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Comparative Study of Modelling Friction Welding Joint Properties for Dissimilar AISI 430 Steel and EN 10028 P355 GH Steel Joint by Response Surface Methodology and Fuzzy Logic

G Senthilkumar[1]*, V Vinodkumar[2], G Rathinasabapathi[1], B Dhanasakkaravarthi[3], T Mayavan[1], V Sivaraman[4]

[1]Department of Mechanical Engineering, Panimalar Engineering College, Chennai, India, [2]Department of Mechanical Engineering, SRM Institute of Science and Technology, Ramapuram, Chennai, India, [3]Department of Mechanical Engineering, Agni College of Technology, Chennai, India, [4]Department of Mechanical Engineering, Sri Muthukumaran Institute of technology, Chennai, India. *Corresponding Author's Email: senthilngt1978@gmail.com

Abstract

This work is to suggest a method to model the friction welded properties for dissimilar AISI 430 steel and EN 10028 P355 GH Steel joints using techniques like response surface methodology (RSM) and fuzzy logic (FL). Modelling used to predict correct parameters and their range without sacrificing weld quality is very crucial in the manufacturing sector. The techniques handled in this work used to find the welded joint properties like ultimate tensile strength (UTS), Impact toughness (IT) and axial shortening (AS) were obtained by solid state friction welding process in advance. The 27 sets of 5 input process variables like frictional pressure, forge pressure, forging time, frictional time, and chuck speed were considered. The fuzzy logic model output values are related to experimental values and the average error is found to be 2.05%, 8.9%, and 8.31% of the responses tensile stress, axial shortening, and impact toughness respectively. Similarly, RSM based model value and experimental values are related, and the average error is estimated to be 7.43%, 10.45%, and 13.78% of the responses tensile stress, axial shrinkage, and impact toughness respectively. The enhanced quality output obtained by fuzzy logic analysis is outperformed as average error yields less than response surface methodology. This work helps us to suggest the best modelling technique for the prediction of friction welded joint properties.

Keywords: Axial Shortening, Friction Welding, Fuzzy Logic, Mathematical Modelling, Response Surface Methodology.

Introduction

Welding is highly used for the fabrication of pressure vessels, pipelines, and offshore structures. Among the solid-state welding technique, friction welding (FW) is applied in the manufacture of automobile parts, and hydraulic and pneumatic tools. Productivity is the main objective in industrial welding applications, therefore the prediction of correct parameters and their range without sacrificing weld quality is very crucial. Modelling is one of the tools for predicting weld quality characteristics in advance. AI techniques have been used in the modelling of the welding process in recent day research. Fuzzy logic is one of the AI tools used for the diagnosis of welding quality characteristics. The RSM is also one of the mathematical model methods used to develop welding quality characteristics. The ANSYS software produced a friction welding model for the duplex stainless steel S31803 joint that demonstrated good agreement with experimental data in terms of peak temperature and length shortening. The peak temperature during the process is measured by an infrared thermometer. The Johnson Cook model and Modified Coulomb's law parameters were fed to the software (1). The Finite Element Analysis (FEA) modelling for two alloy steel tubes bonded by friction welding using DEFORM-2D software. A comparison is made between the residual stress of the welded connection discovered using the hole drilling approach and the model. The model trend matches the experimental data quite well. The experimental results like tensile strength, and hardness predicted are matched with the model (2). The

