Optimisation of Fsw Welding Parameters to Achieve Better Combination of Tensile Strength, Hardness and Corrosion Resistance of Az31b Mg- Alloy Welds

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Abstract
In the present study, influence of friction stir welding (FSW) parameters e.g. rotational speed, welding speed and axial force upon mechanical properties on magnesium alloy AZ31B for tensile strength, hardness was studied. Several experimentation runs were carried by applying Response Surface Methodology (RSM) to estimate the output characteristics of weld. This was carried in-line with Multi-response regression equations. Optimisation of mathematical models was analysed by applying Desirability approach for given constraints to study the influence of various combinations of process parameters. The results indicated while experimentation for the process parameters i.e Transverse Speed (TS) and rotational speed (RS) are having major impact on weldments. Axial force (AF) also played a vital role in deciding mechanical properties by using FSW on magnesium alloy. Present study established relation between various process variables and mechanical properties by developing mathematical models. The experimentation results carried on the specimen plates of magnesium alloy has showed optimum response. The indicative values which has influenced the weld characteristic parameters at rotational speed 600 rpm, welding speed 55 mm/min, and axial force of 8 kN.
Keywords: AZ31B Magnesium alloy, friction stir welding(FSW), corrosion resistance, tensile strength, Response Surface Methodology (RSM), Desirability approach, Genetic Algorithm.

Highlights:

- Emerging manufacturing technology is considering use of magnesium alloys for its advantage over weight to strength ratio.
- The material characteristics of AZ31B Mg alloy is greatly influenced by parameters of the process, and it has a considerable influence on the mechanical characteristics of the weld joints.
- FSW (Friction stir welding) process parameters are studied through statistical modelling method by applying Response surface methodology (RSM) to co relate/calibrate welding parameters on weldment. The correlation between the vital welding process parameters, statistical model, design of experiments(DOE)Multiple response regression analysis, and analysis variance(ANOVA) are applied to achieve better combination of tensile strength, hardness and corrosion resistance.

1. Introduction:

In the recent day technologies, light weight materials are used for structural application in various industries. Among light weight material, one of the best metal. Usage of magnesium alloys in various industries has significantly increased, in view of its advantage over weight to strength factor. Application of light metals in automotive and aerospace [1] industrial applications have largely increased. Weight to strength ratio [2,24] is one of the best mechanical properties of magnesium alloy.Friction Stir Welding (FSW) is considered as prominent solid-state welding technique for welding Magnesium alloys. Predominantly cryogenic fuel tanks in spacecraft industries were fabricated by FSW. The main reason for adapting this method of welding is to prevent/avoid solidification defects [3]. FSW has edge over conventional welding techniques. This method has reduced weld distortions and residual loads [4]. Experimentation was carried on welding magnesium alloy AZ31B by using FSW solid state technique is studied to assess the parametric optimisation of better mechanical properties.FSW technique never create plasticised zone, neither melt nor cast the parent metal. FSW weldments are free from both blow holes and porosity[5]. Besidesc weld imperfections such as deformation, continuity of bond and weld penetrations are integrated in FSW weld joints[6].

Without melting of the metal FSW technique is capable of welding magnesium alloys. Consequently it would eliminate imperfections related to solidification process A good weld quality is obtained through FSW, where filler material is not used, thus it would discard metallurgical issues.

In the present study, FSW welding process parameters have major impact on material flow [7]. These critical welding process parameters are studied through statistical modelling method by applying Response surface methodology (RSM) to co relate/calibrate welding parameters on weldment[8].The correlation between the vital welding process parameters, statistical model, design of experiments(DOE)Multiple response regression analysis, and analysis variance(ANOVA) are applied[9].Various statistical modelling methods related to friction stir and other metal joining methods were presented by Benyounis et.al[10]. Srinivasan Balaji et.al [11] derived optimum level of control factors to envisage output characteristics of AZ31B weld joints by adopting response surface methodology technique.

The control parameters in FSW welding, which are considered for notable contribution for achieving optimal values in physical properties of weld joints in this study are welding speed, Tool rotational speed, and applied axial force. The friction stir welded AA1100 with AA6061 aluminium alloys were studied by Mallieswaran et al. [12] in an effort to set up an experimental relation among process parameters and tensile properties.

Sudhagar et al., [13] studied Friction stir welding of aluminium 2024 alloy by multiple criterion decision making method. Considering various combinations of welding parameters in FSW for tool rotational speed, welding speed, tool tilt angle and shoulder diameter. Rajendran et al studied tensile strength of butt joints. [14] However, statistical methods and optimizing control factors for corrosion resistance and tensile strength by FS welding found insufficient.

Hence, the present study measure impact of FSW welding parameters for corrosion resistance and tensile strength of AZ31B alloy. These parameters are studied by using statistical analysis. In present work suitable experimental model was derived by using response surface methodology [15] with control variables tool rotational speed, welding speed, and axial force. To optimize the multi responses of statistical modelling, multi-objective desirability approach was also taken into consideration for this study.

2. Methods: Design of Experiments: (DOE)

Design of experiments is the method wherein involves performing series of systematic experiments to reach parametric optimisation of control variables of FSW. The input variables were purposefully altered to estimate the cause of significant differences in responses that are obtained in tests [8]. When these results are analysed, they assist in determining not only the proper situation but also the elements which affect the results as well as the interaction among process variables. Table: 1 presents essential factors of the FSW procedure, together with the relevant levels of those factors. These levels of parameters are determined via fundamental tests depending on the capabilities of the operation in order to achieve perfect welds as well as weld configuration. The central composite approach was utilized in the development of models in which the data point was positioned in middle. This method utilizes the data at midpoint of each edge and also taken three levels for each factor. Therefore, in order to assess the quadratic and two-way interactive influences of factors on weld joints, the central composite design permits a total of 31 investigational conditions, which are given in Table 2.

Table. 1. levels of FSW process and Prime factors

S. no	Parameter	Notation	Unit	Level				
				(-2)	(-1)	0	(+1)	(+2)
1	Tool rotational Speed	N	RPM	400	600	800	1000	1200
2	Welding Speed	S	mm/min	40	45	50	55	60
3	Tool tilt Angle	T	Degree	0	0.5	1	1.5	2
4	Axial Force	F	KN	6	8	10	12	14

Table 2. FSW experimental conditions

Experiment Number	Factor Coded Values				Actual Values			
	T	S	N	F	T	S	N	F
1	-1	1	1	1	0.5	55	1000	12
2	0	0	0	0	1	50	800	10
3	0	0	0	0	1	50	800	10
4	-1	-1	-1	-1	0.5	45	600	8
5	1	1	-1	1	1.5	55	600	12
6	2	0	0	0	2	50	800	10
7	1	1	1	-1	1.5	55	1000	8
8	1	-1	1	1	1.5	45	1000	12
9	-2	0	0	0	0	50	800	10
10	1	1	1	1	1.5	55	1000	12
11	-1	-1	-1	1	0.5	45	600	12
12	1	-1	1	-1	1.5	45	1000	8
13	0	0	0	0	1	50	800	10
14	-1	1	-1	-1	0.5	55	600	8
15	0	-2	0	0	1	40	800	10
16	0	2	0	0	1	60	800	10
17	-1	1	1	-1	0.5	55	1000	8
18	-1	-1	1	-1	0.5	45	1000	8
19	0	0	0	0	1	50	800	10
20	1	1	-1	-1	1.5	55	600	8
21	0	0	0	0	1	50	800	10
22	0	0	2	0	1	50	1200	10
23	0	0	0	0	1	50	800	10
24	0	0	0	0	1	50	800	10
25	0	0	0	-2	1	50	800	6
26	0	0	0	2	1	50	800	14
27	-1	1	-1	-1	0.5	55	600	8

Experiment Number	Factor Coded Values				Actual Values			
	T	S	N	F	T	S	N	F
28	0	0	-2	0	1	50	400	10
29	1	-1	-1	1	1.5	45	600	12
30	-1	-1	1	1	0.5	45	1000	12
31	1	-1	-1	-1	1.5	45	600	8

3. Experimentation & results:

In the Present work AZ31B Magnesium alloy of 6 mm thick plates of were used. Table 3 illustrates the AZ31B Alloy's chemical composition.

Table. 3. Alloy AZ31B composition

Element	Al	Zn	Mn	Cu	Si	Ni	Fe	Mg
% Weight Composition	2.904	0.996	0.324	0.049	0.032	0.002	0.004	95.689

In this work, AZ31B alloy plates of 230mm x 300mm x 6mm size were to carry out longitudinal welding experiments by FSW machine. Fig: A Illustrates the tool which was utilised for experimentation and its dimensions. Table 4 shows the various weld parameters operated under different conditions. Depicted obtained weldment by using FSW process in Fig. B. Then the samples are prepared from welded plates for further examination in the transverse direction. The microstructures of different zones in weld joints were examined by using M/s Leica make optical microscope. The study was carried out by Wire EDM (electro-discharge machine). The test specimens were prepared in accordance with ASTM B557M-15 standards/specifications [20]. The specimens were tested for ultimate tensile strengths of on universal testing machine. Vickers micro-hardness test was carried in accordance with ASTM E384 on INSTRON tensile testing machine. Potentio-dynamic polarization studies were performed on test specimens in aerated 3.5% NaCl solution, pH corrected to 10.0. Accordingly welded specimens were studied for corrosion resistance properties. Electrochemical system was used to study corrosion behaviour of the specimens; Consequently, experimentation resulted into positive corrosion potential in terms of Error (or less negative Error) which was less susceptible to corrosion.

