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ORIGINAL ARTICLE

An artificial intelligence system for quality level–based prediction of welding parameters for robotic gas metal arc welding

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Abstract
This study addresses the gap between laboratory-focused welding process parameter identification and their practical application in the industry. Unlike traditional input–output mapping reported in the literature, determining acceptable input process parameters in industry hinges on the acceptable threshold for imperfections. The research aims to devise an artificial intelligence system capable of forecasting acceptable parameters for robotic gas metal arc welding, aligning with the quality standards outlined in AWS B4.0:2016 and BS EN ISO 5817:2014. Parameters, including wire feed rate, travel speed, contact tip to work distance, and electrode work angle, are considered in the prediction model. Throat thickness and joint penetration are critical responses for weldments involving 2-mm-, 4-mm-, and 6-mm-thick 4130 steel plates. The fuzzy model achieves effective defuzzification by employing fuzzy expert rules, triangular membership functions, and the centroid area method via the MATLAB fuzzy logic toolbox. The models are rigorously validated through experimental work. The study culminates in the acquisition of accurately predicted and experimentally acceptable input process parameters across varying quality levels (B, C, and D).

Keywords Artificial intelligence system · Fuzzy logic · Robotic GMAW · Quality levels · JMP

1 Introduction

Currently, there are various artificial intelligence (AI) systems and data modeling 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.

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Welding significantly differs from other manufacturing processes due to its complicated, multi-variable, multi-outcome nature. 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 cannot 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. The complexity and vagueness between the process parameters and weld quality attributes have attracted researchers to use fuzzy logic to develop artificial intelligent systems for different welding processes, for instance, resistance spot welding [1–4]; friction stir welding [5, 6]; submerged arc welding [7, 8]; gas metal arc welding [9–13]; plasma arc welding [14, 15]; tungsten inert gas welding [16], etc. The process parameters optimization of GMAW had been investigated by using statistical and intelligent welding systems like grey-based Taguchi, an ANN with a Levenberg–Marquardt Algorithm (LMA), ANFIS, fuzzy system using triangular membership function (TrMF) and trapezoidal membership function (TMF), deep learning, etc. [17–21].

The welding input parameters from these studies are optimized for desired dilution, bed geometry, material characteristics (ultimate tensile strength, hardness, and impact strength), burn-through, weld depth estimation, etc. Among all the techniques and models, fuzzy logic offers a unique approach to handling uncertainty and imprecision in information processing. Unlike traditional binary logic, which deals strictly with true or false values, fuzzy logic operates on a spectrum of truth, allowing for values that fall between the extremes. This proves invaluable in scenarios like weld quality, where information has a degree of vagueness or uncertainty. Fuzzy logic employs membership functions to assign a value between 0 and 1 to determine an element's degree of belonging to a specific set. Linguistic variables replace precise numerical values with terms like "high" or "likely," representing fuzzy sets with associated membership functions. Fuzzy sets possess flexible boundaries, allowing elements to belong to a set partially. Fuzzy rules establish relationships between input and output variables, accommodating imprecise mappings. During inference, these rules are combined to produce a comprehensive result, and defuzzification converts the fuzzy output back into a precise numerical value. Overall, fuzzy logic furnishes a human-like framework for reasoning and decision-making in situations marked by vagueness, uncertainty, or elusive quantifiability.

Contrary to developing an input–output relation based on lab experiments in most of the aforementioned cited articles, welds must adhere to specific codes and standards due to their complexity rather than conforming to an absolute quantitative specification. For instance, EN ISO 5817:2014 is an international standard specifying quality levels for imperfections in fusion-welded joints in various steel types. It defines four categories (A to D) based on the severity of imperfections like cracks and incomplete fusion. Category A denotes the highest quality, suitable for critical applications like nuclear pressure vessels. Category B is for demanding applications such as aerospace, while category C is standard for general construction. Category D, with basic requirements, is employed in non-critical applications where cosmetic imperfections are less crucial.

The scope of the study is to develop a fuzzy logic–based model 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 study, 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.

2 Materials and methodology

2.1 Base material

AISI SAE 4130 alloy steel material was taken for the experiments. This steel is widely used in general requirements for welded structures and parts such as transmission towers, bridges, the oil and gas industry, boilers, aerospace, and heavy vehicle structures. Copper-coated solid wire was used to weld the specimen. The filler wire selection was based on matching the base metal's physical characteristics and mechanical properties. The chemical composition of AISI SAE 4130 alloy and solid steel wire is shown in Table 1.

2.2 Process parameters and levels

Welding input process parameters were identified based on their significant effect on weld quality characteristics. The selected input parameters were wire feed rate (WFR), travel speed (TS), electrode work angle (EWA), and contact tip-to-work distance (CTWD). The working ranges of welding parameters were assigned based on the industry range that has been used and reinforced by conducting certain experiment works. The input process parameters and their considered levels are shown in Table 2. The robotic welding setup and materials details are indicated in Table 3.

2.3 Limits for imperfections for fillet welded joints

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." Level A is meant for very specific applications, while the present model is meant to serve a wide application range

Table 1 Chemical composition of AISI SAE 4130 alloy steel plate and solid wire in wt. (%)

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
Solid wire		0.07	0.85	1.5	0.04		0.003	0.04	0.018	0.012	0.35	

Table 2 Process parameters and level

Parameters	Plate thickness (mm)	Level 1	Level 2	Level 3	Level 4	Level 5
WFR (m/min)	2	1	3	5		
	4	3	5	7		
	6	5	7	9		
TS (mm/min)	2, 4, and 6	150	250	350	450	550
EWA (deg.)	2, 4, and 6	40	45	50		
CTWD (mm)	2, 4, and 6	10	15	20		

Table 3 Welding set parameters and description

Parameters	Description
Joint geometry	Fillet weld
Droplet transfer	Short-arc
Polarity	DC +
Filler diameter	1.2 mm
Shielding gas type	80% Ar and 20% CO_2
Gas flow rate	15 L/min
Dimension of plate	2 mm, 4 mm, and 6 mm
Filler metal type	BOHLER N ER 70S-6

Table 4 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

in the welded fabrication industry following the quality levels, grades "D," "C," and "B"; thus, A-level is purposefully excluded in the present study. 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. Nominal dimensions, limits for imperfections, and the range of imperfection limits are presented in Table 4, 5, and 6, respectively.

2.4 Throat thickness of fillet weld

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. The effective throat of a fillet weld is a structural way to understand how strong a fillet weld will be. The calculation of nominal throat thickness (a) is executed by Eq. (1).

$$a = \frac{Z}{\sqrt{2}} \tag{1}$$

where a is the nominal throat thickness of the fillet weld in mm (ISO 2553) and Z is the leg length of fillet weld in mm (ISO 2553).

2.5 Joint penetration

Joint penetration is the distance to which fusion extends, creating a common joint in both plates (vertical and horizontal, as shown in Fig. 1). 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.

2.6 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. 2. 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 3×5×3×3 rules, as mentioned in Table 2. The defuzzification unit is composed of mathematical equations that convert the fuzzy values into usable values in the real world.

Table 5 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 6 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

2.7 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 μA: X → [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 protest 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.

