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Multi Response Optimization TIG welding parameters for dissimilar weld of MONEL 400 and AISI 304 using RSM

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***Abstract**: In this experimental study, attempts have been made to model and optimize welding process parameters for welding dissimilar weld of MONEL 400 and AISI 304 based on Response Surface Methodology (RSM) by using statistical software, Design Expert (DX-6). Five independent input parameters, viz., welding current, V grove angle of joint, filler rod material, filler rod diameter and welding speed were performed to explore the influence on hardness and fatigue strength of joint. The regression equation, and ANOVA was developed using the experimental data and graphs were plotted to investigate the effect of process variables on response characteristics. Optimal setting for multi response characteristics means for both hardness and fatigue strength of welding joint are 124 amp welding current, 35^0 joint angle, 0.52 filler rod diameter, MONEL 400 filler rod and 3.40 mm/sec welding speed.*

***Keywords**: Dissimilar Weld, MONEL 400, AISI 304, RSM, Multi Response Optimization*

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I. Introduction

Monel-400 is a nickel-based alloy that contains 20-29 percent copper, small amount of iron, manganese, silicon and carbon and rest nickel. It has high strength, good corrosion resistance, and weldability. Therefore, it has many applications like chemical processing equipment, marine fixtures and fasteners, boiler feed water heaters and other heat exchangers etc. Types 304 stainless steel is the most adaptable and commonly used due to corrosion oxidation resistance at low cost.

Srirangan, and Paulraj (2016) focuses on the multi-objective optimization using grey relational analysis for Incoloy 800HT welded with tungsten inert arc welding process with N82 filler wire of diameter 1.2 mm. Grey relational analysis was applied to optimize the input parameters simultaneously considering multiple output variables. The optimal parameters combination was determined as welding current at 110 A, voltage at 10 V and welding speed at 1.5 mm/s. **Cunha et al. (2016)** Welding tests were conducted with the pulsed TIG process in order to investigate the RMS and mean welding current effect. The geometric aspects of the weld beads obtained, such as their width and penetration, and the welded area were analyzed. It was found that the weld penetration behavior is closely related with mean welding current, while the weld width with the RMS value of the welding current. **Abid et al. (2013)** the effect of different tip angles (30^0, 60^0, 90^0 and 120^0) on the arc and weld pool behaviour is analyzed in 2 mm and 5 mm arc lengths with tilted (70^0) torch. The arc temperature at the tungsten electrode is found the maximum with sharp tip and decreases as the tip angle increases. The arc temperature on the anode (workpiece) surface becomes concentrated with increase in tip angle. The weld pool shape is observed wide and shallow in sharp and narrow and deep in large tip angle. **Marcelino et al. (2011)** the effect of Gas Tungsten Arc Welding (GTAW) repairs on the axial fatigue strength of an AISI 4130 steel welded joint used in airframe critical to the flight-safety was investigated. The fatigue strength decreased with the number of GTAW repairs, and was related to microstructural and microhardness changes, as well as residual stress field and weld profile geometry factors, which gave origin to high stress concentration at the weld toe. **Arivazhagan et al. (2011)** the investigations carried out to study the microstructure and mechanical properties of AISI 304 stainless steel and AISI 4140 low alloy steel joints by Gas Tungsten Arc Welding (GTAW), Electron Beam Welding (EBW) and Friction Welding (FRW). For each of the weldments, detailed analysis was conducted on the phase composition, microstructure characteristics and mechanical properties. The results of the analysis shows that the joint made by EBW has the highest tensile strength (681 MPa) than the joint made by GTAW (635 Mpa) and FRW (494 Mpa). From the fractographs, it could be observed that the ductility of the EBW and GTA weldment were higher with an elongation of 32% and 25% respectively when compared with friction weldment (19%). Moreover, the impact strength of weldment made by GTAW is higher compared to EBW and FRW.

Monel 400 and AISI 304 have common applications in fabrication of heat exchangers, evaporators, piping and vessels in petrochemical. However welding of dissimilar metals is difficult due to the differences in chemical compositions and thermal expansion coefficients. The objective of this work is to multi response optimization of TIG welding parameters for welding of dissimilar weld i.e. Monel 400 and AISI 304 for maximize the hardness and fatigue strength of welded joint.