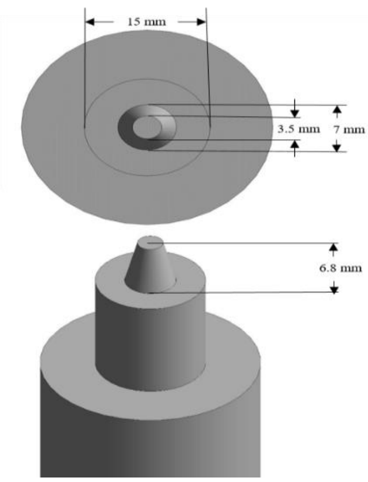

Fig. A Tool Profile

Fig. B Friction stir weldment

Simultaneously, Pitting corrosion in Mg alloys, is generally influenced by inter-metallic precipitates such as β- phase ($Mg_{17}Al1_2$, $Mg_{17}(AlZn)12$), Mg_2Si, AlMn. Galvanic couplings with matrix are formed with these precipitates. Local matrix distribution[21] initiated formation of corrosion.

Potentio-dynamic polarization testing results on weld joints were studied under various conditions is tabulated in Table 4. The results of pitting potentials obtained from potentio-dynamic polarization corrosion tests are interpreted from graph numbers 0-9 and A, these graphs represent pitting potential curves of corresponding models S1-S13.The less negative value of pitting potential of weld joint (i.e., more positive potential) are confirmed high resistant to corrosion. The results obtained for ultimate tensile strength (UTS) and pitting potentials (Epit) are tabulated in Table 4.

Table 4. FSW experimental conditions & Results

Experiment Number	Factor Coded values				Actual values				Corrosion Potential (mV)	Hardness (VHN)	Tensile Strength (MPa)
	T	S	N	F	T	S	N	F			
1	-1	1	1	1	0.5	55	1000	12	-1370	49	202
2	0	0	0	0	1	50	800	10	-1335	54	217
3	0	0	0	0	1	50	800	10	-1342	53	214
4	-1	-1	-1	-1	0.5	45	600	8	-1307	58	228
5	1	1	-1	1	1.5	55	600	12	-1314	57	226
6	2	0	0	0	2	50	800	10	-1335	54	217
7	1	1	1	-1	1.5	55	1000	8	-1377	48	199
8	1	-1	1	1	1.5	45	1000	12	-1370	49	204
9	-2	0	0	0	0	50	800	10	-1342	53	214
10	1	1	1	1	1.5	55	1000	12	-1363	50	205
11	-1	-1	-1	1	0.5	45	600	12	-1314	57	226
12	1	-1	1	-1	1.5	45	1000	8	-1377	48	199
13	0	0	0	0	1	50	800	10	-1328	55	220
14	-1	1	-1	-1	0.5	55	600	8	-1307	58	228
15	0	-2	0	0	1	40	800	10	-1335	54	217
16	0	2	0	0	1	60	800	10	-1328	55	220
17	-1	1	1	-1	0.5	55	1000	8	-1356	51	208
18	-1	-1	1	-1	0.5	45	1000	8	-1363	50	208
19	0	0	0	0	1	50	800	10	-1328	55	220
20	1	1	-1	-1	1.5	55	600	8	-1302	59	230
21	0	0	0	0	1	50	800	10	-1335	54	217
22	0	0	2	0	1	50	1200	10	-1405	44	188
23	0	0	0	0	1	50	800	10	-1335	54	217
24	0	0	0	0	1	50	800	10	-1328	55	220
25	0	0	0	-2	1	50	800	6	-1377	48	199
26	0	0	0	2	1	50	800	14	-1363	50	205
27	-1	1	-1	-1	0.5	55	600	8	-1314	57	226

28	0	0	-2	0	1	50	400	10	-1391	46	193
29	1	-1	-1	1	1.5	45	600	12	-1321	56	223
30	-1	-1	1	1	0.5	45	1000	12	-1328	55	220
31	1	-1	-1	-1	1.5	45	600	8	-1314	57	226

Response Surface modelling:

4.1 Effect of factors on ultimate tensile strength:

FSW welding parameters which are considered vital were studied, for their influence on responses using analysis of variance (ANOVA), as indicated in Table 5. The indicative values i.e probability (P-value) & ration of mean squares (F-value) from analysis of variance shows arithmetical significance and several other combinations among the weld factors.As per ANOVA analysis P- value for UTS represents < 0.05 for tool rotational speed, and for rotational speed F-value is high. Which shows tool rotational speed is the vital weld factor.As represented in main effect plots as shown in Fig. 2, rotational speed influenced on significant effect and response. Ultimate tensile strength(UTS) is effected with rise in tool rotational speed. Fig. 15 depicts optical micrographs of weldment produced under optimum welding parameters. β-phase distribution and size had greater influence on tensile strength and corrosion properties. The high ultimate tensile strength resulted at optimum welding conditions may due to fine grain size and even distribution of coherent β-phase[23]. Unlike coarsened β-phase particles, fine and evenly distributed β-phase precipitation occurred due to severe plastic deformation during FSW added more advantage in terms of enhancing the mechanical properties. If welding parameters are lower than optimum values, they cannot induce sufficient plastic deformation and heat input which could lead to formation of inefficient joining along with welding defects. Also higher values than optimum values can results in dissolution of precipitates due to higher heat input. As well as, extreme deformation results the formation of twins and increases dislocation density than critical value which is detrimental to the tensile strength. The microstructure of “stir zone” at optimum welding parameters visibly shown the fine grain size relatively compared to base metal and any other zones. As fine grain size takes part in improving tensile strength by increasing grain boundary area, the welding parameters tool rotational speed at 600 rpm, welding speed at 55 mm/min, and the maximum axial force of 8 kN enhanced the tensile strength.

Table5: UTS -Analysis of variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	14	2850.77	203.63	3.43	0.010
Linear	4	1093.96	273.49	4.61	0.011
T	1	6.18	6.18	0.10	0.751
S	1	14.97	14.97	0.25	0.622
N	1	1041.55	1041.55	17.56	0.001
F	1	1.37	1.37	0.02	0.881
Square	4	1166.85	291.71	4.92	0.009
T*T	1	19.75	19.75	0.33	0.572
S*S	1	71.33	71.33	1.20	0.289
N*N	1	835.67	835.67	14.09	0.002
F*F	1	184.04	184.04	3.10	0.097
2-Way Interaction	6	361.56	60.26	1.02	0.450
T*S	1	99.16	99.16	1.67	0.214
T*N	1	108.95	108.95	1.84	0.194
T*F	1	37.26	37.26	0.63	0.440
S*N	1	4.18	4.18	0.07	0.794

Source	DF	Adj SS	Adj MS	F-Value	P-Value
S*F	1	97.33	97.33	1.64	0.218
N*F	1	149.23	149.23	2.52	0.132
Error	16	949.10	59.32	---	---
Lack-of-Fit	9	916.24	101.80	21.69	0.000
Pure Error	7	32.86	4.69	---	---
Total	30	3799.87	---	---	---

*DF = Degrees of freedoms, Adj SS = Adjusted sum of squares, Adj MS = Adjusted mean squares

In other way, slope of inclination for tool tilt angle (Fig. 2) is indicating low, which indicates less influence on tensile strength relatively to tool rotational speed. Fig. 3 depicts interaction plot, which indicates that there is mere effect among weld parameters. The correlation among various prime factors and responses were established through regression analysis. Regression equation with reasonable degree is The R^2 94.42% and adjusted R^2 92.75% (1). Equation (1) is significant mathematical model suitably selected to further carry the analysis.