2.8 Triangular-shaped membership function

$$y = trimf(x, params)$$

$$y = trimf(x, [abc])$$

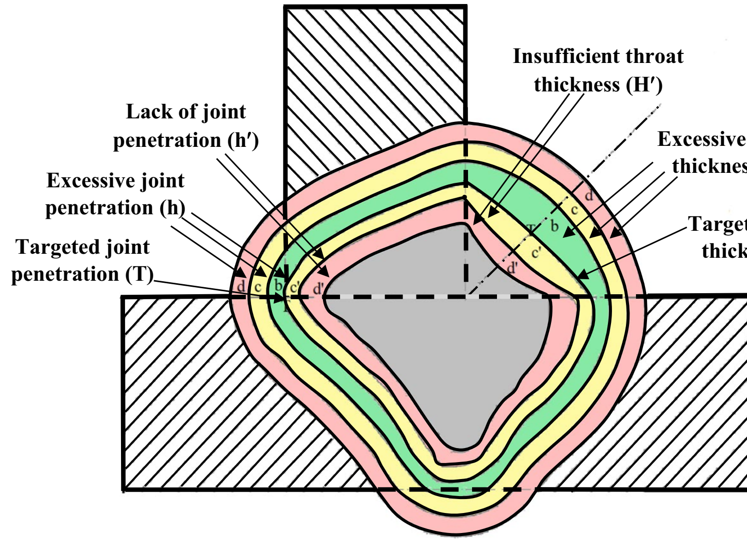

Fig. 1 Weld proportions in relation to throat thickness and joint penetration

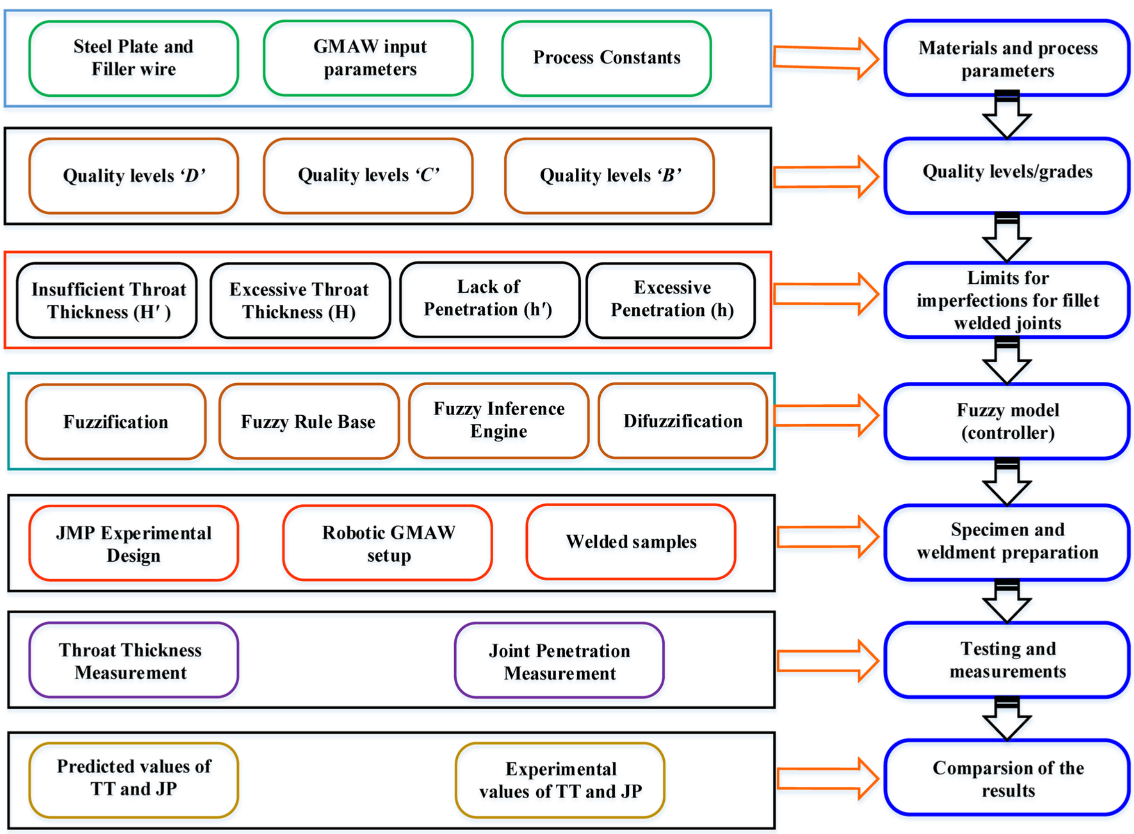

Fig. 2 Architecture of fuzzy logic model and robot welding process

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

$$f = (x, a, b, c) = \left\{ \begin{array}{cc} 0, & X \le a \\ \frac{x-a}{b-a}, & a \le X \le b \\ \frac{c-x}{c-b}, & b \le X \le c \\ 0, & c \le x \end{array} \right\} \quad (2)$$

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. Table 7

2.9 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 as follows:

➢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 as follows (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 8, and the fuzzy output membership function and sets for quality levels "D," "C," and "B" are presented in Table 9, 10, and 11, respectively.

2.10 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), and unacceptable excessive (UN-EXC). Figure 3 shows a fuzzy logic control model for travel speed input parameters. Figures 4 and 5 show the indication of the output membership function for the "D," "C," and "B" quality levels.

2.11 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). 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. A mathematical model has been developed based on these investigations, as shown in Eq. (3). Equations (4) and (5) show the weightage of input parameters on TT and JP, respectively.

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_{11} {x_1}^2 + \beta_{22} {x_2}^2 + \beta_{33} {x_3}^2 + \beta_{44} x_4$$
$$\beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{14} x_1 x_4 + \beta_{23} x_2 x_3 + \beta_{24} x_2 x_4 + \beta_{34} x_3 x_4 \quad (3)$$

$$Input\ parameters\ impact\ on\ TT = 0.39WFR + 0.30TS + 0.12EWA + 0.19CTWD \quad (4)$$

$$Input\ parameters\ impact\ on\ JP = 0.36WFR + 0.28TS + 0.21EWA + 0.15CTWD \quad (5)$$

Table 7 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)

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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)

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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)

Table 7 (continued)

Parameters	Plate thickness (mm)	Levels	Throat thickness (mm)		Joint penetration (mm)	
			Weightage for parameter	Weighted for levels	Weightage for parameter	Weighted for levels

c. **Fuzzy inference system**

- Fuzzy inference system name = "Fuzzy-model- of 2 mm, 4 mm and 6 mm 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 8 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 9 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 10 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]

For the llustration, 4mm thickness selected for the further analysis

Table 11 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]

