.007567444	INT
124	H1	H2	H3	L4	36	11.2	7	10	64.2	0.00733882	INT
125	H1	H2	H3	M4	36	11.2	7	15	69.2	0.00791038	INT
126	H1	H2	H3	H4	36	11.2	7	5	59.2	0.006767261	LAK
127	H1	VH2	L3	L4	36	5.6	21	10	72.6	0.00829904	EXC
128	H1	VH2	L3	M4	36	5.6	21	15	77.6	0.008870599	EXC
129	H1	VH2	L3	H4	36	5.6	21	5	67.6	0.007727481	INT
130	H1	VH2	M3	L4	36	5.6	14	10	65.6	0.007498857	INT
131	H1	VH2	M3	M4	36	5.6	14	15	70.6	0.008070416	EXC
132	H1	VH2	M3	H4	36	5.6	14	5	60.6	0.006927298	INT
133	H1	VH2	H3	L4	36	5.6	7	10	58.6	0.006698674	LAK
134	H1	VH2	H3	M4	36	5.6	7	15	63.6	0.007270233	INT
135	H1	VH2	H3	H4	36	5.6	7	5	53.6	0.006127115	LAK
Sum									8748	1	

APPENDIX-III

Rules for Throat thickness and Joint Penetration

A. Rules for Throat thickness

[Rules]	Weightages		
1 1 1 1, 3	(0.0070256): 1	2 2 1 1, 3	(0.0078274): 1
1 1 1 2, 4	(0.008477): 1	2 2 1 2, 5	(0.0092788): 1
1 1 1 3, 3	(0.0077507): 1	2 2 1 3, 4	(0.0085526): 1
1 1 2 1, 2	(0.0065673): 1	2 2 2 1, 3	(0.0073692): 1
1 1 2 2, 4	(0.0080187): 1	2 2 2 2, 4	(0.0088206): 1
1 1 2 3, 3	(0.0072925): 1	2 2 2 3, 4	(0.0080943): 1
1 1 3 1, 2	(0.0061091): 1	2 2 3 1, 3	(0.006911): 1
1 1 3 2, 3	(0.0075605): 1	2 2 3 2, 4	(0.0083624): 1
1 1 3 3, 2	(0.0068343): 1	2 2 3 3, 3	(0.0076361): 1
1 2 1 1, 2	(0.0063382): 1	2 3 1 1, 3	(0.0071401): 1
1 2 1 2, 3	(0.0077896): 1	2 3 1 2, 4	(0.0085915): 1
1 2 1 3, 3	(0.0070634): 1	2 3 1 3, 3	(0.0078652): 1
1 2 2 1, 2	(0.00588): 1	2 3 2 1, 2	(0.0066819): 1
1 2 2 2, 3	(0.0073314): 1	2 3 2 2, 4	(0.0081333): 1
1 2 2 3, 2	(0.0066052): 1	2 3 2 3, 3	(0.007407): 1
1 2 3 1, 1	(0.0054218): 1	2 3 3 1, 2	(0.0062237): 1
1 2 3 2, 3	(0.0068732): 1	2 3 3 2, 3	(0.0076751): 1
1 2 3 3, 2	(0.0061469): 1	2 3 3 3, 3	(0.0069488): 1
1 3 1 1, 1	(0.0056509): 1	2 4 1 1, 2	(0.0064528): 1
1 3 1 2, 3	(0.0071023): 1	2 4 1 2, 3	(0.0079042): 1
1 3 1 3, 2	(0.006376): 1	2 4 1 3, 3	(0.0071779): 1
1 3 2 1, 1	(0.0051927): 1	2 4 2 1, 2	(0.0059946): 1
1 3 2 2, 2	(0.0066441): 1	2 4 2 2, 3	(0.007446): 1