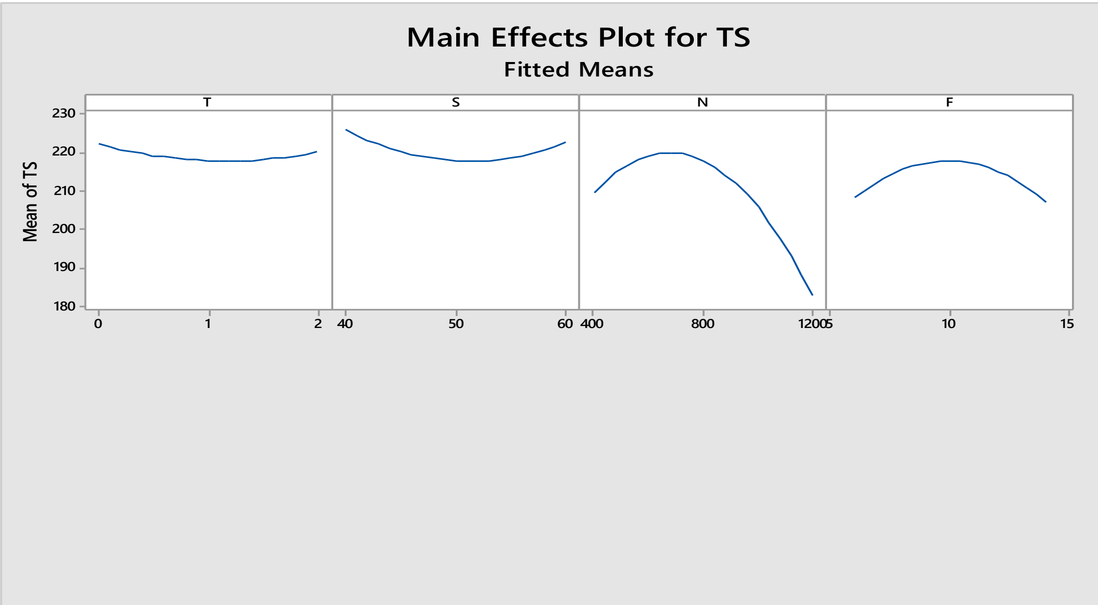

Fig. 2 Main effect plot for UTS

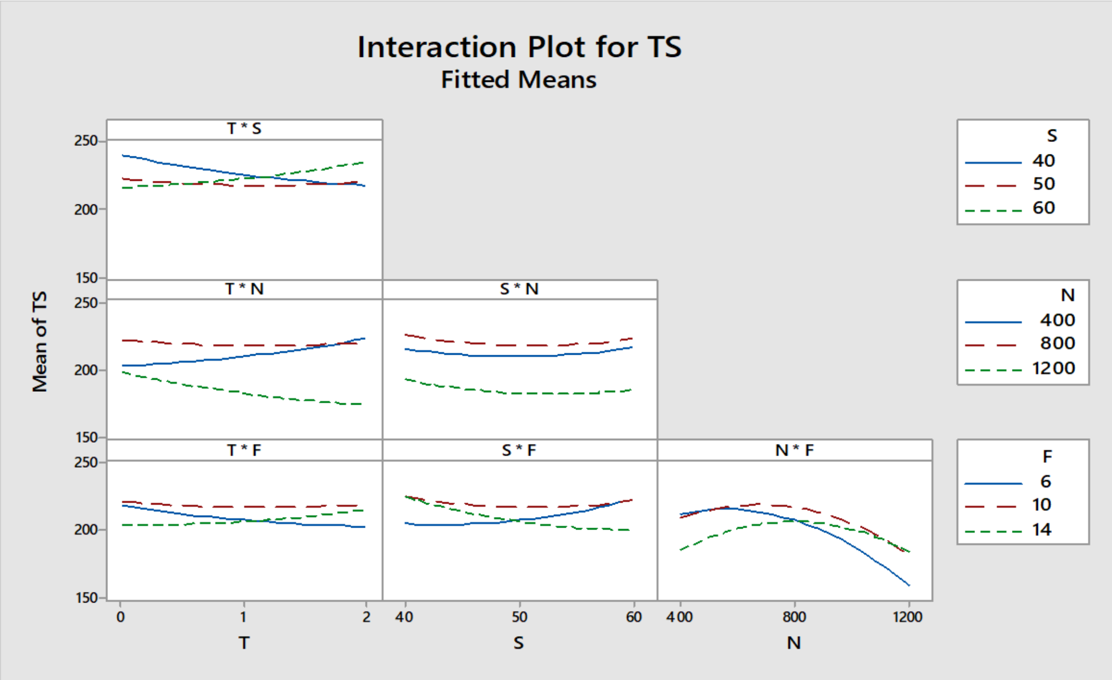

Fig. 3 Interaction plot for UTS

4.2 The Effect of factors upon corrosion resistance:

The effects of factors are remarkable on corrosion resistance parameters[25]. These parameters were analysed using ANOVA . In Table. 6 pitting potentials indicates > 0.05 for the factor rotational speed, and F-value is on higher side for rotational speed. Thus indicates rotational speed is vital factor. Fig. 4, represent pitting potentials (E_{pit}), where factors are graphically assessed. The graph shows corrosion resistance got reduced with increase in rotational speed. Slope in Fig. 4, indicates rotational speed is influencing corrosion resistance. Besides tool tilt angle shows mere effect on corrosion resistance. It is evident fine grain size in Fig 15, which is categorically influenced in enhancing corrosion resistance of weldment by relieving the mismatch between matrix and intermetallics [Ref. 22]. During FSW, the severe plastic deformation causes the formation of sub-grain boundaries, and even distribution of intermetallic precipitates. However, the optimum welding parameters results better corrosion resistance than other welding conditions (From Table 4). To analyse the impact of weld factors for efficiency and interactions on corrosion resistance, suitable mathematical model was derived. The R^2 94.97% and adjusted R^2 92.39%(2) of developed model indicates significant. Equation (2) is significant mathematical model suitably selected to further carry the analysis.

Table. 6: Pit Potential E_{pit} - Analysis of variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	14	16564.5	1183.18	3.49	0.009
Linear	4	6648.1	1662.02	4.91	0.009
T	1	32.4	32.38	0.10	0.761
S	1	38.8	38.75	0.11	0.740
N	1	6393.8	6393.79	18.88	0.001
F	1	11.2	11.23	0.03	0.858
Square	4	6570.6	1642.65	4.85	0.009
T*T	1	107.6	107.65	0.32	0.581
S*S	1	388.8	388.63	1.15	0.300
N*N	1	4761.2	4761.24	14.06	0.002

F*F	1	1001.6	1001.59	2.96	0.105
2-Way Interaction	6	1965.5	327.59	0.97	0.478
T*S	1	546.0	545.96	1.61	0.222
T*N	1	546.0	545.96	1.61	0.222
T*F	1	133.3	133.32	0.39	0.539
S*N	1	6.5	6.54	0.02	0.891
S*F	1	565.0	565.01	1.67	0.215
N*F	1	921.2	921.23	2.72	0.199
Error	16	5419.4	338.71	---	---
Lack-of-Fit	9	5226.9	580.77	21.12	0.000
Pure Error	7	192.5	27.50	---	---
Total	30	21983.9	---	---	---

*DF = Degrees of freedom, Adj SS = Adjusted sum of squares, Adj MS = Adjusted mean squares