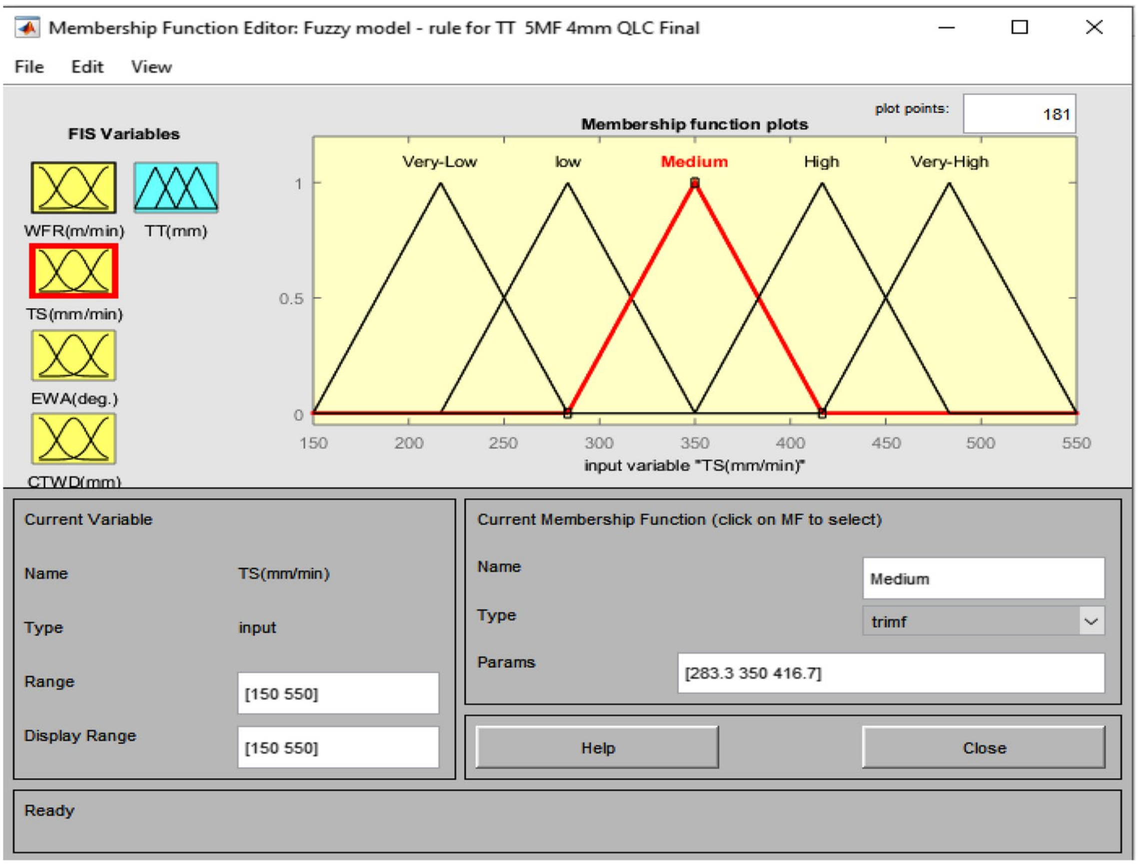


Fig. 3 Fuzzy logic control model for travel speed input parameters

The impact of each parameter and the impact of each level of parameters are assigned based on their effect on each response (Table 7). Weightage is calculated and appointed for each rule; the sum of weight assigned for all rules (135 rules for each response) equals 1.

As per the data in Table 5 and 6, 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 2-mm, 4-mm, and 6-mm thicknesses. The maximum values for excessive throat thickness have been taken as 6 mm, 7.5 mm, and 8 mm, 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 4-mm-thickness plate has been conducted. Quality level "C'"was chosen because most industry products fall under this quality level. For the

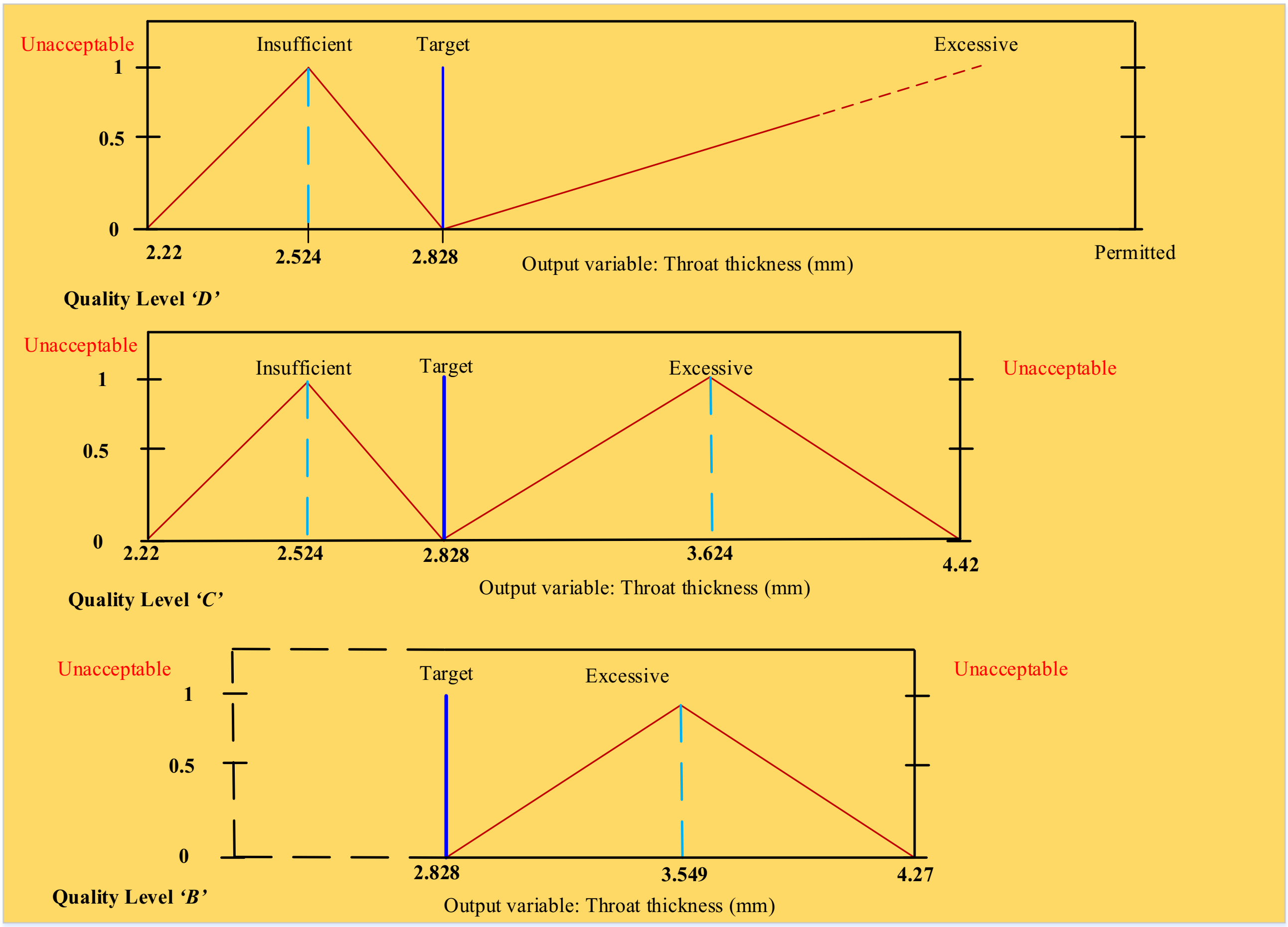


Fig. 4 Membership function for throat thickness of 4-mm plate

4-mm plate, WFR was set in the range of 3–7 m/min, and the membership functions ranged from 2.22 to 4.42 mm for throat thickness and from 3.7 to 8.0 mm for joint penetration, considered for both weld characteristics. Full penetration requires welding on both sides in the case of 6-mm-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.

2.12 Design of experiments

The selected design of the experiment model is a custom design comprising four sets of parameters, which include WFR (m/min), TS (mm/min), EWA (deg), and CTWD (mm) (refer to Table 12). Depending on the process parameters, other welding parameters, such as welding current, are 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 JMP software was used for designing the experiments. This software was designed to generate 27 experimental runs for each thickness. In this process, each run was randomized and replicated based on three repetitions for each specimen, and the average was calculated.