1 3 2 3, 2	(0.0059178): 1	2 4 2 3, 2	(0.0067197): 1
1 3 3 1, 1	(0.0047345): 1	2 4 3 1, 1	(0.0055364): 1
1 3 3 2, 2	(0.0061859): 1	2 4 3 2, 3	(0.0069878): 1
1 3 3 3, 1	(0.0054596): 1	2 4 3 3, 2	(0.0062615): 1
1 4 1 1, 1	(0.0049636): 1	2 5 1 1, 2	(0.0057655): 1
1 4 1 2, 2	(0.006415): 1	2 5 1 2, 3	(0.0072169): 1
1 4 1 3, 1	(0.0056887): 1	2 5 1 3, 2	(0.0064906): 1
1 4 2 1, 1	(0.0045054): 1	2 5 2 1, 1	(0.0053073): 1
1 4 2 2, 2	(0.0059568): 1	2 5 2 2, 2	(0.0067587): 1
1 4 2 3, 1	(0.0052305): 1	2 5 2 3, 2	(0.0060324): 1
1 4 3 1, 1	(0.0040472): 1	2 5 3 1, 1	(0.004849): 1
1 4 3 2, 1	(0.0054986): 1	2 5 3 2, 2	(0.0063004): 1
1 4 3 3, 1	(0.0047723): 1	2 5 3 3, 1	(0.0055742): 1
1 5 1 1, 1	(0.0042763): 1	3 1 1 1, 5	(0.010004): 1
1 5 1 2, 2	(0.0057277): 1	3 1 1 2, 5	(0.011455): 1
1 5 1 3, 1	(0.0050014): 1	3 1 1 3, 5	(0.010729): 1
1 5 2 1, 1	(0.0038181): 1	3 1 2 1, 5	(0.0095457): 1
1 5 2 2, 1	(0.0052695): 1	3 1 2 2, 5	(0.010997): 1
1 5 2 3, 1	(0.0045432): 1	3 1 2 3, 5	(0.010271): 1
1 5 3 1, 1	(0.0033599): 1	3 1 3 1, 4	(0.0090875): 1
1 5 3 2, 1	(0.0048112): 1	3 1 3 2, 5	(0.010539): 1
1 5 3 3, 1	(0.004085): 1	3 1 3 3, 5	(0.0098126): 1
2 1 1 1, 4	(0.0085148): 1	3 2 1 1, 5	(0.0093166): 1
2 1 1 2, 5	(0.0099661): 1	3 2 1 2, 5	(0.010768): 1
2 1 1 3, 5	(0.0092399): 1	3 2 1 3, 5	(0.010042): 1
2 1 2 1, 4	(0.0080565): 1	3 2 2 1, 4	(0.0088584): 1
2 1 2 2, 5	(0.0095079): 1	3 2 2 2, 5	(0.01031): 1
2 1 2 3, 4	(0.0087817): 1	3 2 2 3, 5	(0.0095835): 1
2 1 3 1, 3	(0.0075983): 1	3 2 3 1, 4	(0.0084002): 1
2 1 3 2, 4	(0.0090497): 1	3 2 3 2, 5	(0.0098516): 1
2 1 3 3, 4	(0.0083235): 1	3 2 3 3, 4	(0.0091253): 1

3 3 1 1, 4 (0.0086293): 1
 3 3 1 2, 5 (0.010081): 1
 3 3 1 3, 5 (0.0093544): 1
 3 3 2 1, 4 (0.0081711): 1
 3 3 2 2, 5 (0.0096225): 1
 3 3 2 3, 4 (0.0088962): 1
 3 3 3 1, 3 (0.0077129): 1
 3 3 3 2, 5 (0.0091643): 1
 3 3 3 3, 4 (0.008438): 1
 3 4 1 1, 3 (0.007942): 1
 3 4 1 2, 5 (0.0093934): 1
 3 4 1 3, 4 (0.0086671): 1
 3 4 2 1, 3 (0.0074838): 1
 3 4 2 2, 4 (0.0089352): 1