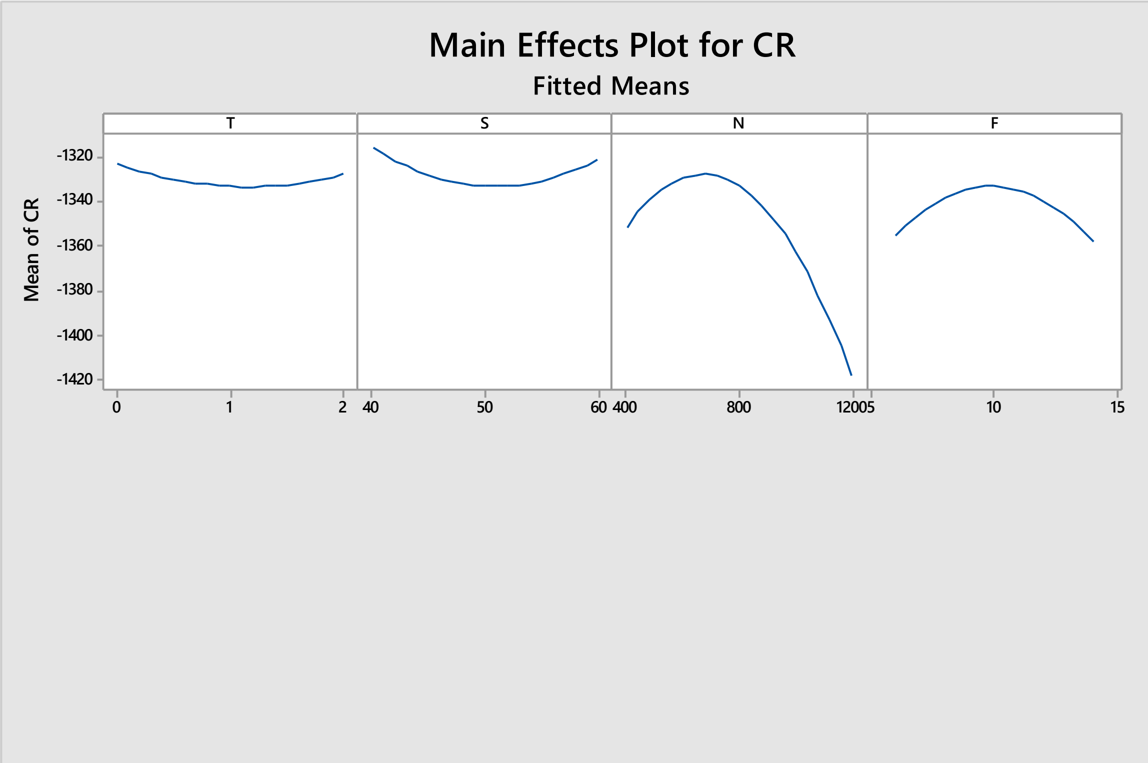

Fig. 4 Main effect plot for CR

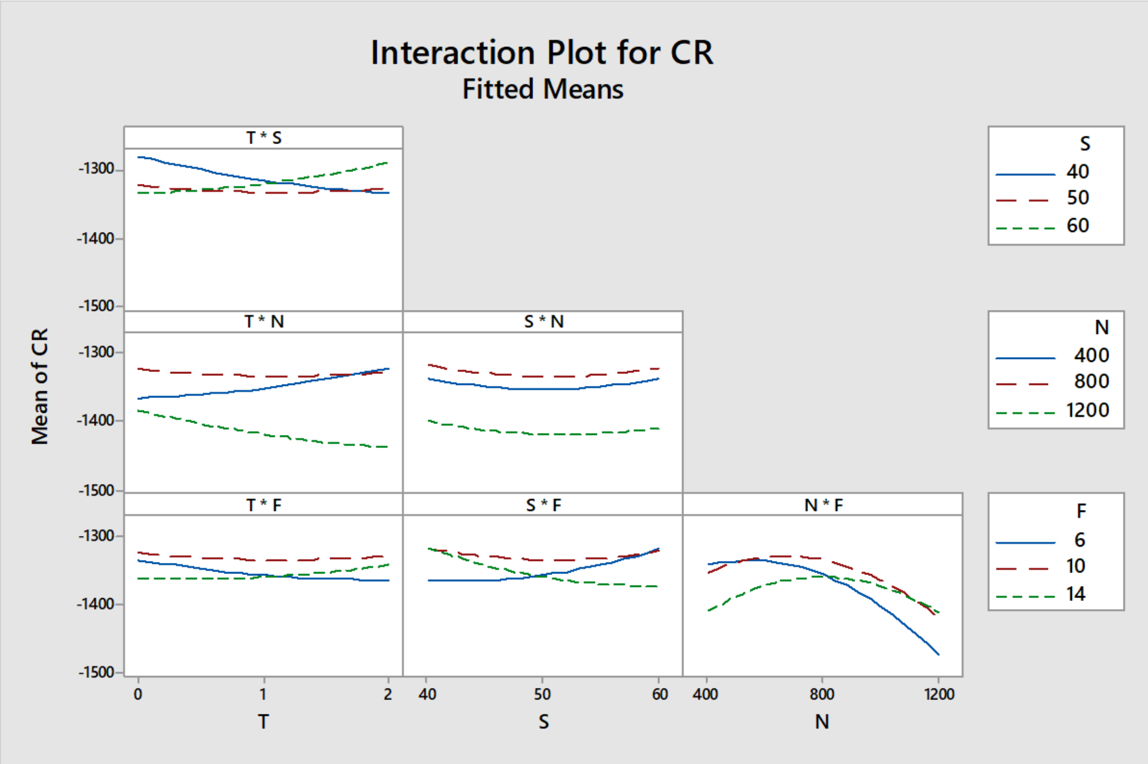

Fig. 5 Interaction plot for CR

4.

2 Effect of factors upon Hardness (VHN):

The effects of factors are remarkable on hardness. These parameters were analysed using ANOVA. In Table: 7 hardness represent < 0.05 for the factor rotational speed, and F-value is on higher side for rotational speed. Thus indicates rotational speed is vital factor. Graphical representation in Fig. 6 depicts plots of main effects on hardness. Slope in Fig. 6, indicates rotational speed is influencing value of hardness. Hardness got reduced while increase in rotational speed. Besides, tool tilt angle shows less effect on hardness (Fig. 6). From Table 4, the higher values than optimum welding parameters shown lower hardness values may be due to formation of precipitate free zones and brittle networks near grain boundaries. The dissolution of strengthening precipitates mostly influences the above phenomena. And also lower values than optimum welding parameters often leads to improper material flow and end up with lower hardness values. The optimum parameters resulted in higher hardness values for even distribution of intermetallic precipitate and fine grains. The impact of weld parameters, shown in Fig. 7, depicts there is no significant effect among the welding parameters. To analyse efficiency of input processing parameters and impact on hardness, a suitable mathematical model was derived. The R^2 96.25% and adjusted R^2 93.12%(3) of developed model indicates significant. Equation (3) is significant mathematical model suitably selected to further carry the analysis.

Table. 7: Analysis of variance upon Hardness

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	14	340.952	24.354	3.51	0.009
Linear	4	136.689	34.172	4.92	0.009
T	1	0.548	0.548	0.08	0.782
S	1	0.720	0.720	0.10	0.752
N	1	131.420	131.420	18.94	0.000
F	1	0.295	0.295	0.04	0.839

Square	4	133.921	133.480	18.94	0.000
T*T	1	2.231	2.231	0.32	0.579
S*S	1	7.996	7.996	1.15	0.299
N*N	1	96.943	96.943	13.97	0.002
F*F	1	20.337	20.337	2.93	0.106
2-Way Interaction	6	41.980	6.997	1.01	0.454
T*S	1	11.736	11.736	1.69	0.212
T*N	1	11.736	11.736	1.69	0.212
T*F	1	2.537	2.537	0.37	0.554
S*N	1	0.172	0.172	0.02	0.877
S*F	1	12.065	12.065	1.74	0.206
N*F	1	19.480	19.480	2.81	0.113
Error	16	111.048	6.941	---	---
Lack-of-Fit	9	107.120	11.902	21.21	0.000
Pure Error	7	3.929	0.561	---	---
Total	30	452.000	---	---	---

*DF = Degrees of freedoms, Adj SS = Adjusted sum of squares, Adj MS = Adjusted mean squares