II. Experimentations

Various input process parameters varied during the experimentation are welding current of TIG welding, V grove angle of joint, filler rod material, filler rod diameter and welding speed. Apart from the parameters mentioned above following parameters were kept constant at a fixed value during the experimentation

1. Work piece : MONEL 400 and AISI 304
2. Work piece Diameter : 8 mm
3. Welding Technique : TIG welding
4. Welding Angle : 60^0

In the present work, two important response variables viz. Hardness and Fatigue strength were being measured and studied for analysis the effect of TIG welding process parameters.

III. Results And Discussions

The influences of different input parameters of TIG welding i.e. welding current, V grove angle of joint, filler rod material, filler rod diameter and welding speed on response factors i.e. Hardness and Fatigue strength in the experiments performed with the help of Response surface methodology method are being discussed. A scientific approach to planning and conducting of experiments on TIG welding of dissimilar weld of MONEL 400 and AISI 304 was incorporated in order to perform the experiments most effectively. RSM approach was taken as the basis for planning and conducting the experiments so that the appropriate data is collected which may be analyzed to obtain valid and objective conclusions. Table 1 shows the ranges of the selected control factors for experimentations.

Table 1: Control factors and their Ranges

Coded Factor	Parameter Name	Unit	Lower Limit	Upper Limit
A	Welding Current	Amps	120	320
B	Joint Angle	Degree	30	60
C	Filler Rod Diameter	MM	0.5	1.5
D	Filler Rod Material		1	3
E	Welding Speed	Mm/sec	3	6

A well designed experimental plan can substantially reduce the total number of experiments. Central composite designs are one of those means. Preceding a step ahead, Central composite designs of second order have been found to be the most efficient tool in RSM to establish the mathematical relation of the response surface using the smallest possible number of experiments without losing its accuracy.

Table 2: Design of Experiments and Response Data

Run	A	B	C	D	E	Hardness	Fatigue Strength
1.	220	45	1.0	2	6.0	142	12661
2.	220	45	1.0	2	3.0	149	15265
3.	220	45	1.0	2	4.5	146	13688
4.	220	45	1.0	2	4.5	147	13658
5.	320	60	1.5	1	3.0	148	19585
6.	120	60	1.5	1	6.0	148	11864
7.	120	60	1.5	3	3.0	157	11178
8.	120	60	0.5	3	6.0	155	16852
9.	320	30	0.5	3	6.0	135	14236
10.	320	60	0.5	1	6.0	162	15661
11.	220	45	1.0	1	4.5	136	13865
12.	220	30	1.0	2	4.5	135	13847
13.	220	45	1.0	2	4.5	146	13646
14.	120	45	1.0	2	4.5	141	11585
15.	220	45	1.0	3	4.5	143	15864
16.	320	30	1.5	3	3.0	152	16178
17.	320	45	1.0	2	4.5	148	15852
18.	120	30	0.5	1	3.0	138	12236
19.	220	60	1.0	2	4.5	152	12647
20.	320	30	1.5	1	6.0	144	13265
21.	220	45	1.5	2	4.5	149	13685
22.	220	45	0.5	2	4.5	165	13718

23.	120	30	1.5	3	6.0	142	11585
24.	220	45	1.0	2	4.5	146	13864
25.	320	60	0.5	3	3.0	142	16877
26.	220	45	1.0	2	4.5	147	13852

3.1 ANOVA for Hardness

In order to statistically analyze the results, ANOVA was performed. Process variables having p-value less than 0.05 are considered significant terms for the requisite response characteristics. The insignificant parameters were pooled using backward elimination method. The pooled version of ANOVA for Hardness of weld joint (Table 3) indicates that (A), (B), (C), (D), (E), the interaction terms (AB), (AC), (AD), (BC), (BD), (CD), (CE), (DE) and the quadratic terms (A^2, B^2, C^2, D^2) are significant parameters affecting hardness of weld joint.