3 4 2 3, 4 (0.0082089): 1
 3 4 3 1, 3 (0.0070256): 1
 3 4 3 2, 4 (0.008477): 1
 3 4 3 3, 3 (0.0077507): 1
 3 5 1 1, 3 (0.0072547): 1
 3 5 1 2, 4 (0.0087061): 1
 3 5 1 3, 3 (0.0079798): 1
 3 5 2 1, 2 (0.0067965): 1
 3 5 2 2, 4 (0.0082478): 1
 3 5 2 3, 3 (0.0075216): 1
 3 5 3 1, 2 (0.0063382): 1
 3 5 3 2, 3 (0.0077896): 1
 3 5 3 3, 3 (0.0070634): 1

B. Rules for Joint Penetration

[Rules] weightages

1 1 1 1, 4 (0.0081161): 1
 1 1 1 2, 4 (0.0086877): 1
 1 1 1 3, 3 (0.0075446): 1
 1 1 2 1, 3 (0.007316): 1
 1 1 2 2, 3 (0.0078875): 1
 1 1 2 3, 2 (0.0067444): 1
 1 1 3 1, 2 (0.0065158): 1
 1 1 3 2, 3 (0.0070873): 1
 1 1 3 3, 2 (0.0059442): 1
 1 2 1 1, 3 (0.007476): 1
 1 2 1 2, 4 (0.0080476): 1
 1 2 1 3, 3 (0.0069044): 1
 1 2 2 1, 2 (0.0066758): 1
 1 2 2 2, 3 (0.0072474): 1
 1 2 2 3, 2 (0.0061043): 1
 1 2 3 1, 2 (0.0058756): 1
 1 2 3 2, 2 (0.0064472): 1
 1 2 3 3, 1 (0.0053041): 1
 1 3 1 1, 2 (0.0068358): 1
 1 3 1 2, 3 (0.0074074): 1
 1 3 1 3, 2 (0.0062643): 1
 1 3 2 1, 2 (0.0060357): 1
 1 3 2 2, 2 (0.0066072): 1
 1 3 2 3, 1 (0.0054641): 1
 1 3 3 1, 1 (0.0052355): 1
 1 3 3 2, 2 (0.005807): 1
 1 3 3 3, 1 (0.0046639): 1
 1 4 1 1, 2 (0.0061957): 1
 1 4 1 2, 2 (0.0067673): 1
 1 4 1 3, 1 (0.0056241): 1
 1 4 2 1, 1 (0.0053955): 1
 1 4 2 2, 2 (0.0059671): 1
 1 4 2 3, 1 (0.004824): 1
 1 4 3 1, 1 (0.0045953): 1
 1 4 3 2, 1 (0.0051669): 1
 1 4 3 3, 1 (0.0040238): 1
 1 5 1 1, 1 (0.0055556): 1
 1 5 1 2, 2 (0.0061271): 1
 1 5 1 3, 1 (0.004984): 1
 1 5 2 1, 1 (0.0047554): 1
 1 5 2 2, 1 (0.0053269): 1
 1 5 2 3, 1 (0.0041838): 1
 1 5 3 1, 1 (0.0039552): 1