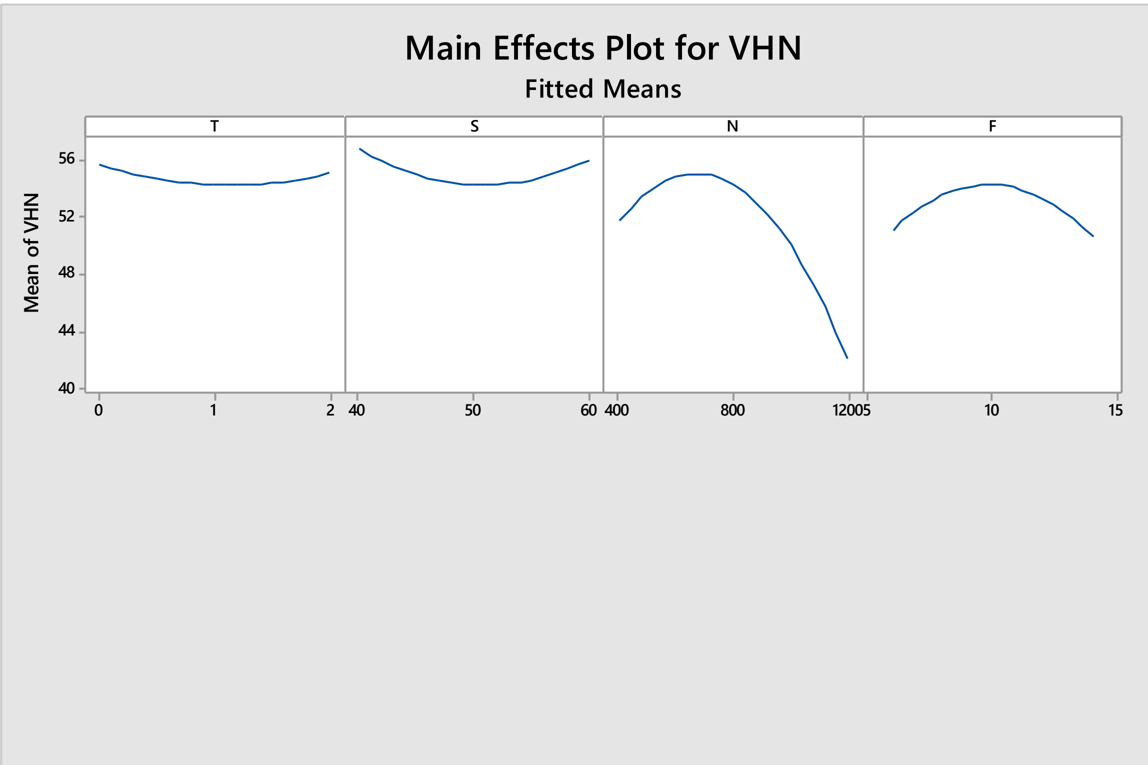

Fig. 6 Main effect plot for VHN

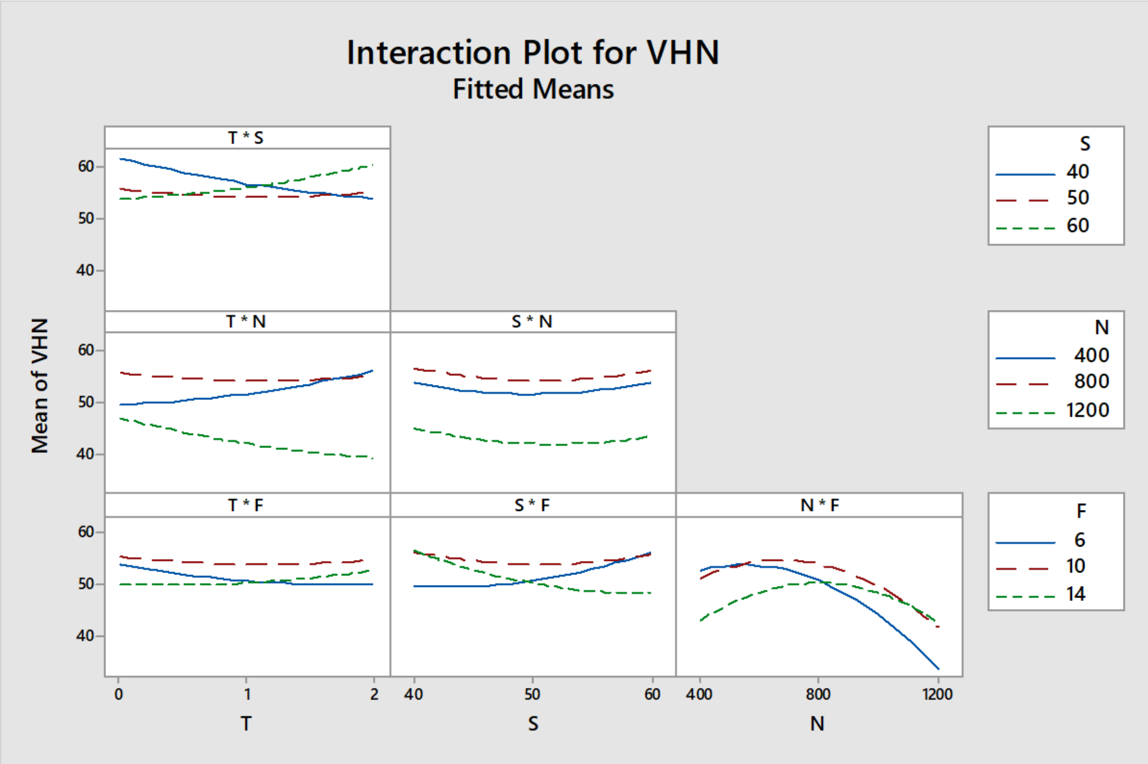

Fig. 7 Interaction plot for VHN

5. Multi-objective optimization using desirability approach

CONTOUR PLOTS AND RESPONSE GRAPHS

Contour plots has pivotal role in examining and analysing response surface. With generation of contour plots by using suitable software, to study response surface analysis, the optimum plots would be located and specified with justifiable accuracy. Shape of the surface is characterised by software programming. According to contour patterns for circular shaped, it suggests factor effects are independent. Elliptical contours predicts about interactions of weld factors. Response surfaces have been derived for the proposed model By taking two parameters in the mid position and two parameters in the 'X' and 'Y' axis as well as the response in the 'Z' axis , Response surfaces was derived for the proposed model. The plots in response surfaces indicates optimal.

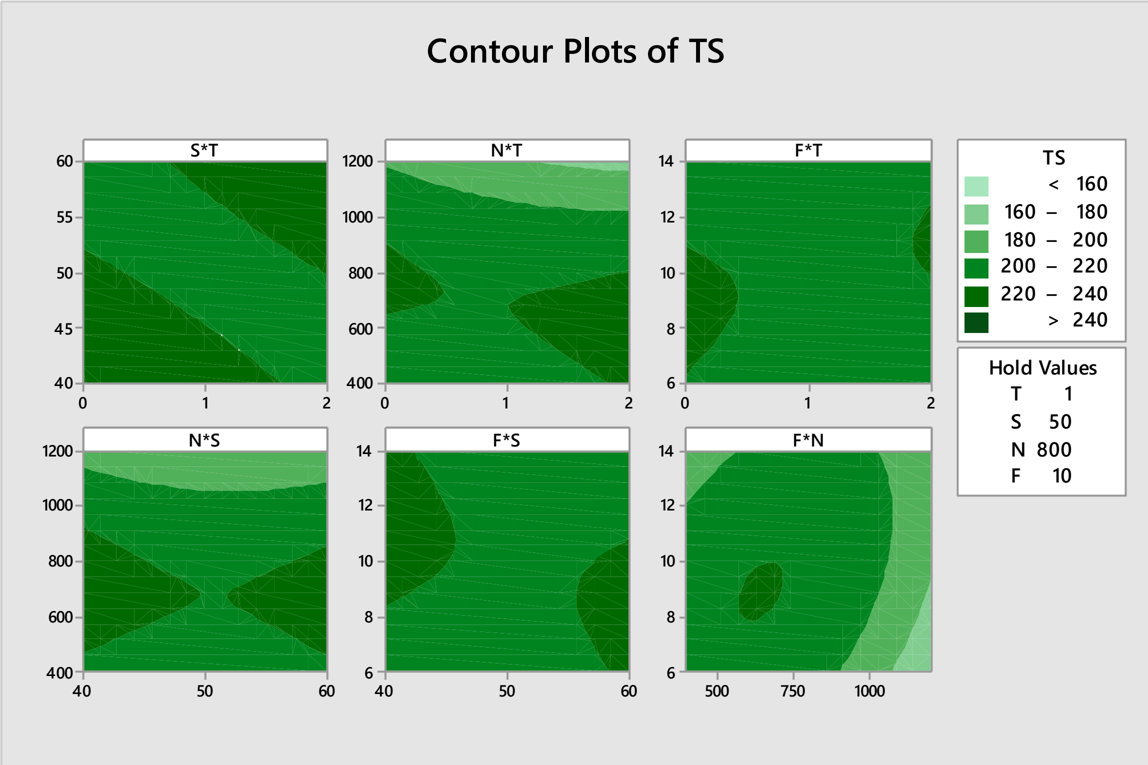

Fig. 8 contour plots of Tensile strength

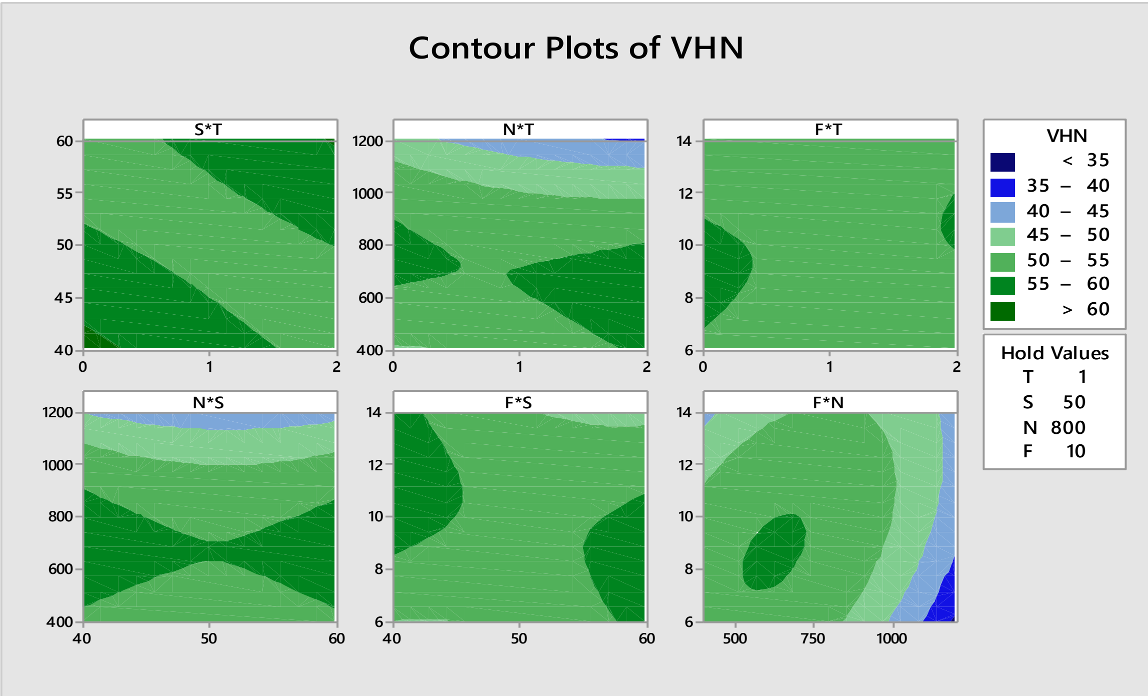

Fig. 9 contour plots of VHN

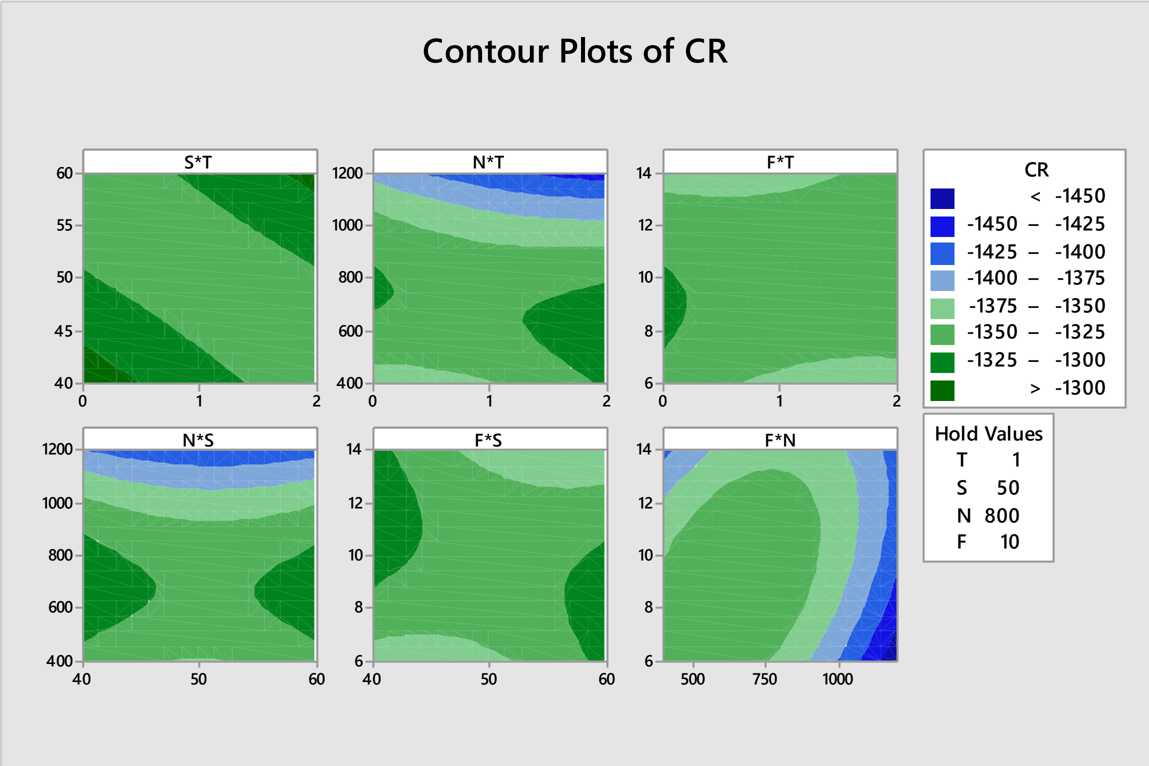

Fig. 10 contour plots of Corrosion resistance

Response Surface & Contour Plots Analysis.