Table 3: Pooled ANOVA for Hardness

Source	Sum of Squares	DF	Mean Square	F Value	p-value Prob>F	
Model	1397.27	17	82.19	171.05	<0.0001	Significant
A	32.03	1	32.03	66.67	<0.0001	
B	264.03	1	264.03	549.49	<0.0001	
C	189.46	1	189.46	394.29	<0.0001	
D	28.75	1	28.75	59.83	<0.0001	
E	28.75	1	28.75	59.83	<0.0001	
A^2	5.48	1	5.48	11.41	0.0097	
B^2	15.58	1	15.58	32.43	0.0005	
C^2	314.23	1	314.23	653.95	<0.0001	
D^2	107.52	1	107.52	223.77	<0.0001	
AB	122.65	1	122.65	255.26	<0.0001	
AC	73.61	1	73.61	153.20	<0.0001	
AD	189.44	1	189.44	394.25	<0.0001	
BC	10.45	1	10.45	21.74	0.0016	
BD	175.59	1	175.59	365.42	<0.0001	
CD	152.20	1	152.20	316.75	<0.0001	
CE	127.67	1	127.67	265.70	<0.0001	
DE	8.02	1	8.02	16.69	0.0035	
Residual	3.84	8	0.48			
Lack of Fit	2.64	4	0.66	2.20	0.2315	Not significant
Pure Error	1.20	4	0.30			
Cor Total	1401.12	25				
Std. Dev	069			R-Squared	0.9973	
Mean	146.73			Adj R-Squared	0.9914	
C.V.	0.47			Pred R-Squared	0.8507	
PRESS	209.25			Adeq Precision	53.187	

- The Model F-value of 171.05 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise.
- Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, C, D, E, A2, B2, C2, D2, AB, AC, AD, BC, BD, CD, CE, DE are significant model terms.
- The "Lack of Fit F-value" of 2.20 implies the Lack of Fit is not significant relative to the pure error. There is a 23.15% chance that a "Lack of Fit F-value" this large could occur due to noise. Non-significant lack of fit is good which shows that the model to fit.
- The "Pred R-Squared" of 0.8507 is in reasonable agreement with the "Adj R-Squared" of 0.9914. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 53.187 indicates an adequate signal.

By using table 3, the regression equation for the hardness of welding joint as a function of five input process variable was developed from the software (RSM) and is given below. The coefficients (insignificant identified from ANOVA) of some terms of the quadratic equation have been omitted.

Hardness = 75.79 + 0.44 x welding current + 3.86 x joint angle – 231.32 x Filler rod Diameter + 69.13 x filler rod material – 11.73 x welding speed – 1.45E-004 x welding current^2 – 0.01 x joint angle^2 + 44.16 x Filler rod diameter^2 – 6.45 x Filler rod material^2 – 6.26E-003 x welding speed^2 + 0.11 x welding current x filler rod diameter – 0.09 x welding current x filler rod material + 0.29 x Joint angle x filler rod diameter – 0.60 x joint angle x filler rod material + 14.93 X filler rod diameter x filler rod material + 12.79 x filler rod diameter x welding speed -1.60 x filler rod material x welding speed

3.2 ANOVA for Fatigue Strength

The pooled version of ANOVA for fatigue strength (Table 4) indicates that (A), (B), (D), (E) the interaction terms (AB), (AC), (AD), (AE), (BC), (BE), (CD), (DE) and the quadratic terms (B^2), (D^2) are significant parameters of TIG welding affecting fatigue strength.