1 5 3 2, 1 (0.0045267): 1
 1 5 3 3, 1 (0.0033836): 1
 2 1 1 1, 5 (0.0094879): 1
 2 1 1 2, 5 (0.010059): 1
 2 1 1 3, 4 (0.0089163): 1
 2 1 2 1, 4 (0.0086877): 1
 2 1 2 2, 5 (0.0092593): 1
 2 1 2 3, 4 (0.0081161): 1
 2 1 3 1, 3 (0.0078875): 1
 2 1 3 2, 4 (0.0084591): 1
 2 1 3 3, 3 (0.007316): 1
 2 2 1 1, 4 (0.0088477): 1
 2 2 1 2, 5 (0.0094193): 1
 2 2 1 3, 4 (0.0082762): 1
 2 2 2 1, 4 (0.0080476): 1
 2 2 2 2, 4 (0.0086191): 1
 2 2 2 3, 3 (0.007476): 1
 2 2 3 1, 3 (0.0072474): 1
 2 2 3 2, 3 (0.0078189): 1
 2 2 3 3, 2 (0.0066758): 1
 2 3 1 1, 4 (0.0082076): 1
 2 3 1 2, 4 (0.0087791): 1
 2 3 1 3, 3 (0.007636): 1
 2 3 2 1, 3 (0.0074074): 1
 2 3 2 2, 3 (0.007979): 1
 2 3 2 3, 2 (0.0068358): 1
 2 3 3 1, 2 (0.0066072): 1
 2 3 3 2, 3 (0.0071788): 1
 2 3 3 3, 2 (0.0060357): 1
 2 4 1 1, 3 (0.0075674): 1
 2 4 1 2, 4 (0.008139): 1
 2 4 1 3, 3 (0.0069959): 1
 2 4 2 1, 2 (0.0067673): 1
 2 4 2 2, 3 (0.0073388): 1
 2 4 2 3, 2 (0.0061957): 1
 2 4 3 1, 2 (0.0059671): 1
 2 4 3 2, 2 (0.0065386): 1
 2 4 3 3, 1 (0.0053955): 1
 2 5 1 1, 3 (0.0069273): 1
 2 5 1 2, 3 (0.0074989): 1
 2 5 1 3, 2 (0.0063557): 1
 2 5 2 1, 2 (0.0061271): 1
 2 5 2 2, 2 (0.0066987): 1

2 5 2 3, 1 (0.0055556): 1
 2 5 3 1, 1 (0.0053269): 1
 2 5 3 2, 2 (0.0058985): 1
 2 5 3 3, 1 (0.0047554): 1
 3 1 1 1, 5 (0.01086): 1
 3 1 1 2, 5 (0.011431): 1
 3 1 1 3, 5 (0.010288): 1
 3 1 2 1, 5 (0.010059): 1
 3 1 2 2, 5 (0.010631): 1
 3 1 2 3, 5 (0.0094879): 1
 3 1 3 1, 5 (0.0092593): 1
 3 1 3 2, 5 (0.0098308): 1
 3 1 3 3, 4 (0.0086877): 1
 3 2 1 1, 5 (0.010219): 1
 3 2 1 2, 5 (0.010791): 1
 3 2 1 3, 5 (0.0096479): 1
 3 2 2 1, 5 (0.0094193): 1
 3 2 2 2, 5 (0.0099909): 1
 3 2 2 3, 4 (0.0088477): 1
 3 2 3 1, 4 (0.0086191): 1
 3 2 3 2, 5 (0.0091907): 1
 3 2 3 3, 4 (0.0080476): 1
 3 3 1 1, 5 (0.0095793): 1
 3 3 1 2, 5 (0.010151): 1
 3 3 1 3, 4 (0.0090078): 1
 3 3 2 1, 4 (0.0087791): 1
 3 3 2 2, 5 (0.0093507): 1
 3 3 2 3, 4 (0.0082076): 1
 3 3 3 1, 3 (0.007979): 1
 3 3 3 2, 4 (0.0085505): 1
 3 3 3 3, 3 (0.0074074): 1
 3 4 1 1, 4 (0.0089392): 1
 3 4 1 2, 5 (0.0095107): 1
 3 4 1 3, 4 (0.0083676): 1
 3 4 2 1, 4 (0.008139): 1
 3 4 2 2, 4 (0.0087106): 1
 3 4 2 3, 3 (0.0075674): 1
 3 4 3 1, 3 (0.0073388): 1
 3 4 3 2, 3 (0.0079104): 1
 3 4 3 3, 2 (0.0067673): 1
 3 5 1 1, 4 (0.008299): 1
 3 5 1 2, 4 (0.0088706): 1
 3 5 1 3, 3 (0.0077275): 1
 3 5 2 1, 3 (0.0074989): 1
 3 5 2 2, 4 (0.0080704): 1
 3 5 2 3, 3 (0.0069273): 1
 3 5 3 1, 2 (0.0066987): 1
 3 5 3 2, 3 (0.0072702): 1
 3 5 3 3, 2 (0.0061271): 1