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heat generated, flash creation, and stress, produced in the friction welding predicted by the FEA model using DEFORM software using coupled field analysis (3). The fuzzy model outperforms the linear regression model in predicting thermal inaccuracy in the machining center (4). The second order polynomial equation to determine the association between surface roughness and tool wear. Additionally, this model lists the parameter interaction effects. (5). A 3D FEA model of the studies on the distribution of temperature for FW of two different materials and predicted that to get uniform heat distribution, low thermal conductivity material has to be fixed in a rotating chuck in the machine (6). The output of three distinct energy system models to examine the effects of varying import prices for hydrogen and its derivatives on the German energy system provides a solution to the research issue regarding the range that installed capacities for electrolysis, installed capacities for electricity generation, and electricity generation volumes exhibit (7). Artificial Neural Network (ANN), FL, and RSM modelling techniques have been used to predict the extraction of oleonolic acid from Ocimum sanctum theoretically. Results from experiments are compared with those from the RSM, ANN, and FL (8). Although the K nearest neighbour models yielded poorer performances, the soil remediation efficiency models outperformed the RSM models in terms of performance (9). Model evaluations with Bayesian information Criterion, Akaike weights, and predictive model assessment showed that our model outperformed other models that were only based on the technology acceptance model in terms of predicting accuracy (10). When the experimental and predicted values from the fuzzy model are compared, it can be concluded that the fuzzy model performs well because it produces the least amount of error (11). When the models are compared using the test dataset, it becomes clear that the generated FL model outperforms the two empirical models in terms of coefficient of determination (R^2), root mean square error (RMSE), and mean absolute error (MAE) (12). The FEA model for FW of titanium and tungsten material. The material property is used in the pre-processing stage as per the Johnson Cook model. The flash produced in the FW process shows a good fit with numerically developed (13). Previously, mathematical model to predict the friction welded joint properties was given less attention. In this study, joint properties of friction welded dissimilar materials American Iron and Steel Institute (AISI) 430 Steel and EN 10025 P355 GH Steel and have been found experimentally and in mathematical models using response surface methodology and fuzzy logic analysis. The experimental values related to model values and errors accumulated have been arrived at. The best mathematical model can be selected based on the model at which yields a low error.

Methodology

A dissimilar material AISI 430 and EN 10025 P355 GH Steel are fastened together by solid state friction welding. The composition of the material is listed in Table 1. The specimen diameter is 12 mm and the length of 75 mm on each side is made in the required numbers for joining. The end surfaces of the specimen were polished by a grinding machine before fastening to eliminate surface roughness.

Table 1: Material Composition

AISI 430 Ferritic Stainless Steel											
Elements	Cr	C	Mn	Ni	S	Si	Mo	P	V	Cu	Fe
%	16.38	0.13	1.58	0.46	-	0.41	0.21	0.038	-	-	Balance
EN 10025 P355 GH Steel											
Elements	Cr	C	Mn	Ni	S	Si	Mo	P	V	Cu	Fe
%	0.3	0.18	1.1	0.5	0.01	0.5	-	-	0.1	0.3	Balance

Figure 1 shows continuous drive rotary friction welding equipment. The equipment capacity is rated at 0.012 MW with a main spindle running at a high speed of 50 r/second. The servo motor gearbox is used for linear movement of the non-rotating chuck and the parameters are accurately set by the 'Rexroth controller'. Friction welded samples of combined AISI 430 and EN 10028 P 355GH Steel are shown in Figure 2. The parameters used and their values are listed in Table 2.

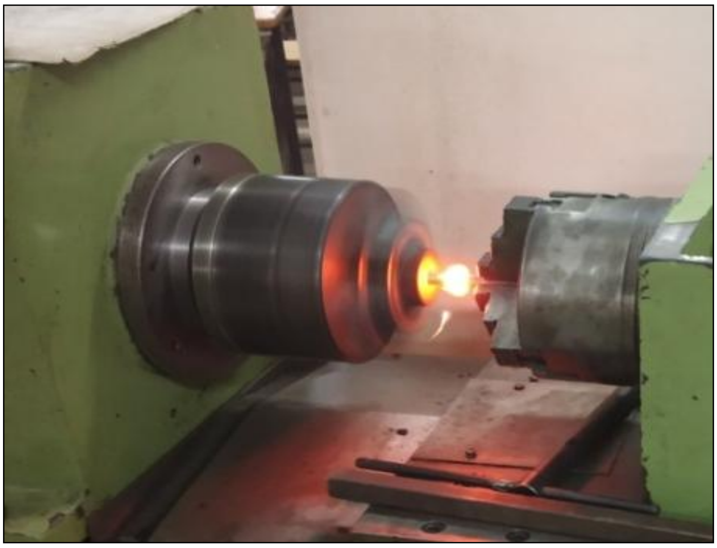

Figure 1: Friction welding Equipment

Table 2: Process Parameters and Their Values

S.No	Process Parameters	Units	AISI 430 and EN 10028 P 355 GH Steel	
			Low	**High**
1	Friction Pressure -FP(p)	MPa	60	80
2	Upset Pressure -UP (q)	MPa	70	110
3	Frictional Time -FT (r)	s	3	7
4	Upset Time -UT (s)	s	3	7
5	Speed-S (t)	Rpm	800	1200