Figure: 11-13 Represents Three-Dimensional Response Surface Plots For Response Tensile Strength, Corrosion Resistance And Hardness Obtained From Regression Equations. The Optimum Value Is Exhibited By Apex Of Response Surfaces.

Following Inferences Can Be Interpreted From Contour Plots And Response Surfaces. The Optimal Tensile Strength Of 228.091mpa, Optimal Corrosion Resistance Of -1307.08mv And Optimal Hardness Of 58.158vhn Was Obtained At The Optimal Combination Of 1.5 Tool Tilt Angle, 55mm/Min Welding Speed, 600rpm Rotational Speed And 8 Kn Axial Force

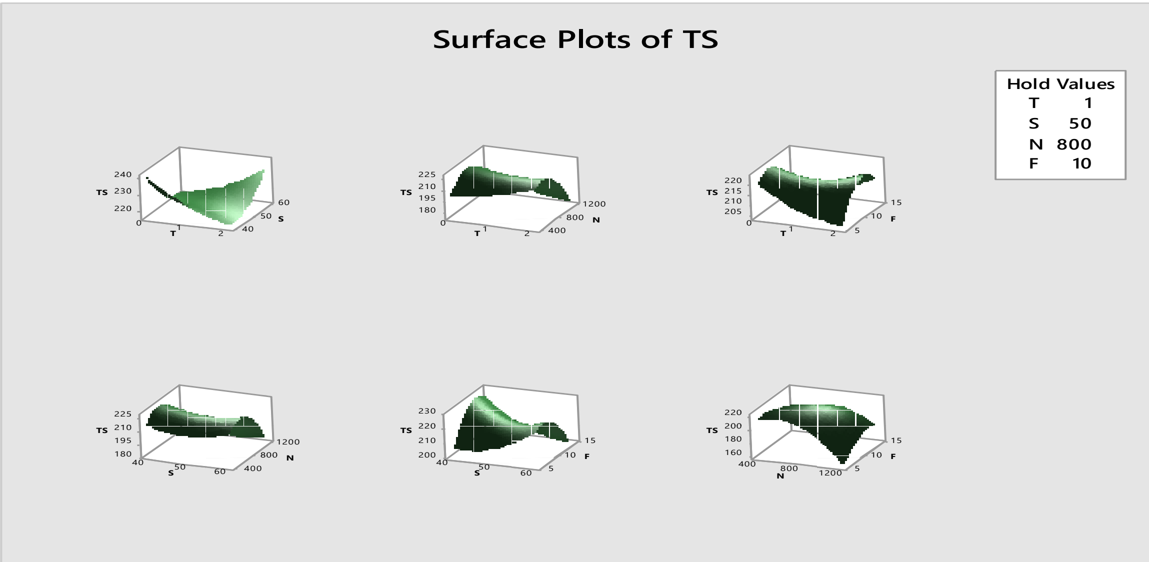

Fig. 11 surface plots of TS

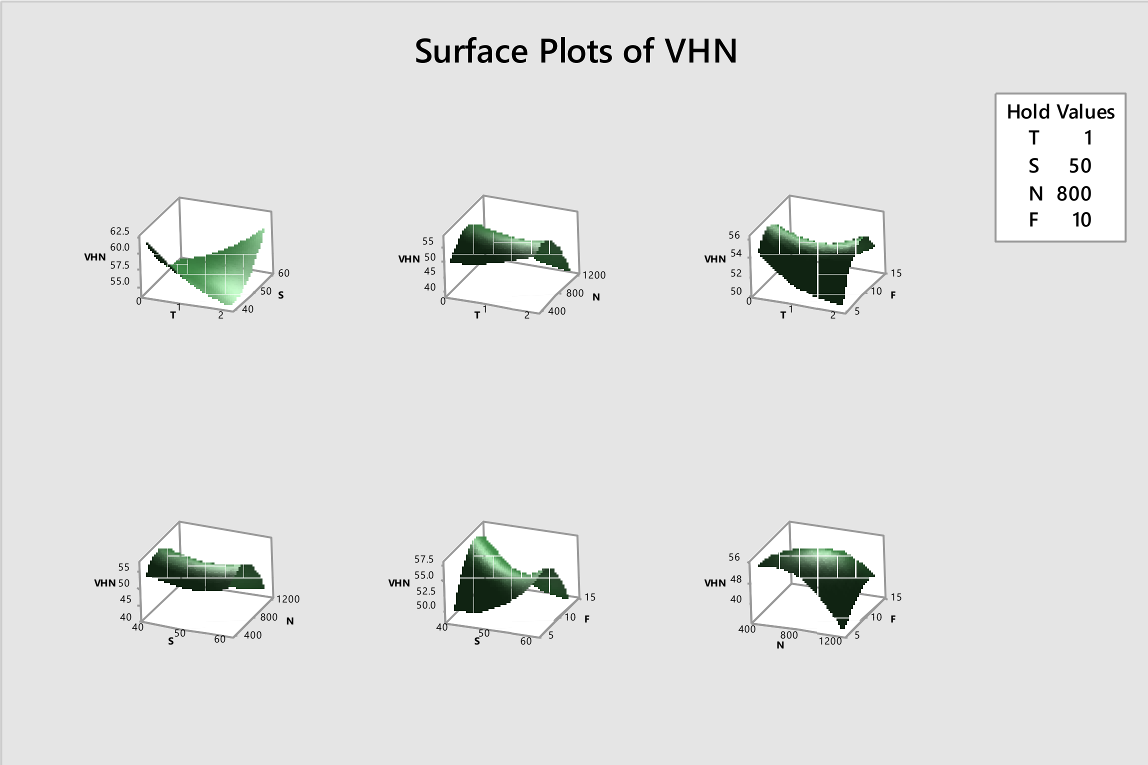

Fig. 12 surface plots of VHN

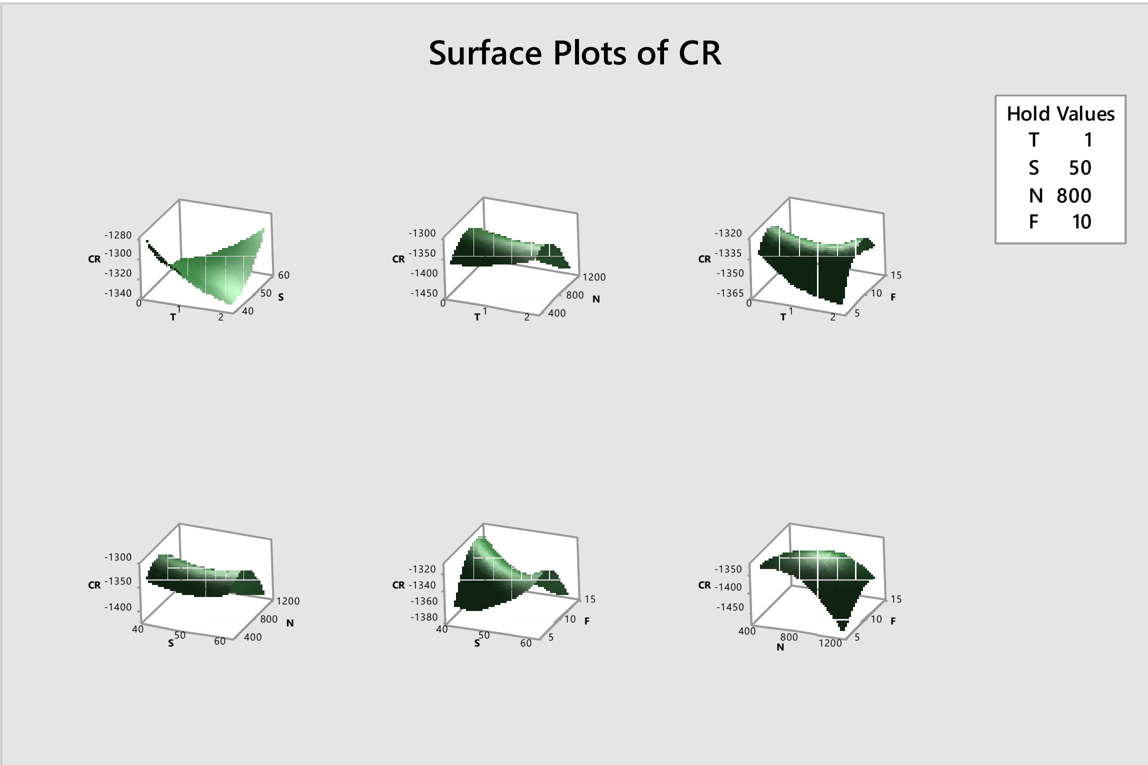

Fig. 13 surface plots of CR

In the present day welding technology, selection of suitable operating parameters has been a herculean job. Welding parameters are usually assessed through referring manuals and handbooks which later resulted into non-optimal parameters. Optimal welding parameters can be effectively derived by various input combinations. Accordingly, formidable optimization structure is specified for welding parameters. Subsequently correlated and optimized with desirability approach. The main objective functions deduced from the regression analysis are detailed in equations 1, 2 and 3.