2.13 Experiments performed

T-joint weld specimens of dimensions 152 × 101 × 6 mm and 152 × 76 × 6 mm were prepared following AWS B4.0:2016 standards and welded in a horizontal position. Throat thickness and joint penetration measurements followed BS EN ISO

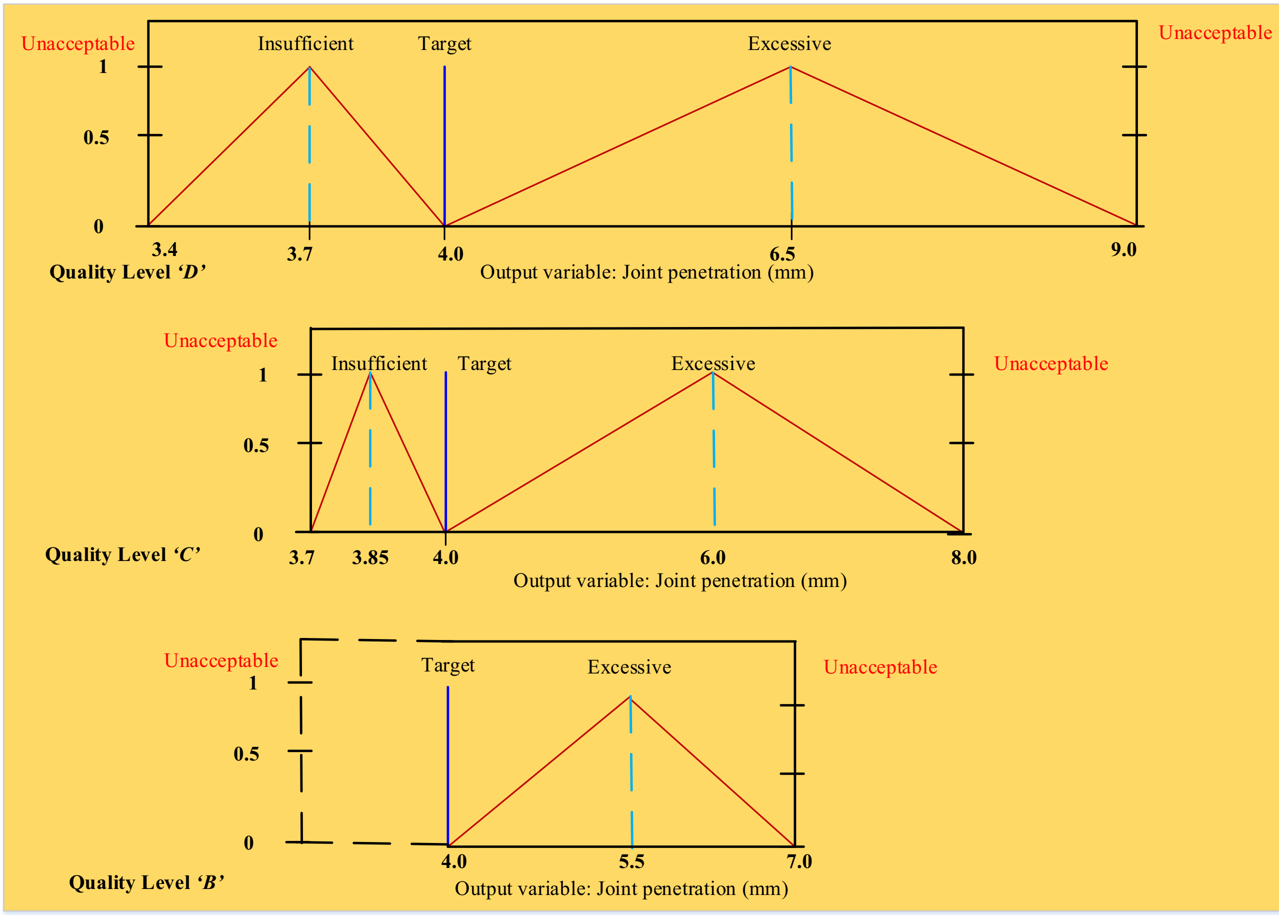


Fig. 5 Membership function for joint penetration of 4-mm plate

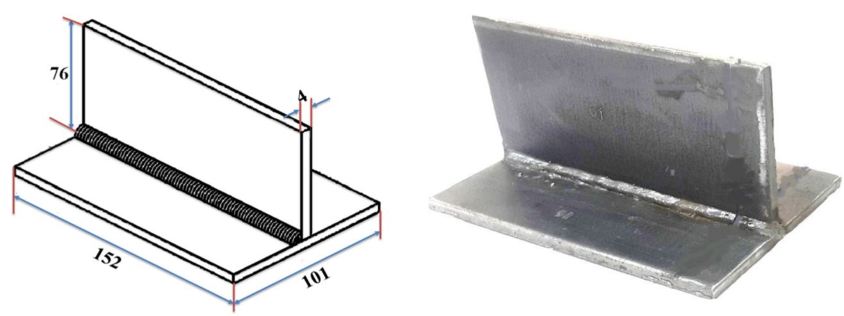
5817:2014 standard. Figure 6a displays a schematic diagram with dimensions of the fillet T-joint, while Fig. 6b shows a sample of the welded joint. In total, 27 welded joints were created for each plate thickness, as specified in the DoE section.

3 Results and discussion

In this study, fuzzy logic models have been developed for predicting the throat thickness and joint penetration of plates with 2-mm, 4-mm, and 6-mm 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 13. 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 13. For 2-mm thickness, the response of throat thickness and joint penetration of experiment numbers TJ8, TJ15, TJ20, and TJ22 are of the highest quality levels ("B") for both weld quality characteristics. Hence, they can be recorded as experiments with acceptable results. Also, for 4-mm thickness, TJ13, TJ18, and TJ21 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 2-mm thickness, TJ8, TJ15, TJ20, and TJ22 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. 7, though the use of different sets of parameters may have an impact on other aspects. For instance, by using TJ8, TJ15, and TJ20 (350 mm/min travel speed), productivity increases by 57.13% compared to TJ22 (150 mm/min travel speed). On the other hand, lower, lower TS (that results in a

Table 12 Experimental design for 2-mm-, 4-mm-, and 6-mm-thick steel plate

Run	WFR (m/min)			TS (mm/min)	EWA (deg)	CTWD (mm)
	2 mm	4 mm	6 mm			
TJ-1	3	5	7	250	50	10
TJ-2	3	5	7	150	45	15
TJ-3	1	3	5	450	40	15
TJ-4	3	5	7	350	40	20
TJ-5	1	3	5	250	40	15
TJ-6	3	5	7	450	50	15
TJ-7	1	3	5	550	45	20
TJ-8	1	3	5	350	45	10
TJ-9	5	7	9	550	50	20
TJ-10	5	7	9	350	50	15
TJ-11	5	7	9	250	45	20
TJ-12	3	5	7	550	40	10
TJ-13	1	3	5	150	40	15
TJ-14	5	7	9	450	45	10
TJ-15	1	3	5	350	50	15
TJ-16	5	7	9	150	45	10
TJ-17	5	7	9	150	45	15
TJ-18	3	5	7	250	40	15
TJ-19	1	3	5	250	45	20
TJ-20	3	5	7	350	45	10
TJ-21	5	7	9	250	50	10
TJ-22	1	3	5	150	50	20
TJ-23	3	5	7	450	45	20
TJ-24	5	7	9	350	40	20
TJ-25	3	5	7	550	50	20
TJ-26	1	3	5	450	50	10
TJ-27	5	7	9	550	40	15



(a) Dimensional specimen (mm) **(b)** T-Joint welded sample of 4130 steel

Fig. 6 T-Joint welded specimen

larger weld bead), in the case of TJ-22, necessitates higher CTWD to prevent the torch from touching the baed.