Figure 2: AISI 430 and EN 10028 P355 GH Steel Friction Welded Samples

Tensile strength is one of the important mechanical properties required for any welded joint. A Universal testing machine used to carry out tensile tests is shown in Figure 3. As per American Standard Testing of Materials (ASTM) E8M-04 Standard, the tensile test specimen is prepared. Toughness is the capacity of the material to withstand the impact load. According to the ASTM E23 standard, Charpy V-notch testing is used to determine impact strength. Figure 4 shows the Charpy V-notch testing machine. The experimental results gathered are listed in Table 3.

Figure 3: Universal Testing Machine

Figure 4: Impact Toughness Testing Machine

Table 3: The Experimental Results of Friction Welded AISI 430 Steel and EN 10028 P355GH Steel

	Process Parameters					Characteristics		
Trial	UP (MPa)	FP (MPa)	UT (s)	FT (s)	SPEED (Rpm)	UTS (MPa)	AS (mm)	IT (J)
1	70	60	3	3	800	444.5	8.65	15
2	70	60	5	5	1000	461.2	14.8	15
3	70	60	7	7	1200	514.15	20.92	19
4	90	60	5	3	1200	485.7	14.98	19
5	90	60	7	5	800	508.55	20.78	17
6	90	60	3	7	1000	524.55	14.38	16
7	110	60	7	3	1000	553.5	21.35	17
8	110	60	3	5	1200	501.4	18.28	18
9	110	60	5	7	800	537.8	22.5	18

10	70	70	3	3	800	546.25	10.5	20
11	70	70	5	5	1000	546.25	17.5	20
12	70	70	7	7	1200	560.25	21.65	17
13	90	70	5	3	1200	542.15	20.56	19
14	90	70	7	5	800	536.10	20.15	21
15	90	70	3	7	1000	548.15	22.41	18
16	110	70	7	3	1000	530.10	23.21	19
17	110	70	3	5	1200	508.15	18.56	21
18	110	70	5	7	800	510.10	20.76	21
19	70	80	3	3	800	542.10	14.56	20
20	70	80	5	5	1000	563.15	20.85	16
21	70	80	7	7	1200	560.25	24.36	19
22	90	80	5	3	1200	518.25	21.80	20
23	90	80	7	5	800	567.2	21.6	18
24	90	80	3	7	1000	555.41	22.52	16
25	110	80	7	3	1000	556.95	20.56	17
26	110	80	3	5	1200	566.15	21.62	19
27	110	80	5	7	800	540.4	22.16	21

Fuzzy Logic Based Modelling

In soft computing, it may be argued that it is a group of algorithms utilized to find answers to extremely difficult problems for which conventional approaches did not produce affordable or workable alternatives. The ability of fuzzy logic to learn the relationship between input parameters and output characteristics is one of its distinctive qualities. Fuzzy logic is a non-linear, highly flexible modelling tool. Five inputs frictional pressure, forge pressure, frictional time, forge time, and speed, and three characteristics tensile strength, impact toughness, and axial shrinkage of the welded joint are used in the current study experiment. This issue was addressed using a Mamdani-based fuzzy logic since Mamdani produces better outcomes (8). Mamdani produces good results in fuzzy logic modelling when interpretability and qualitative rule based system are priorities (14). Using the MATLAB fuzzy logic toolbox, the triangle membership function was used for the fuzzification and defuzzification process. Welding process variables play a vital role in estimating the weld quality characteristics (15). A fuzzy method is very useful for the continuous improvement of product quality (16).

Fuzzy Model for EN 10028 P355GH Steel and AISI 430 Friction Welded Joint

The input factor and the output characteristics are entered into the fuzzy logic toolbox in MATLAB R2013a software and are displayed in Figure 5.