APPENDIX-IV

Results of 3D Plot Predicted by Artificial Intelligence System

Table 1. 3D Plot Results for Throat Thickness

	Maximum (4.42)		Above average (>3.32)		Average (3.32)		Below average (<3.32)		Minimum (2.22)	
	1	2	1	2	1	2	1	2	1	2
1WFR and 2TS	3.2-4.7 5-5.8 6.2-6.7	180-220 230-350 380-570	3-5 4.5-6.2 5.2-7	150-290 220-420 350-550	5-7 6.2-7 3-3.8	150-210 210-350 490-550	3-4.5 4-5.5	275-490 400-550	3.2-3.8 4.2-5	350-470 490-570
1WFR and 2EWA	5-5.8	40.75-45	4-6.2	40-48	3-3.8 6.2-7 5-7	40-42.1 40-50 48-50	3-5	42-50	3.3-3.8	45-50
1 WFR and 2CTWD	6.2-6.7 6.2-6.7 4.7-5.8	10.6-14.2 15.7-19.3 15	4.3-7	10-20	3-3.8	10-12	3-3.5	10-20	3.3-3.8 4.2-5	12.9-19.10 10.8-12.1
1TS and 2EWA	290-350 230-290 175-270	40-45 42.9-49.3 45.8-49.3	150-430	45-50	150-210 150-270 430-500 325-390	40-45 40-42.1 40-42 47.9-50	400-500	42.5-50	490-575	45-49.1
1TS and 2CTWD	175-210 175-260 240-350	10-14.20 15.80-19.30 15	150-420	10-20	490-550	10-12.10	375-500	10-20	350-470 490-525	12.9-19.10 10.7-12.10
1EWA and 2CTWD	40.9-45	15	40-47	12.10-18	40-42.1 47.9-50 40-50	10-12.1 15-20 17.9-20	42-50	10-15	45-49.5	10.80-12.10

Table 2. 3D Plot Results for Joint Penetration

	Maximum (8)		Above average (>5.85)		Average (5.85)		Below average (<5.85)		Minimum (3.7)	
	1	2	1	2	1	2	1	2	1	2
1WFR and 2TS	5-5.8 6.2-6.7	230-260 380-520	4-6.1 5.3-7	210-350 350-550	3-3.80 3-7 6.10-7 3-3.90	150-260 150-210 150-350 490-550	3-5.5	250-550	3.2-3.8 4.2-5	350-420 490-525
1WFR and 2EWA	5-5.8 6.1-6.7	40.6-42.1 45.7-49.4	3.8-6.1 5-7	40-45 45-50	3-3.8 6.1-7	40-42.1 40-45	3-5	42-50	3.25-4.80	45-49.2
1 WFR and 2CTWD	6.20-6.70 6.20-6.70	10.70-14.40 15.70-19.40	5-7	10-20	3-3.8	17.9-20	3-5.5	10-20	3.25-3.80 4.25-5	10.8-17.5 17.9-19.20
1TS and 2EWA	290-410 230-320 160-210	40.7-42.2 42.9-45 45.7-49.4	150-210	40-50	150-210 150-270 490-550	40-45 40-42.1 40-42.1	350-550	43-50	490-525 430-490	45-49.10 47.9-49.20
1TS and 2CTWD	180-230 160-260 180-210	10.6-14.2 15.7-19.3 10.6-14.2	150-350	10-20	490-550	17.9-20	260-550	10-20	430-525 490-525 350-460	10.5-12 10.5-17 17.7-19.2
1EWA and 2CTWD	40.6-42.1	10.8-15	40-45	10-18	40-42.1	17.9-20	42-50 45-50	10-15 15-20	47.9-49.2 45-49.2	10.8-12.1 17.9-19.2