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 2-mm thickness (TJ3, TJ6, TJ8, TJ12, TJ14, TJ15, TJ20, TJ22, TJ23, and TJ27) are all in the same quality level "B." Hence, by using TJ12 and TJ27 (550 mm/min travel speed), productivity increases by 72.73%, which is higher than TJ22 (150 mm/min travel speed); 36.37% higher than TJ8, TJ15, and TJ20 (350 mm/min travel speed); and 18.19% higher than TJ3, TJ6, TJ14, and TJ23 (450 mm/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

Table 13 Predicted and experimental values for quality level D, C, and B

Run	2-mm-thick plate						4-mm-thick plate						6-mm-thick plate					
	PVTT (mm)	EVTT (mm)	PEQLTT (mm)	PVJP (mm)	EVJP (mm)	PEQLJP (mm)	PVTT (mm)	EVTT (mm)	PEQLTT (mm)	PVJP (mm)	EVJP (mm)	PEQLJP (mm)	PVTT (mm)	EVTT (mm)	PEQLTT (mm)	PVJP (mm)	EVJP (mm)	PEQLJP (mm)
TJ-1	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
TJ-2	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
TJ-3	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
TJ-4	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
TJ-5	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
TJ-6	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
TJ-7	NP	1.06	UI	NP	0.7	UI	NP	1.41	UI	NP	1.1	UI	NP	2.25	UI	NP	1.1	UI
TJ-8	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
TJ-9	NP	1.06	UI	NP	1.0	UI	NP	2.20	UI	NP	1.6	UI	NP	3.51	UI	NP	2.0	UI
TJ-10	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
TJ-11	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
TJ-12	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
TJ-13	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
TJ-14	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
TJ-15	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
TJ-16	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
TJ-17	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
TJ-18	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
TJ-19	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
TJ-20	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
TJ-21	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
TJ-22	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
TJ-23	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
TJ-24	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
TJ-25	NP	1.05	UI	NP	1.0	UI	NP	2.15	UI	NP	1.0	UI	NP	2.86	UI	NP	1.6	UI
TJ-26	NP	0.98	UI	NP	0.6	UI	NP	1.21	UI	NP	1.2	UI	NP	2.41	UI	NP	1.6	UI
TJ-27	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

TJ T-joint, *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

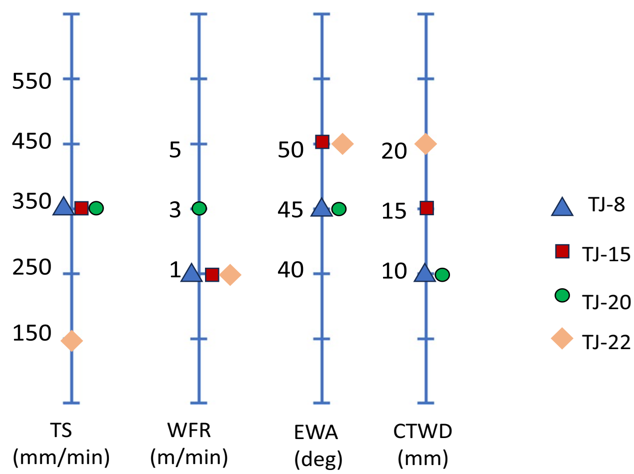


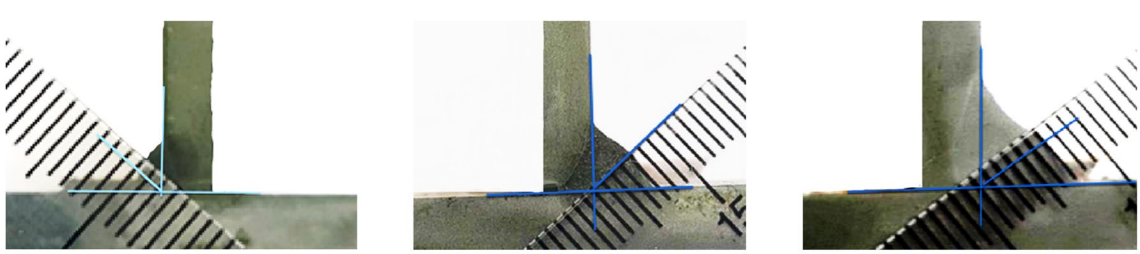
Fig. 7 Acceptable process conditions for achieving quality level "B" for 2-mm plate

high-quality level "B" (which would increase production cost). For instance, the same quality level has been recorded for 2-mm plate thickness in quality level "B" with TJ20 (WFR at 3 m/min, TS at 350 mm/min, EWA at 45°, and CTWD at 10 mm), which can be alternated with TJ22 (WFR at 1 m/min, TS at 150 mm/min, EWA at 50°, and CTWD at 20 mm). 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" (TJ1 for 2-mm-thick plate) or in the opposite throat thickness quality level "B" and joint penetration quality level "D" (TJ1 for 4-mm-thick plate) input parameter settings can be used (see Table 13). 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.

3.1 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. 8.

The effect of process parameters on throat thickness is shown in Fig. 9 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 4.42 mm has been observed at a WFR of 3.2–4.7 m/min and TS of 180–220 mm/min; WFR 5–5.8 m/min and TS of 230–350 mm/min; and WFR of 6.2–6.7 m/min and TS of 380–570 mm/min. The minimum throat thickness of 2.22 mm has been noted at a WFR of 3.2–3.8 m/min and TS of 350–470 mm/min; WFR of 4.2–5 mm/min, and TS of 490–570 mm/min. A throat thickness of 3.32 mm is obtained at WFR of 5–7 m/min and TS of 150–210 mm/min; WFR of 6.2–7 m/min and TS of 210–350 mm/min; and WFR of 3–3.8 m/min and TS of 490–550 mm/min. Throat thickness is above the average at WFR of 3–5 m/min and