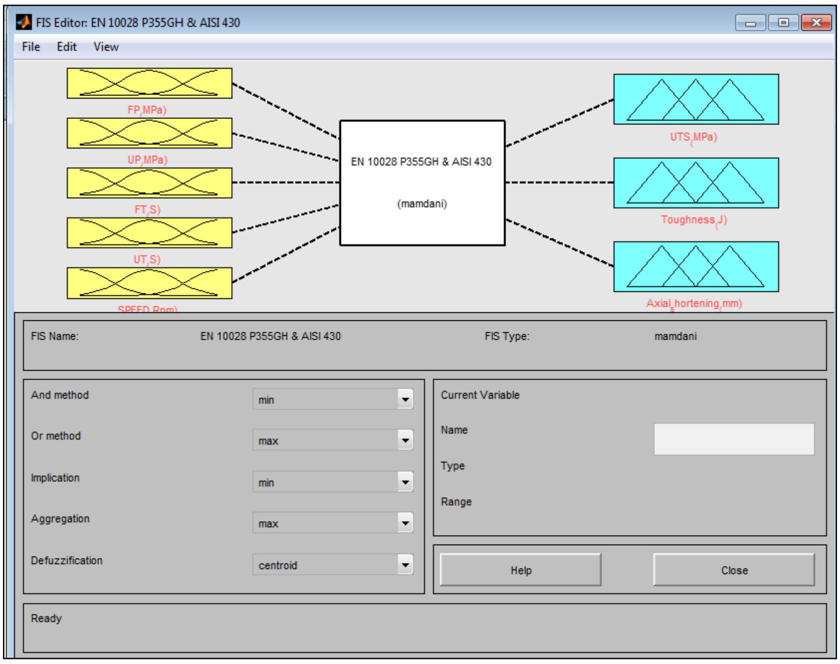

Figure 5: Fuzzy Model for AISI 430 and EN 10028 P355GH Steel FW Joint

The parameter speed of rotation is defined as triangular membership function in the name of low, med, and high for modelling of Friction Welded EN10028 P355GH Steel and AISI 430 Joint are displayed in Figure 6. The rule set framed for trial 20 is "If (FP_(MPa) is High) and (UP_(MPa) is low) and (FT_(s) is med) and (UT_(s) is med) and (SPEED_(Rpm) is med) then (UTS_(MPa) is high)(Toughness_(J) is med)(Axial shortening_(mm) is med)". The fuzzy based prediction model is displayed in Figure 7.

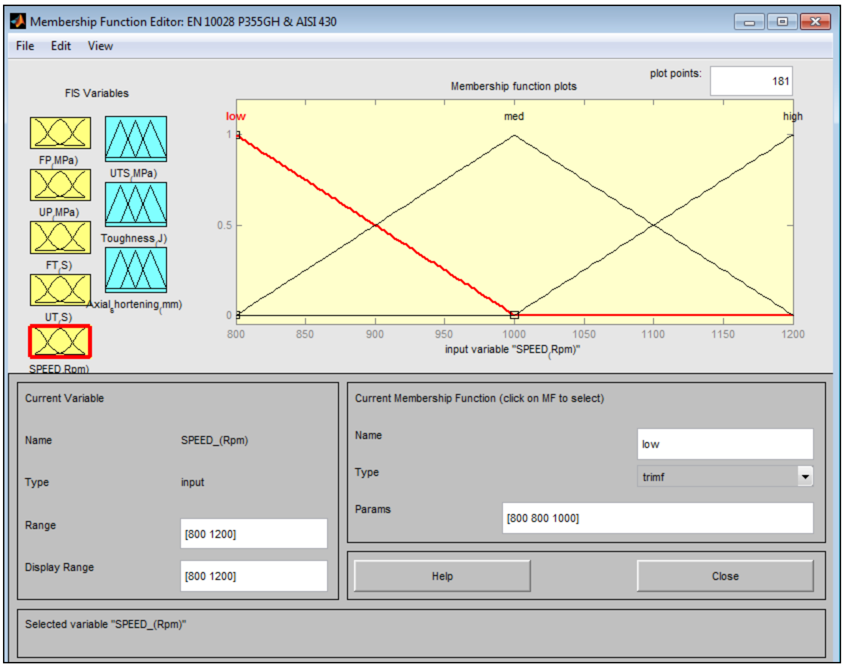

Figure 6: Implementation of Membership Function for AISI 430 Steel and EN 10028 P355GH Steel FW Joint