APPENDIX-V

MATLAB code for interpolation of welding parameters

```
clc
clf
close all
theta1 = mean ([35 37.5]);
theta2= mean([37.6 42.5]);
theta3= mean([42.6 47.5]);
theta4= mean([47.6 52.5]);
theta5= mean([52.6 55]);
theta = [35 theta1 theta2 theta3 theta4 theta5 55];
WFR = [9 9 8.29 7 7.40 7.26 7.26];
TS =[358.78 358.78 243 418.98 159.26 281.31 281.31];
CTWD= [16.22 16.22 10 10 16.63 14.38 14.38];
theta_range = 35:0.1: 55;
xx=theta_range;
yy = spline(theta,WFR,theta_range);
WFR_interplated=yy;
figure(1)
plot(theta,WFR,'o',xx,yy)
clear yy
yy = spline(theta,TS,theta_range);
TS_interplated=yy;
figure(2)
plot(theta,TS,'*',xx,yy)
clear yy
yy = spline(theta,CTWD,theta_range);
CTWD_interplated=yy;
figure(3)
plot(theta,CTWD,'*',xx,yy)
value= [ theta_range' WFR_interplated' TS_interplated'
CTWD_interplated' ]
theta_estimated=theta_range';
theta = input(' Enter the value of torch angle between 35 deg to
55 degree==');
[c index] = min(abs(theta-theta_estimated(:,1))));
WFR_WC_TS_CTWD= value(index,2:4);
X = sprintf('The value of WFR,CTWD,TS is: \n %.2f \n %.2f \n %.2f
\n %.2f \n corresponding to torch angle== \n %.2f ',
AV_WC_TS_CTWD,theta );
display(X)
```

APPENDIX-VI

XRD result of base metal and weld fusion zone

1. Base materials

Peak Data List

peak no.	2Theta (deg)	d (Å)	I/I ₁	FWHM (deg)	Intensity (Counts)	Integrated Int (Counts)
1	44.8224	2.02045	100	0.28880	1086	18778
2	65.0600	1.43247	8	0.49870	91	2563
3	82.4078	1.16935	17	0.37100	184	4356

2θ (°)	Cos θ	K (rad.Å ⁻²)	λ (nm)	FWHM (β) (°)	FWHM (β) (rad)	Crystallite Size (nm)
44.8224	0.9244	0.9	0.15406	0.2888	0.0050	30.00
65.0600	0.8431	0.9	0.15406	0.4987	0.0087	18.90
82.4078	0.7524	0.9	0.15406	0.3710	0.0065	28.35
Average crystal size						25.75

Table 1. Calculation and result of crystal size of AISI SAE 4130 alloy steel base metal

2. Weld fusion zone

Strongest 3 peaks

no. peak no.	2Theta (deg)	d (Å)	I/I ₁	FWHM (deg)	Intensity (Counts)	Integrated Int (Counts)
1 2	44.6832	2.02642	100	0.29800	743	11454
2 5	82.2965	1.17065	11	0.45070	79	2241
3 4	65.0052	1.43355	8	0.45500	62	1583

Peak Data List

peak no.	2Theta (deg)	d (Å)	I/I ₁	FWHM (deg)	Intensity (Counts)	Integrated Int (Counts)
1	44.2512	2.04520	6	0.17000	45	830
2	44.6832	2.02642	100	0.29800	743	11454
3	45.0907	2.00905	8	0.16800	57	1169
4	65.0052	1.43355	8	0.45500	62	1583
5	82.2965	1.17065	11	0.45070	79	2241

2θ (°)	Cos θ	K (rad.Å ⁻²)	λ (nm)	FWHM (β) (°)	FWHM (β) (rad)	Crystallite Size (nm)
44.6832	0.9250	0.9	0.15406	0.29800	0.0052	28.83
82.2965	0.7530	0.9	0.15406	0.45070	0.0077	23.91
65.0052	0.8434	0.9	0.15406	0.45500	0.0079	20.81
Average crystal size						24.51

Table 2. Calculation and result of crystal size of AISI SAE 4130 alloy steel fusion zone