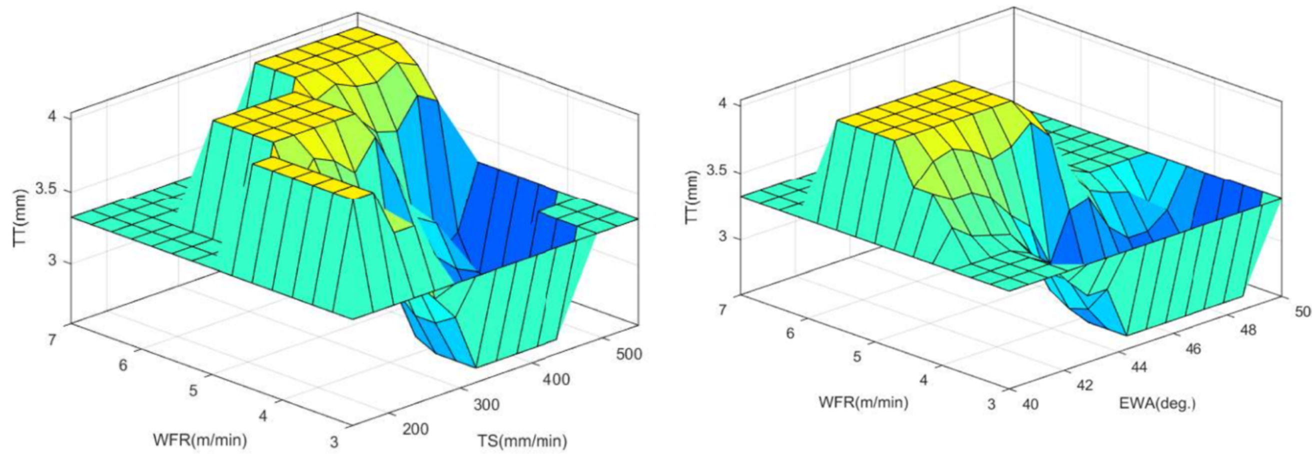


(a) Throat thickness of TJ25 TT=2.15mm

(b) Throat thickness of TJ10 TT=4.12mm

(c) Throat thickness of TJ18 TT=6.07mm

Fig. 8 Welded samples for throat thickness measurement for a 4-mm plate

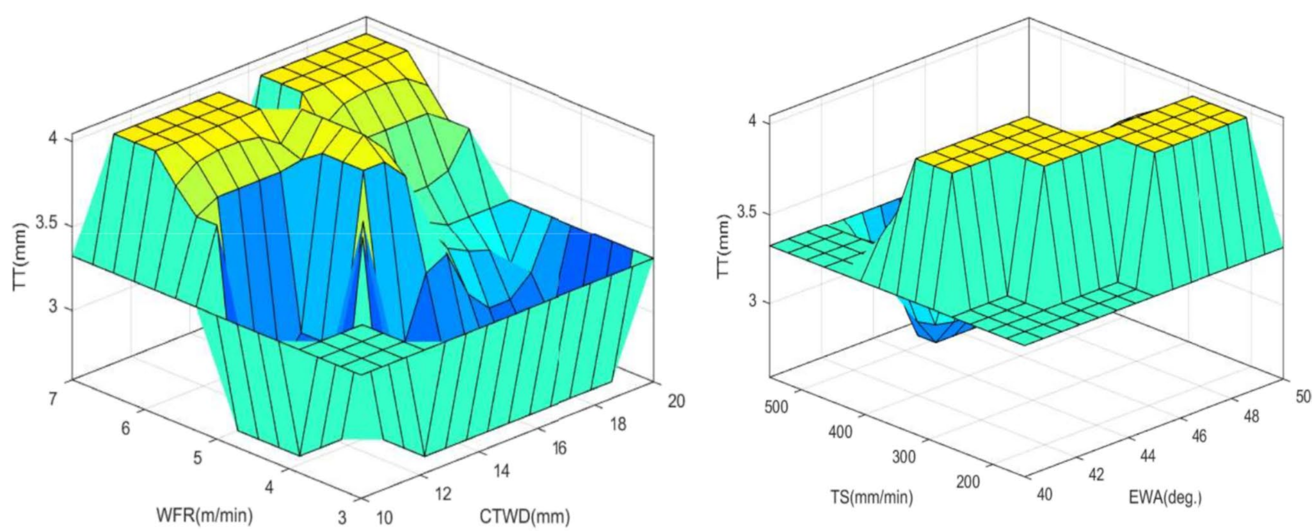


(a) WFR and TS effect

(b) WFR and EWA effect

Fig. 9 Surface plots of process parameters' effects on TT

TS of 150–290 mm/min; WFR of 4.5–6.2 m/min and TS of 220–420 mm/min; and WFR of 5.2–7 m/min and TS of 350–550 mm/min. Throat thickness is lower, below 3.32 mm, when WFR is at 3–4.5 m/min and TS 275–490 mm/min and WFR at 4–5.5 m/min and TS 400–550 mm/min (Fig. 9a). 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 [22, 23] 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 4.42 mm at WFR 5–5.8 m/min and EWA 40.75–45°, and the minimum thickness is at WFR 3.3–3.8 m/min and EWA 45–50°, measuring 2.22 mm. In other combinations, such as WFR 3–3.8 m/min, 6.2–7 m/min, and 5–7 m/min, and EWA 40–42.1°, 40–50°, and 48–50°, the average throat thickness is calculated as 3.32 mm. The above-average throat thickness, i.e., 3.32 mm, is seen at WFR 4–6.2 m/min and EWA 40–48° combinations. The lower thickness of the throat is noted at WFR 3–5 m/min and EWA 42–50°, below the 3.32 mm (Fig. 9b). A similar trend has been observed from [24, 25] findings that the throat thickness increases when EWA increases.



(a) WFR and CTWD effect

(b) TS and EWA effect

Fig. 10 Surface plots of process parameters' effects on TT

Figure 10a and 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 4.42 mm at WFR 6.2–6.7 m/min and CTWD 10.6–14.2 mm; WFR 6.2–6.7 m/min and CTWD 15.7–19.3 mm; WFR 4.7–5.8 m/min and CTWD 15 mm; throat thickness is 3.32 mm at WFR of 3–3.8 m/min and CTWD 10–12 mm. Throat thickness above average (> 3.32 mm) was recorded at WFR of 4.3–7 m/min and CTWD 10–20 mm. Throat thickness below average (< 3.32 mm) was recorded at WFR 3–3.5 m/min and CTWD 10–20 mm. The minimum is seen at WFR of 3.3–3.8 m/min and CTWD of 12.9–19.10 mm and WFR of 4.2–5 m/min and CTWD of 10.8–12.1 mm as 2.22 mm. 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 [22, 26].

In the case of TS and EWA combinations (Fig. 10b), the throat thickness is a maximum of 4.42 mm at TS 290–350 mm/min and EWA 40–45°; TS 230–290 mm/min and EWA 42.9–49.3°; and TS 175–270 mm/min and EWA 45.8–49.3°. The lesser thickness value, 2.22 mm, is noted at TS 490–575 mm/min and EWA 45–49.1°. The average thickness is observed as 3.32 mm at TS 150–210 mm/min and EWD 40–45°; TS 150–270 mm/min and EWD: 40–42.1°; TS 430–500 mm/min and EWD 40–42°; and TS 325–390 mm/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 [23].

Similarly, the effects of TS, CTWD, EWA, and CTWD combinations are observed and plotted in the 3D form (Fig. 11a, b). In the case of Fig. 11a, CTWD does not have a significant effect on throat thickness; throat thickness is higher (above 3.32 mm) at lower travel speeds (150–420 mm/min). The throat thickness is below 3.32 mm at higher travel speeds (375–550 mm/min) and without significant effect of CTWD.

For EWA and CTWD combinations, throat thickness recorded a maximum of 4.42 mm at 15 mm CTWD and 40.9–45° EWA. The average throat thickness is 3.32 mm at EWA 40–42.1° and CTWD 10–12.1 mm; EWA 47.9–50° and CTWD 15–20 mm; and EWA 40–50° and CTWD 17.9–20 mm. The throat thickness is recorded below 3.32 mm at EWA 42–50° and CTWD 10–15 mm (Fig. 11b).

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.