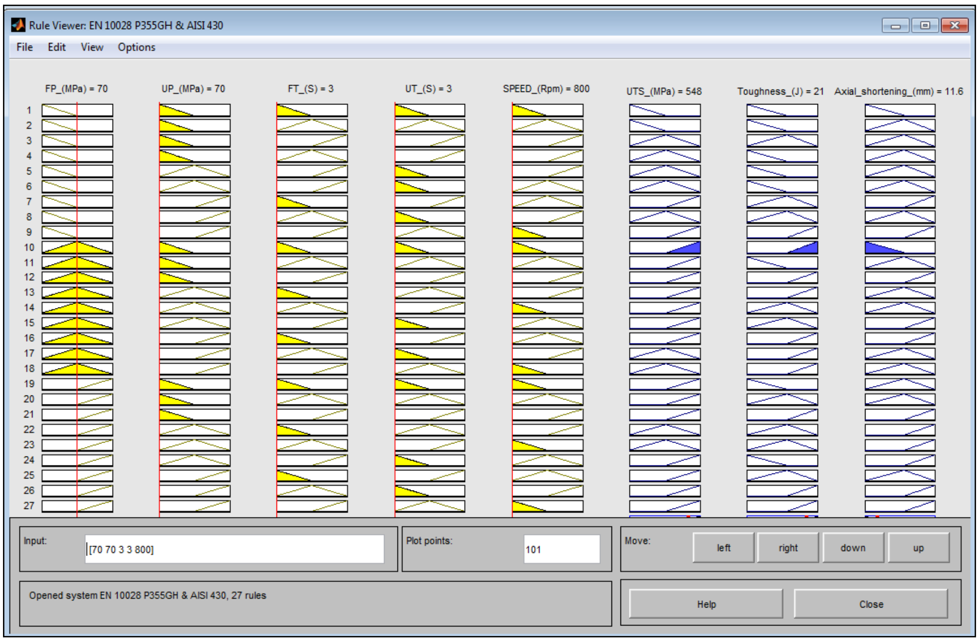

Figure 7: Fuzzy Based Output Model for EN 10028 P355GH STEEL and AISI 430 Steel FW Joint

Modeling by Response Surface Methodology

The field of applied statistics known as "design of experiments" organizes, carries out, evaluates, and interprets the data to determine the parameters' influencing factors. DOE serves as the foundation for RSM (17). The Characteristics tensile strength (X), impact toughness (Y), and axial shrinkage (Z) which are a function of welding parameters namely friction pressure (p), forge pressure (q), frictional time (r), forge time (s) and speed (t) are given by the equation 1.

$$X,Y,Z = f\,(p,q,r,s,t) \qquad [1]$$

The selected quadratic equation can be related as per the equation 2.

$$X,Y,Z = \alpha_0 + \alpha_1(p)+\alpha_2(q)+\alpha_3(r)+\alpha_4(s)+\alpha_5(t)+\alpha_{12}(pq)+\alpha_{13}(pr)+\alpha_{23}(qr)+\alpha_{34}(rs)+\alpha_{45}(st)+\alpha_{11}(p^2)+\alpha_{22}(q^2)+\alpha_{33}(r^2)+\ldots\ldots \qquad [2]$$

Where α_0, α_1,...... α_k are regression coefficients.

The regression coefficients were calculated by Design Expert V.11 Software. The importance of every coefficient is predicted by 'p' value and 'F' value. The assumptions made in the development of regression equations are, that the independent parameters in this study are continuous, controllable, and measurable and error is neglected (18). The model suitability has been assessed by regression coefficient and analysis of variance (19).

Modeling of Friction Welding Parameters for Aisi 430 And En 10028 P355 Gh Steel by Response Surface Methodology

The friction welding input and output parameters are modelled by response surface methodology technique using Design Expert V.11 software.