Regression Equation in Un-coded Units

TS = 226 - 54.0 T - 4.48 S + 0.155 N + 17.6 F + 3.33 T*T + 0.0633 S*S - 0.000135 N*N - 0.636 F*F + 1.037 T*S - 0.0272 T*N + 1.62 T*F - 0.00053 S*N - 0.262 S*F + 0.00812 N*F

CR = -1302 - 122 T - 10.6 S + 0.326 N + 41.7 F + 7.8 T*T + 0.148 S*S - 0.000323 N*N - 1.483 F*F + 2.43 T*S - 0.0608 T*N + 3.07 T*F - 0.00067 S*N - 0.632 S*F + 0.0202 N*F

VHN = 58.0 - 17.5 T - 1.50 S + 0.0468 N + 6.01 F + 1.12 T*T + 0.0212 S*S - 0.000046 N*N - 0.211 F*F + 0.357 T*S - 0.00892 T*N + 0.424 T*F - 0.000108 S*N - 0.0924 S*F + 0.00293 N*F

Optimization Plot

Variable Values

Variable	Values
T	1.5
S	55
N	600
F	8

Solution

Solution	T	S	N	F	TS Fit	VHN Fit	CR Fit	Composite Desirability
1	1.5	55	600	8	228.091	58.1585	-1307.08	0.949705

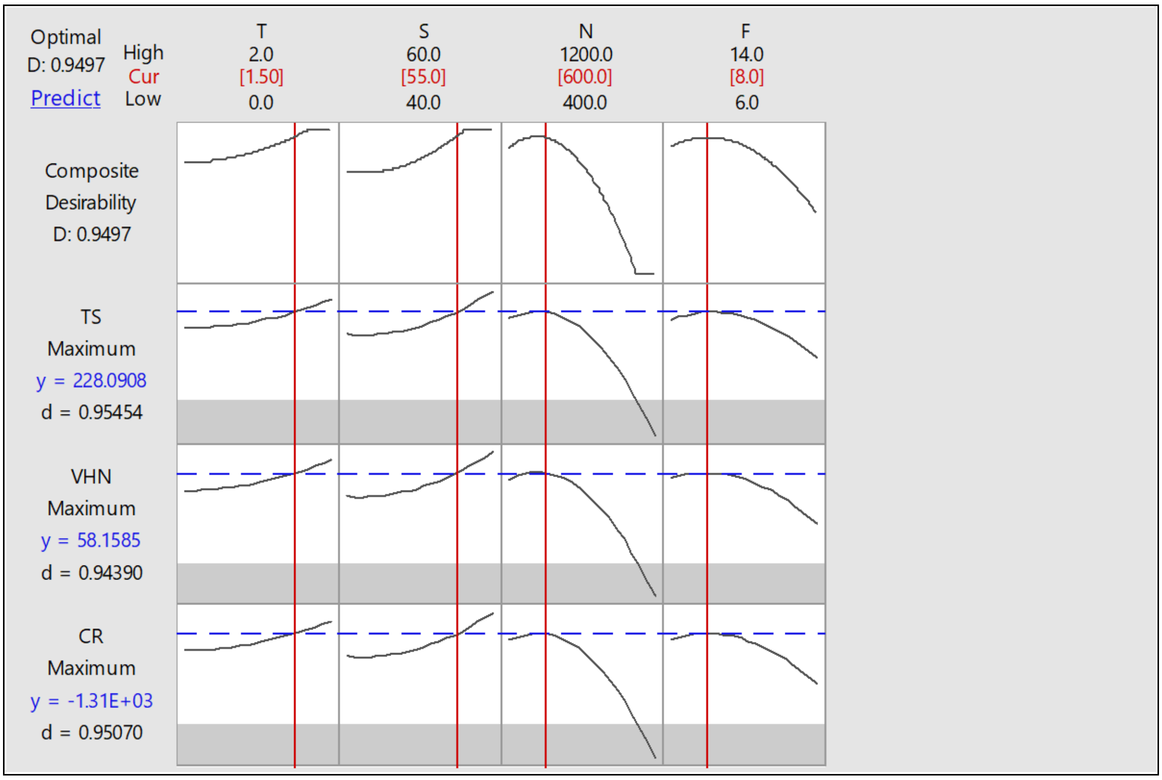

Fig. 14 response optimizer plot

The objective of desirability approach method was used to solve the various functions. MINITAB response optimizer toolbox was imparted for this work. The optimal value of tensile strength i.e 228.091 Mpa, Corrosion resistance of -1307.08 mV and hardness of 58.158VHN were derived at the optimal combinations of 1.5° tool tilt angle, 55 mm/min welding speed, 600 rpm rotational speed and 8 kN axial force. It clearly indicates from micrographs (Fig. 15), tensile strength at optimum welding conditions (i.e., T= 1.5, S = 55 mm/min, N = 1600 rpm, and F = 8 kN) is purely associated with dynamic recrystallisation in plastic deformation state while welding. The resistance to corrosion of welds is on higher side by adopting optimal welding conditions in accordance with relatively fine grain size in comparison to welds operated in various other combinations.

As the processing of FSW involves mechanical deformation and frictional heating, the properties like grain size, texture, dislocation density, twins influences the corrosion behaviour of weldment. The formation of MgO film on surface during passivation, creates tension between MgO film and Mg substrate due to mismatch in free volume. This tension facilitates cracking and results instable protective film which leads to low corrosion resistance. Fine grain microstructure is likely to reduce the tension by supplying porosity via vacancy supply from grain boundaries. This, in turn, minimizes MgO layer cracking and increases corrosion resistance [Ref. 22].

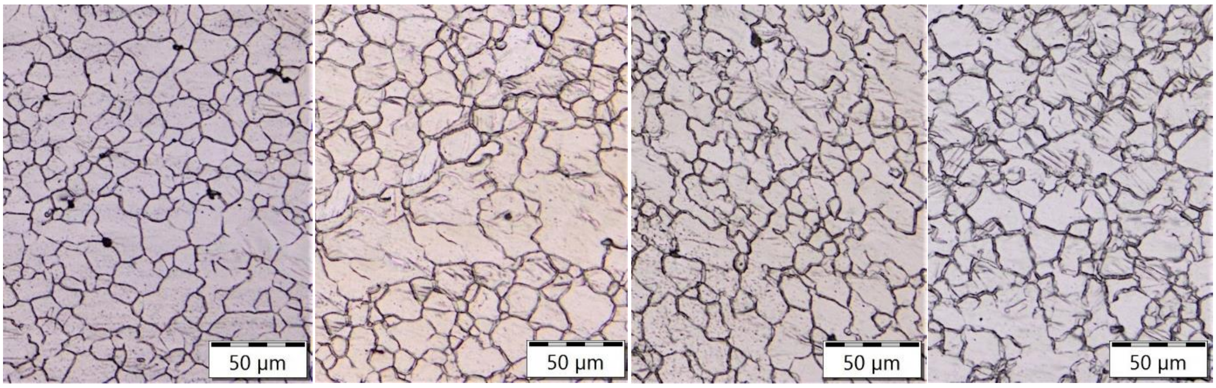

Fig.15. Microstructure of AZ31B FSW weld a) BM, b) HAZ, c) TMAZ, d) WZ

The following figure (Fig.15) shows fine grain size compared to base metal and Ecorr values of both zones (Fig. 16) evidently proves the importance of parameters on corrosion behaviour. At optimum welding conditions (i.e., T= 1.5, S= 55 mm/min, N= 1600 rpm, and F= 8 kN) better results are obtained in UTS, hardness and corrosion resistance compared to other welding conditions. The welding conditions higher than the optimum values resulted inferior values may be due to increased dislocation density than critical value which increases twins and other defects. These defects acts as precursors to the corrosion attack and accelerates the dissolution of surrounding matrix. And moreover, these higher parameters might result in the dissolution of precipitates (usually β-phase), which functions as anodic barrier when present in higher volume fraction. This also lowers the resistance to corrosion. The welding conditions lower than optimum conditions also shown lower mechanical and corrosion properties may be due to improper material flow and insufficient heating.