3.2 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

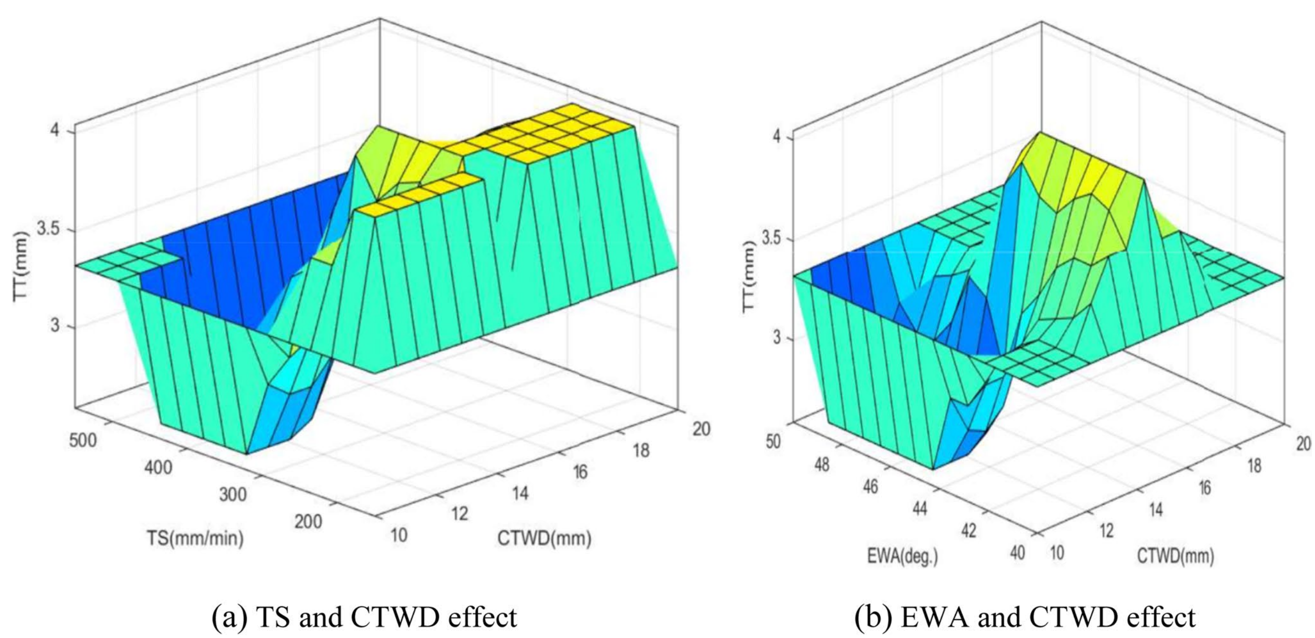
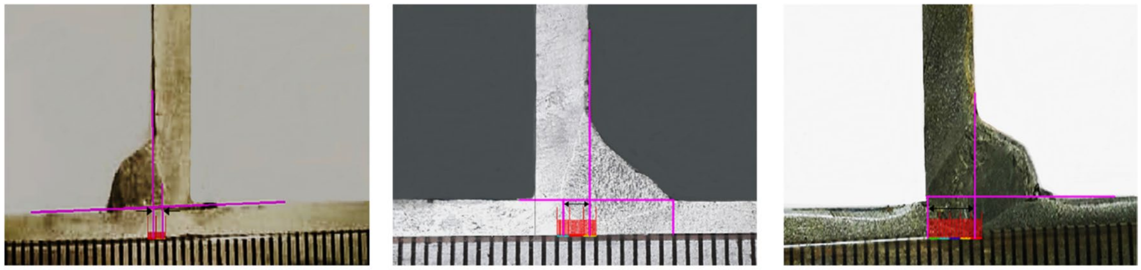


Fig. 11 Surface plot of process parameters' effects on TT



(a) Joint penetration of TJ25 JP=1mm **(b)** Joint penetration of TJ27 JP=2mm **(c)** Joint penetration of TJ13 JP=4.0mm

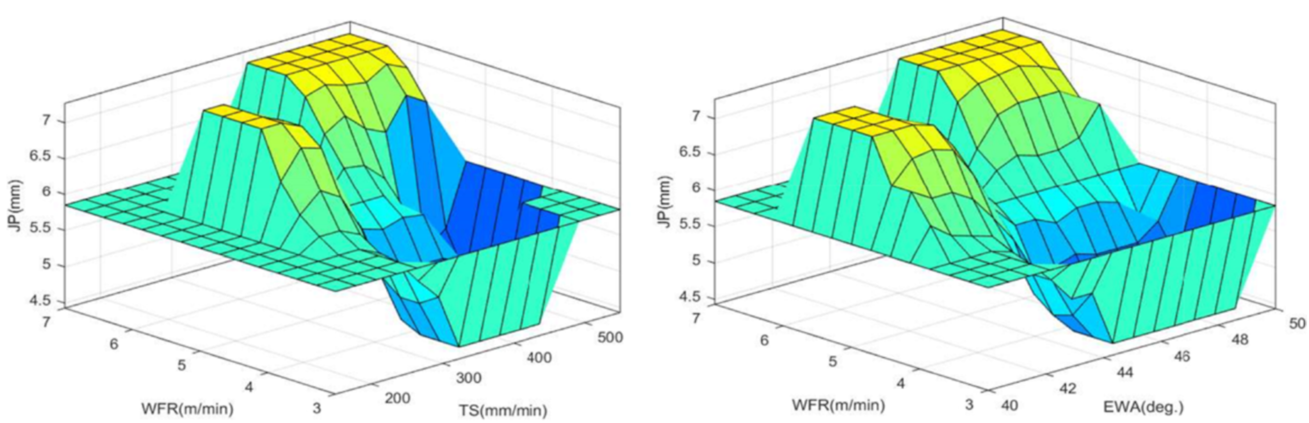
Fig. 12 Welded samples for joint penetration measurement for 4mm plate

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. 12.

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 5–5.8 m/min and TS of 230–260 mm/min, and also at a WFR of 6.2–6.7 m/min with TS of 380–520 mm/min. The lesser value of joint penetration, 3.7 mm, is noted at a WFR of 3.2–3.8 m/min and TS of 350–420 mm/min, as well as a WFR of 4.2–5 m/min and TS of 490–525 mm/min. Joint penetration is recorded above the average (5.85 mm) at a WFR of 4–6.1 m/min and TS of 210–350 mm/min, as well as a WFR of 5.3–7 m/min and TS of 350–550 mm/min. Joint penetration is recorded below 5.85 mm at a WFR of 3–5.5 m/min and TS of 250–550 mm/min (Fig. 13a). WFR mostly determines the joint penetration; increasing the WFR increases the amount of heat input in the weld pool zone, increasing the joint penetration [22, 23].

The other set of combinations of parameters' effect in terms of WFR and EWA on joint penetration is observed as the maximum thickness of 8 mm at a WFR of 5–5.8 m/min and EWA of 40.6–42.1°, also at a WFR of 6.1–6.7 m/min and EWA of 45.7–49.4°. The minimum penetration is at a WFR of 3.25–4.80 m/min and EWA of 45–49.2°, measured as 3.7 mm. The value of joint penetration was recorded above 5.85 mm at a WFR of 3.8–6.1 m/min and EWA of 40–45°, as well as a WFR of 5–7 m/min and EWA of 45–50°. Joint penetration was recorded in the average range (5.85 mm) at a WFR of 3–3.8 m/min and EWA of 40–42.1° and a WFR of 6.1–7 m/min and EWA of 40–45° (Fig. 13b).