Development of Mathematical model for Tensile Strength, Impact Toughness, and Axial Shortening:

Tensile Strength (MPa) $X = 541.93 - 1.22\ p - 7.08\ q + 1.75\ r + 32.33\ s + 0.\ 2\ E + 0.5\ p*r - 5.78\ r*s + 0.04q^2$ [3]

Impact Toughness (J) $Y = -50.37 + 2.54\ p - 0.66\ q + 0.31\ r + 0.14\ s + 0.004\ t - 0.02\ p^2 + 0.004\ q^2$ [4]

Axial Shortening (mm) $Z = -70.05 + 0.67\ p + 0.87\ q + 0.98\ r + 5.25\ s - 0.015\ t - 0.0055\ p*q - 0.058p*s + 0.0003\ p*t - 0.0021q^2$ [5]

Results and Discussion

The selected materials AISI 430 and EN 10028 P 355 GH Steel are finding increased applications these days. Friction welding produces defect free joints whereas other fusion welding produces defects like porosity, undercut, and heterogeneous microstructure. The ANOVA for the characteristic tensile strength is shared in Table 4. The tensile strength can be estimated theoretically by equation 3. It is witnessed that the factors 'p, q, r, t r*s, q²' have a significant effect on the response tensile strength. The model is significant as the p-value is 0.0001 which is much less than 0.05 (20). This model indicates expected performance as the values of R^2=0.8558, Pred R^2=0.6809, and Adj R^2=0.7918, come nearer to 1 and Adequate Precision is 12.0656 which is greater than 4. So this model is evidently relevant.

Table 4: ANOVA for the Tensile Strength

Source	SS	DOF	MS	F-value	p-value	Model
Model	41065.54	8	5133.19	13.36	< 0.0001	Significant
p	12194.97	1	12194.9	31.73	<0.0001	-
q	9474.21	1	9474.21	24.65	0.0003	-
r	2202.44	1	2202.44	5.73	0.0278	-
s	804.33	1	804.33	2.09	0.1555	-
t	10362.4	1	10362.4	26.96	0.0001	-
P*r	1035.28	1	1035.28	2.69	0.1181	-
r*s	3209.52	1	3209.52	8.35	0.0098	-
q^2	1220.24	1	1220.24	3.18	0.0916	-
Residual	6916.64	18	384.26	-	-	-
Cor Total	47982.19	26	-	-	-	-

Table 5: ANOVA for the Impact Toughness

Source	SS	DOF	MS	F-value	p-value	Model
Model	68.93	7	9.85	7.93	0.0002	Significant
p	15.79	1	15.79	12.71	0.0021	-
q	19.06	1	19.06	15.35	0.0009	-
r	6.72	1	6.72	5.41	0.0312	-
s	1.39	1	1.39	1.12	0.3035	-
t	10.89	1	10.89	8.77	0.0080	-
p^2	18.96	1	18.96	15.27	0.0009	-
q^2	14.52	1	14.52	11.69	0.0029	-
Residual	23.59	19	1.24	-	-	-
Cor Total	92.52	26	-	-	-	-

The ANOVA table for the impact toughness is shared in Table 5 and it can be estimated theoretically by equation 4. It is witnessed that the individual factors 'p,q,r,t' and interaction factors p^2 and q^2 have a significant effect on the response impact toughness. The model is significant as the p-value is <0.0001 which is much less than 0.05. This model indicates expected performance as the values of R^2=0.7450, Pred R^2=0.4999 and Adj R^2=0.6510 comes nearest to 1 and Adeq Precision is 9.9834 which is greater than 4. So this model is evidently relevant.

Table 6: ANOVA for the Axial Shortening

Source	SS	DOF	MS	F-value	p-value	Model
Model	368.12	9	40.90	21.48	< 0.0001	Significant
p	12.00	1	12.00	6.31	0.0183	-
q	30.26	1	30.26	15.92	<0.0001	-
r	24.97	1	24.97	13.14	0.0003	-
s	0.0143	1	0.0143	0.0075	0.9321	-
t	21.47	1	21.47	11.3	0.0005	-
P*q	10.50	1	10.50	5.52	0.0234	-
P*s	12.15	1	12.15	6.39	0.0097	-
P*t	4.33	1	4.33	2.27	0.1499	-
p^2	4.49	1	4.49	2.36	0.1431	-
Residual	32.38	17	1.90	-	-	-
Cor Total	400.49	26	-	-	-	-

The ANOVA table for the axial shortening is shared in Table 6. The axial shortening can be estimated theoretically by equation 5. It is witnessed from that all individual factors 'r and t' and interaction factors 'p*q p*s' have a significant effect on the response axial shortening. The model is significant as the p-value is <0.0001 which is much less than 0.05. This model indicates expected performance as the values of R^2=0.9192, Pred R^2=0.8185, and Adj R^2=0.8764 are coming nearest to 1 and Adequate Precision is 20.2196 which is greater than 4. So this model is evidently relevant (21). The predicted values from fuzzy logic and response surface methodology are listed in Table 7. The comparative analyses for experimental and modelled values are presented in charts. In these charts, the X-axis represents the experiment number, while the Y-axis corresponds to tensile strength (MPa) in Figure 8, axial shrinkage (mm) in Figure 9, and impact toughness (J) in Figure 10.