APPENDIX-VII
Welding Procedure Specification Format

Specimen Number _____
Date _____

WELDING PROCESS: Gas Metal Arc Welding

WELD TYPE: Fillet

Root Opening _____

Groove Angle _____

Backing: Yes ☐ No ☐ Backing Type _____

ELECTRICAL CHARACTERISTICS

Current: DC +

Transfer Mode (GMAW): pulse-arc

BASE METAL

Material Specification AISI SAE 4130 alloy steel

Welded to: Material Specification _____ Grade _____

Maximum Carbon Equivalent 0.33

Specimen size _____

Plate Thickness _____

FILLER METAL

Specification Böhler EMK 6 D

AWS Classification AWS A5.18: ER70S-6

Filler diameter (mm) _____

SHIELDING

Gas: Single ☐ Mixture ☐ Composition 80%Ar, 20CO₂

Nozzle opening (mm) _____

PREHEAT/INTERPASS

Preheat / Interpass Temperature (Min) _____ Interpass Temperature
(Max) _____

WELDING PARAMETERS

S. No	Parameters	Unit	Values	Remark
1	WFR	m/min		
3	Travel speed	mm/min		
4	Electrode to work angle	Deg.		
5	Contact tip to work distance	mm		

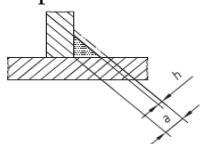
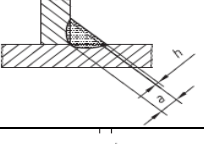
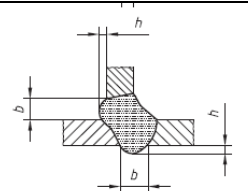
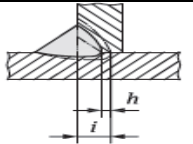
APPENDIX-VIII

Equivalent of grade of *AISI SAE 4130* alloy steel

EU	25CrMo4
USA	Germany, DIN, WNr
SAE4130	25CrMo4
Japan, JIS	SCM420, SCM430
France, AFNOR	25CD4
England, BS	708A25, 708M25, CFS10
Italy, UNI	25CrMo4
China, GB	30CrMo
Sweden, SS	2225
Finland, SFS	25CrMo4
Russia, GOST	20KHM, 30KHM, 30KHMA
Inter, ISO	25CrMo4

APPENDIX-IX

Table 1-Limits for imperfections - BS EN ISO 5817:2014

No.	Reference to ISO 6520-1	Imperfection designation	Remarks	t mm	Limits for imperfections for quality levels		
					D	C	B
1 Surface imperfections							
1.20	5213	Insufficient throat thickness	Not applicable to process with proof of greater depth of penetration 	0.5 to 3	Short imperfections $H \leq 0.2\text{mm} + 0.1a$	Short imperfections: $H \leq 0.2 \text{ mm}$	Not permitted
				>3mm	Short imperfections: $H \leq 0.3\text{mm} + 0.1a$, but max. 2mm	Short imperfections: $H \leq 0.3\text{mm} + 0.1a$ but max. 1mm	Not permitted
1.21	5214	Excessive throat thickness	The actual throat thickness of the fillet weld is too large 	≥ 0.5	Unlimited	$H \leq 1\text{mm} + 0.2a$, but max. 4mm	$H \leq 1\text{mm} + 0.15a$, but max. 3mm
1.11	504	Excess penetration		0,5 to 3	$h \leq 1 \text{ mm} + 0,6 b$	$h \leq 1 \text{ mm} + 0,3 b$	$h \leq 1 \text{ mm} + 0,1 b$
				>3	$h \leq 1\text{mm} + 1,0 b$, but max. 5 mm	$h \leq 1 \text{ mm} + 0,6 b$, but max. 4 mm	$h \leq 1 \text{ mm} + 0,2 b$, but max. 3 mm
2 Internal imperfections							
213	402	Lack of penetration		>0.5	T-joint: $h \leq 0,2a$, but max. 2 mm	Fillet joint: $h \leq 0,1 a$, but max. 1,5 mm	Not permitted