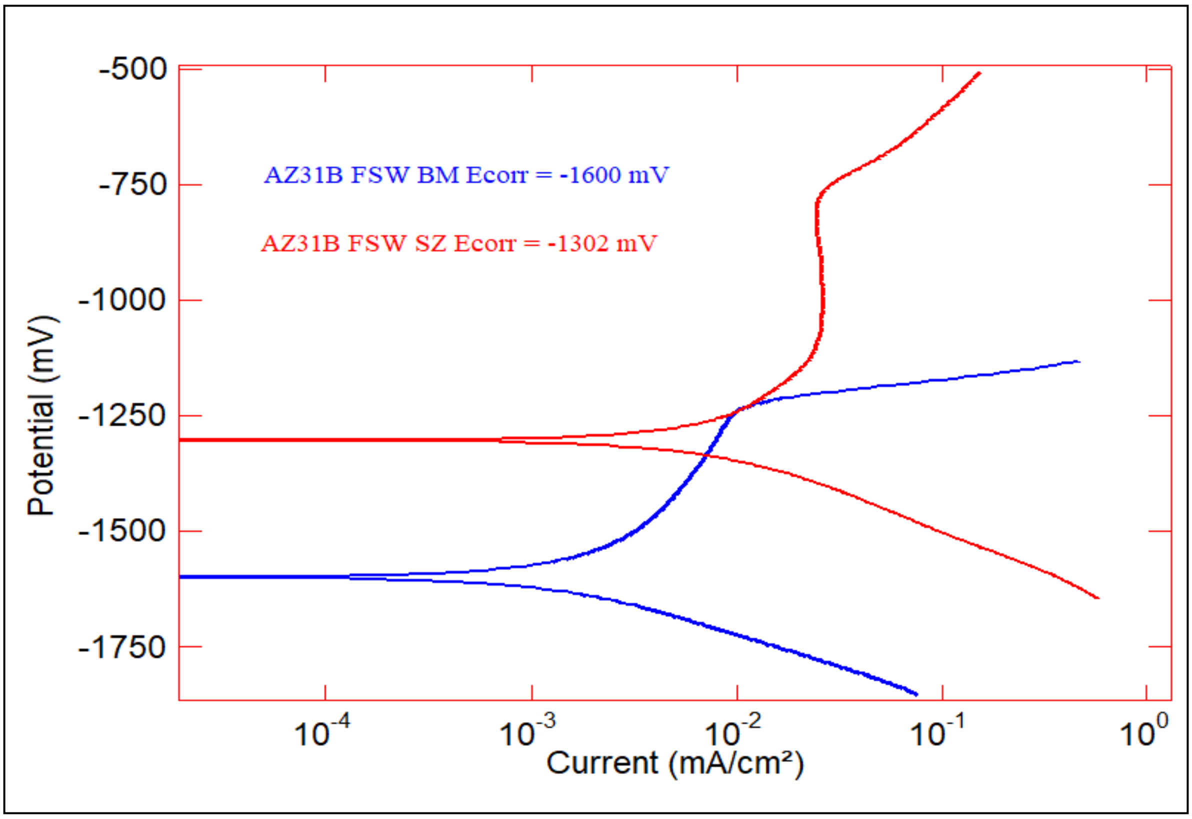

Fig.16. Potentio-dynamic polarization curves of AZ31B FSW weld, BM and SZ

The experimentation validation was carried out to understand practical optimal machining factors. Which are determined (T= 1.5°, S = 55 mm/min, N = 1600 rpm, and F = 8 kN) for the tensile strength, corrosion resistance and hardness. Confirmed weld runs for the following vital factors tensile strength, corrosion resistance and hardness are shown in Table 7. The validation error among projected and confirmed weld runs of prime factors i.e tensile strength, corrosion resistance and hardness are 3.189%, 2.613% and 3.863%.

Table. 7 Validation of results

Responses	Tool tilt Angle	Welding Speed mm/min	Rotational Speed RPM	Axial Force KN	Experimental Value	Desirability Approach	Validation Error (%)
Tensile Strength UTS (Mpa)	1.5	55	600	8	727.382	228.091	3.189
Corrosion Resistance CR (mV)					3415.400	-1307.08	2.613
Hardness VHN					224.664	58.158	3.863

6.

Conclusion:

A strategic method is developed an derived to analyse optimal approach on FSW (friction stir welding) weld parameters. This method has been successfully executed using RSM and desirability approach methodology. The significant affect of FSW process on responses were explained through analysis of variance and main plot graphs. Considerable regression modelling was also executed through response surface method in

Minitab. Based upon the results following imperative conclusions are listed below.

1. Rotation speed is most vital factor in influencing ultimate tensile strength, corrosion resistance and hardness of AZ31BMg alloy welded by friction stir welding. With increase in tool rotational speed ultimate tensile strength is increased. However, corrosion resistance got reduced with rise in rotational speed.
2. The derived regression equations developed for tensile strength, corrosion resistance and hardness are R^2 94.42%, R^2 94.97% and R^2 96.25%, respectively, The coefficients derived are significant in obtaining the objective of study for FSW.
3. The optimal values of tensile strength 228.091 MPa, corrosion resistance -1307.08 mV and hardness 58.158 VHN were obtained at optimal combination of 1.5° tool tilt angle, 55 mm/min welding speed, 600 rpm rotational speed and 8 kN axial force.
4. The validation error for welding parameters tensile strength, corrosion resistance and hardness are 3.189%, 2.189% and 1.613% respectively for predicted results and confirmed results, This is very much indicative in obtaining optimal weld joint without weld defect, better tensile strength and corrosion resistance.
5. The weld pool of Magnesium alloy AZ31B is greatly influenced by process parameters, which has reasonable impact on its mechanical properties. Altering and involving other process parameters with other statistical methodology can be opted to further evaluate optimisation of weldment characters.

Future work:

6. The material characteristics of AZ31B Mg alloy is greatly influences by parameters of the process, and it has a considerable influence on the mechanical characteristics of the weld joints. It is possible to alter the process parameters and conduct additional research using the same methodology.
7. Experiments in a larger range of process parameters can be conducted to develop an empirical relationship between the process parameter and the responses.
8. The same research can be done with various other alloys.

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References:

[1] "Review on friction stir welding of Magnesium alloys",Kulwant Singh, Gurbhinder Singh, Harmeet Singh-Journal of Magnesium and alloys 6 (2018) 399-416

[2] "Influence of tool pin profile and welding parameter on Tensile strength of Magnesium alloy AZ91 during FSW", Nikul Patel, K.D. Bhatt, Vishal Mehta-procedia technology 23(2016) 558-565

[3] "Influence of tool pin profile and rotational speed on the formation of friction stir welding zone in AZ31 Magnesium alloy", Dr.S.Ugender-Journal of Magnesium and Alloys 6(2018) 205-213

[4] "Friction-based welding processes: friction welding and friction stir welding", Dipen Kumar Rajak, Durgesh D. Pagar et al.

[5] " Influence of tool material and rotational speed on mechanical properties of friction stir welded AZ31BBMagnesium alloy", Ugender Singarapu, Kumar adepu, Somi Reddy- Journal of Magnesium and alloys 3 (2015) 335-344

[6] "Welding and processing of metallic materials by using friction stir technique" : A review Mostafa M. El-Sayeda , A.Y. Shashb,c,∗ , M. Abd-Raboub,d , Mahmoud G. ElSherbiny

[7] K.S.V.Kumar,S.V,Kailas,Mater.Sci.Eng.:A 485(1-2) (2008) 367-374

[8] Montgomery, Douglas C. Design and analysis of experiments. John wiley & sons, 2017.

[9] "Characterisation of Mechanical properties and microstructural analysis of friction stir welded AZ31BMg alloy through optimized process parameters", Sevvel P, Jaiganesh V

[10] Benyounis KY and Olabi AG. Optimization of different welding processes using statistical and numerical approaches—a reference guide. Adv Eng Softw 2008; 39(6): 483–496.

[11] Balaji, S., & Mahapatra, M. M. Experimental study and modeling of friction stir welding process to produce optimized AA2219 butt welds for

aerospace application. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, (2013); 227(1), 132-143.

[12] Mallieswaran, K., R. Padmanabhan, and V. Balasubramanian. "Friction stir welding parameters optimization for tailored welded blank sheets of AA1100 with AA6061 dissimilar alloy using response surface methodology." Advances in Materials and Processing Technologies 4, no. 1 (2018): 142-157.

[13] Sudhagar, S., M. Sakthivel, Prince J. Mathew, and S. Ajith Arul Daniel. "A multi criteria decision making approach for process improvement in friction stir welding of aluminium alloy." Measurement 108 (2017): 1-8.

[14] Rajendran, C., K. Srinivasan, V. Balasubramanian, H. Balaji, and P. Selvaraj. "Identifying the combination of friction stir welding parameters to attain maximum strength of AA2014-T6 aluminum alloy joints." Advances in Materials and Processing Technologies 4, no. 1 (2018): 100-119.

[15] Myers, Raymond H., Douglas C. Montgomery, and Christine M. Anderson-Cook. Response surface methodology: process and product optimization using designed experiments. John Wiley & Sons, 2016.

[16] "The Response Surface Methdology thesis paper", Indiana University South Bend

[17] R.S.Mishra , Z.Y.Ma, Mater.sci.Eng.R.Rep.50(2005) 1-78

[18] "A review paper on Friction Stir Welding Process Parameters", by Hira SinghPending

[19] "Micro structural changes and mechanical properties of friction stir processed extruded AZ31BMg alloy", S.Ramesh Babu, V. S. Senthil Kumar, G.Madhusudana Reddy, L. Karoonamurthy.

[20] ASTM International Standard B557M–15. Standard test methods for tension testing Wrought and cast aluminium- magnesium alloy products. ASTM, International; 2015.

[21] "Selection of FSW tool pin profile , shoulder diameter and material for joining AZ31B Magnesium alloy", G. Padmanaban, V. Balasubramanian

[22] Liao, J., Hotta, M., & Yamamoto, N. (2012). Corrosion behaviour of fine-grained AZ31B magnesium alloy. Corrosion Science, 61, 208-214.

[23] IOP Conf. Series: Materials Science and Engineering 870 (2020) 012141 IOP Publishing doi:10.1088/1757-899X/870/1/012141

*[24] Experimental and numerical analysis of friction stir welding: a review. IOP publishing. 2022 Eng. Res. Express **4** 032004**DOI** 10.1088/2631-8695/ac7f1e.*

[25] Additive manufacturing of magnesium and its alloys: process-formability-microstructure-performance relationship and underlying mechanism. IOP Publishing Ltd on behalf of the IMMT. Shang Sui et al 2023 Int. J. Extrem. Manuf. 5 042009