Table 7: The RSM and Fuzzy Logic Predicted Output Responses for the AISI 430 EN 10028 P355 GH Steel Joint

Trial	**Fuzzy Logic Based Output Responses**			**RSM Based Output Responses**		
	UTS (MPa)	**AS (mm)**	**IT (J)**	**UTS (MPa)**	**AS (mm)**	**IT (J)**
1	465	11.6	16.3	484.35	9.31	12.98
2	465	11.6	16.3	470.03	16.41	19.68
3	507	22.1	18.7	559.47	21.51	18.38
4	506	16.5	18.5	517.33	18.13	19.46
5	506	16.5	18.5	573.29	22.43	18.76
6	507	11.6	16.3	558.39	17.91	19.62
7	548	22.1	18.7	549.11	25.47	15.74
8	507	16.8	18.7	557.97	20.95	15.6
9	548	22.1	21	590.53	23.25	21.9
10	548	11.6	21	472.15	12.82	17.38
11	548	16.8	16.3	557.83	18.36	19.08
12	548	22.1	21	597.27	25.9	20.78
13	548	22.1	21	598.53	20.58	18.86
14	548	22.1	18.7	561.09	21.52	18.16
15	548	22.1	18.7	586.19	19.92	19.02
16	548	22.1	21	536.91	21.06	21.14
17	507	16.8	21	605.77	20.46	18
18	507	22.1	21	578.33	22.4	17.3
19	548	16.8	16.3	459.95	17.33	12.78
20	548	16.8	18.7	545.63	21.31	14.48
21	548	22.1	21	585.07	25.29	16.18
22	507	16.8	18.7	586.33	22.03	14.26
23	507	16.8	18.7	548.89	22.62	13.56
24	548	22.1	16.3	583.99	23.93	14.42
25	548	16.8	18.7	574.71	22.65	16.54
26	548	22.1	21	583.57	25.97	18
27	548	22.1	21	566.13	24.55	18.52

The fuzzy output values are compared with experimental values and the average error is found to be 2.05%, 8.9%, and 8.31% of the output tensile stress, axial shortening, and impact toughness respectively. RSM based model value and experimental values are compared and the average error is estimated to be 7.43%, 10.45%, and 13.78% of the output tensile stress, axial shortening, and impact toughness respectively. The enhanced quality output obtained by fuzzy logic analysis is outperformed as average error yields less than response surface methodology (8, 11).