In the combination of WFR and CTWD, the extent of joint penetration is above 5.85 mm at a WFR of 5–7 m/min and CTWD of 10–20 mm. Joint penetration is recorded in the average range for the setting combination of a WFR of



(a) WFR and TS effect (b) WFR and EWA effect

Fig. 13 Surface plot of process parameters effects on JP

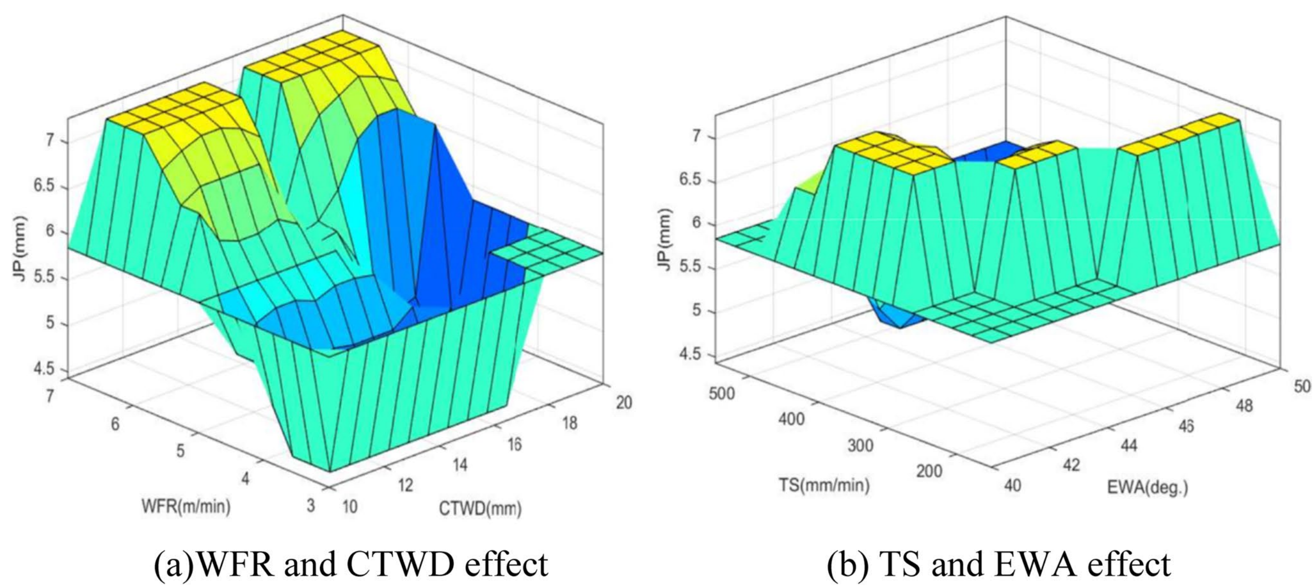


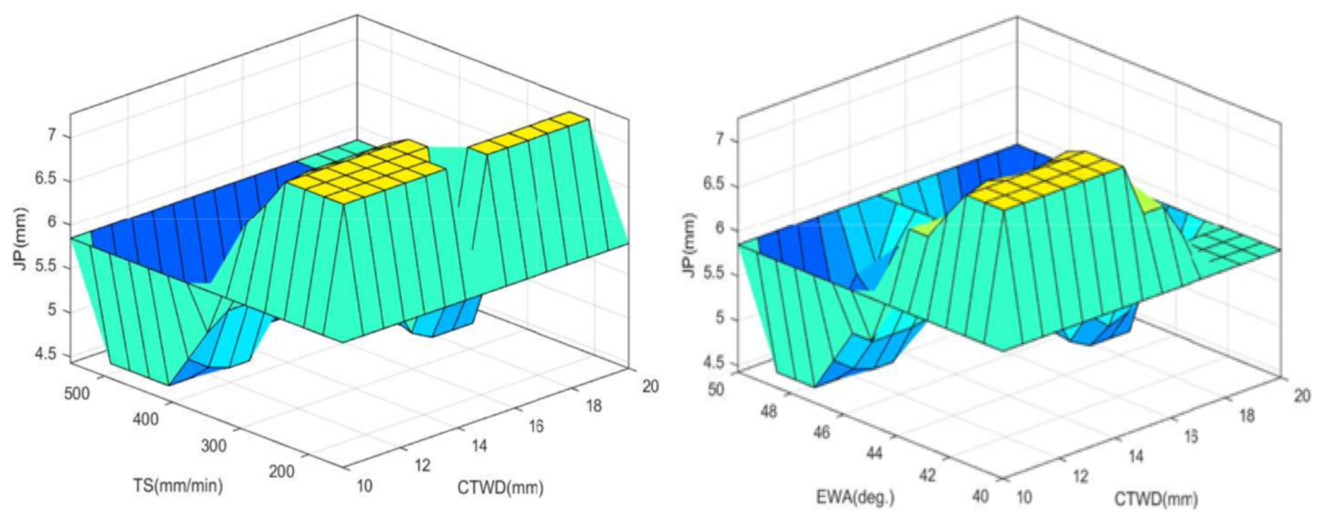
Fig. 14 Surface plot of process parameters effects on JP

3–3.8 m/min and CTWD 17.9–20 mm. Below 5.85 mm of joint penetration has been recorded at a WFR of 3–5.5 m/min and CTWD of 10–20 mm (Fig. 14a). 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 [22].

Joint penetration recorded a maximum value of 8 mm at TS of 290–410 mm/min and EWA of 40.7–42.2°; TS of 230–320 mm/min and EWA of 42.9–45°; and TS of 160–210 mm/min and EWA of 45.7–49.4°. Recorded joint penetration is at an average of 5.85 mm at a TS of 150–210 mm/min and EWA of 40–45°; TS of 150–270 mm/min and EWA of 40–42.1°; and TS of 490–550 mm/min and EWA of 40–42.1°. Joint penetration was recorded below the average of 5.85 mm at TS of 350–550 mm/min and EWA of 43–50° (Fig. 14b). 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 [21, 23, 27].

The value of joint penetration is 8 mm at TS of 180–230 and CTWD of 10.6–14.2 mm; TS of 160–260 and CTWD of 15.7–19.3 mm; and TS of 180–210 and CTWD of 10.6–14.2 mm. An average joint penetration (5.85 mm) has been noted at a TS of 490–550 mm/min and CTWD of 17.9–20 mm. Joint penetration is below 5.85 mm at a TS setting of 260–550 mm/min, and CTWD of 10–20 mm, and joint penetration is noted above average at a TS of 150–350 mm/min and CTWD of 10–20 mm. The recorded joint penetration reaches the minimum value (3.7 mm) at a TS of 430–525 mm/min and CTWD of 10.5–12 mm; TS of 490–525 mm/min and CTWD of 10.5–17; and TS of 350–460 mm/min and CTWD of 17.7–19.2 mm (Fig. 15a). At the combination of EWA and CTWD, the value of joint penetration is above 5.85 mm at EWA of 40–45° and CTWD of 10–18 mm. The noted joint penetration has been averaging at EWA 40–42.1° and CTWD 17.9–20 mm. Joint penetration was registered below 5.85 mm at EWA of 42–50° and CTWD of 10–15 mm, and EWA 45–50° and CTWD of 15–20 mm. The extent of penetration has reached the maximum point at the combined setting of EWA 40.6–42.1° and CTWD 10.8–15 mm. Conversely, the lower joint penetration (3.7 mm) has been recorded at the setting of EWA 47.9–49.2° and CTWD 10.8–12.1 mm, and EWA 45–49.2° and CTWD 17.9–19.2 mm (Fig. 15b). 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.

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



(a) TS and CTWD effect (b) EWA and CTWD effect

Fig. 15 Surface plot of process parameters effects on JP

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 Conclusions

This study 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 2 mm, 4 mm, and 6 mm. 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 study are as follows:

1) 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.
2) 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.
3) 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.
4) 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.

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Author contribution Tesfaye Negash Wordofa: conceptualization, data curation, formal analysis, investigation, methodology, resources, software, validation, visualization, writing original draft.

Perumalla Janki Ramulu: supervision, writing—review and editing.

Abhay Sharma: writing—review and editing.

All authors approved the final version of the manuscript and agree to be held accountable for the content therein.

Data availability The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical approval The authors declare that there is no ethical issue applied to this article.

Consent to participate The authors declare that all authors have read and approved to submit this manuscript to IJAMT.

Consent for publication The authors declare that all authors agree to sign the transfer of copyright for the publisher to publish this article upon on acceptance.

Conflict of interest The authors declare no competing interests.

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