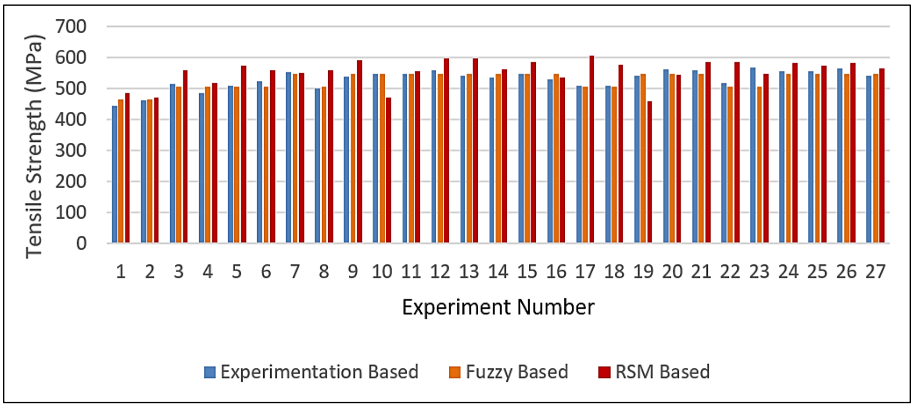

Figure 8: Comparison Plot for Ultimate Tensile Strength

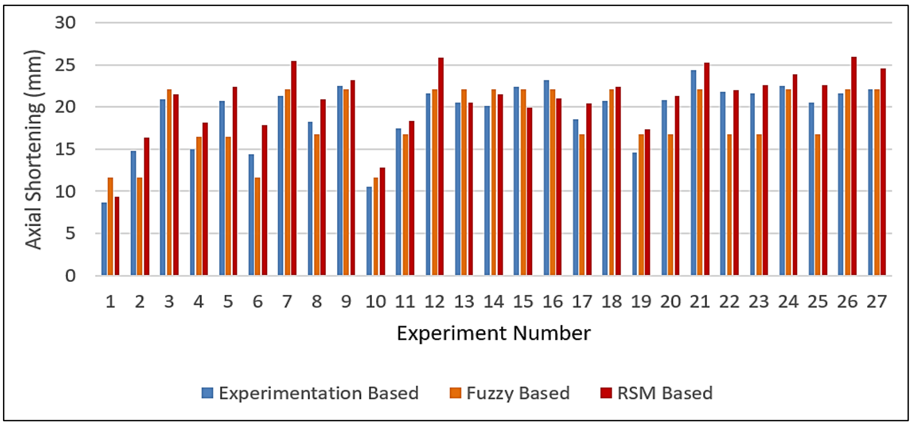

Figure 9: Comparison Plot for Axial Shortening

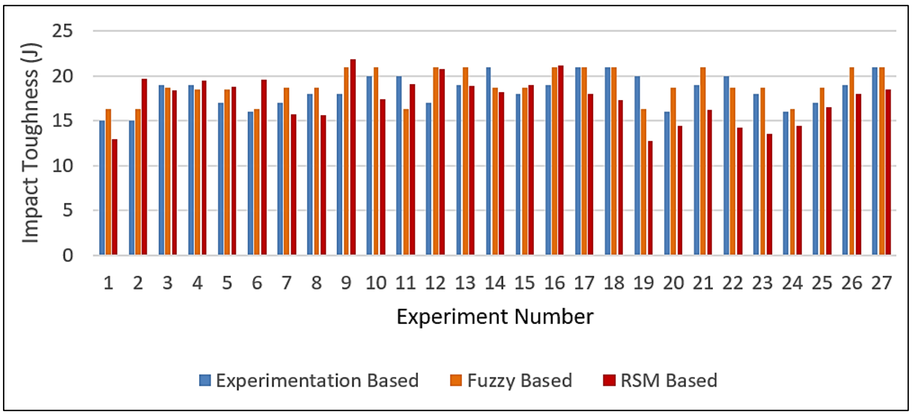

Figure 10: Comparison Plot for Impact Toughness

Conclusion

In the present research, mathematical modelling of friction welding quality characteristics by fuzzy logic and response surface methodology is carried out and conclusions have been listed below.

The dissimilar materials AISI 430 and EN 10028 P355 GH Steel were joined successfully by friction welding. The welded joint characteristics have been measured and a mathematical model has been created using fuzzy logic and response surface methodology. The fuzzy output values are compared with experimental values and the average error is found to be 2.05%, 8.9%, and 8.31% of the output tensile stress, axial shortening, and impact toughness respectively. RSM based model value and experimental values are compared and the average error is estimated to be 7.43%, 10.45%, and 13.78% of the output tensile stress, axial shortening, and impact toughness respectively. The enhanced quality output obtained by fuzzy logic analysis is outperformed as the average error yields less than the response surface methodology.

Abbreviations

AISI: American Iron and Steel Institute, ANOVA: Analysis of Variance, AS: Axial Shortening, ASTM: American Standard Testing of Materials, FEA: Finite Element Analysis, FL: Fuzzy Logic, FP: Friction Pressure, FT: Friction Time, IT: Impact Toughness, RSM: Response Surface Methodology, UP: Upset Pressure, UTS: Ultimate Tensile Strength, UT: Upset Time.

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Author Contributions

G Senthilkumar: Data Curation, Writing – original draft, V Vinodkumar: Software, Methodology, G Rathinasabapathi: Conceptualization, Supervision, B Dhanasakkaravarthi: Validation, T Mayavan: Writing – review and editing, V Sivaraman: Investigation.

Conflict of Interest

The Authors Declares that no conflict of interest.

Ethics Approval

Not Applicable.

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