Table 4: Pooled ANOVA for Fatigue Strength

Source	Sum of Squares	DF	Mean Square	F Value	p-value Prob>F	
Model	9.515E+007	15	6.343E+006	338.38	<0.0001	Significant
A	3.359E+007	1	3.359E+007	1792.07	<0.0001	
B	7.129E+005	1	7.129E+005	38.03	0.0001	
C	18748	1	18748	1	0.3409	
D	2.895E+006	1	2.895E+006	154.44	<0.0001	
E	4.765E+006	1	4.765E+006	254.22	<0.0001	
B^2	9.740E+005	1	9.740E+005	51.96	<0.0001	
D^2	3.926E+006	1	3.926E+006	209.42	<0.0001	
AB	1.208E+006	1	1.208E+006	64.43	<0.0001	
AC	3.366E+005	1	3.366E+005	17.96	0.0017	
AD	7.991E+006	1	7.991E+006	426.30	<0.0001	
AE	6.943E+005	1	6.943E+005	37.04	0.0001	
BC	5.796E+005	1	5.796E+005	30.92	0.0002	
BE	8.396E+006	1	8.396E+006	447.89	<0.0001	
CD	5.590E+006	1	5.590E+006	298.22	<0.0001	
DE	1.492E+005	1	1.492E+005	7.96	0.0181	
Residual	1.875E+005	10	18745.58			
Lack of Fit	1.413E+005	6	23547.43	2.04	0.2555	Not significant
Pure Error	46171.20	4	11542.80			
Cor Total	9.534E+007	25				
Std. Dev	136.91		R-Squared	0.9980		
Mean	14123.62		Adj R-Squared	0.9951		
C.V.	0.97		Pred R-Squared	0.9484		
PRESS	4.919E+006		Adeq Precision	78.706		

- The Model F-value of 338.38 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise.
- Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, D, E, B^2, D^2, AB, AC, AD, AE, BC, BE, CD, DE are significant model terms. Values greater than 0.1000 indicate the model terms are not significant.
- The "Lack of Fit F-value" of 2.04 implies the Lack of Fit is not significant relative to the pure error. There is a 25.55% chance that a "Lack of Fit F-value" this large could occur due to noise. Non-significant lack of fit is good.
- The "Pred R-Squared" of 0.9484 is in reasonable agreement with the "Adj R-Squared" of 0.9951. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 78.706 indicates an adequate signal. This model can be used to navigate the design space.

By using table 4, the regression equation for the fatigue strength as a function of input process variable was developed from the software (RSM) and is given below. The coefficients (insignificant identified from ANOVA) of some terms of the quadratic equation have been omitted. Fatigue strength = 21840.80 + 64.13 x welding current – 484.78 x joint angle + 5597.23 x Filler rod Diameter + 4077.08 x filler rod material – 5129.78 x welding speed – 2.39 x joint angle^2 + 1079.69 x Filler rod material^2 + 0.52 x welding current x joint angle – 8.29 x welding current x filler rod diameter – 3.97 x welding current x filler rod material – 3.97 x welding current x welding speed + 81.87 x Joint angle x filler rod diameter + 103.86 x joint angle x welding speed – 3813.94 x filler rod diameter x filler rod material + 207.68 x filler rod material x welding speed

3.3 Multi Response Optimization

Multi response optimization was carried out using desirability function in conjunction with RSM to overcome the problem of contradictory responses of single response optimization. All possible multi characteristics models have been developed. Goals and limits were established for each response in order to accurately determine their impact on overall desirability. A maximum or minimum level is provided for all response characteristics which are to be optimized. Weights are assigned in order to give extra emphasis to upper or lower bounds or to emphasize a target value. Figures shows the ranges of all input and output variables. Table 5 show the desirability of hardness and fatigue strength.

Table 5: Range of Input Parameters, hardness and fatigue strength for Desirability

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
Welding current	is in range	120	320	1	1	3
Joint angle	is in range	30	60	1	1	3
Filler rod diameter	is in range	0.5	1.5	1	1	3
Filler rod material	is in range	1	3	1	1	3
Welding speed	is in range	3	6	1	1	3
Hardness	maximize	135	165	1	1	3
Fatigue strength	maximize	11178	19585	1	1	3

By applying the multi response optimization with RSM, we get optimal solution shown in the table 6.

Table 6: Set of Optimal Solutions for hardness and fatigue strength

Number	Welding current	Joint angle	Filler rod diameter	Filler rod material	Welding speed	hardness	Fatigue strength	Desirability	
1	124.91	35	0.52	2.99	3.40	168.76	19800.2	1	Selected
2	122.66	30.10	0.50	2.97	3.55	165.36	20331.8	1	
3	256.69	39.67	0.52	2.99	3.02	165.94	20296.5	1	
4	300.89	31.74	0.60	2.18	3.06	166.34	19655.6	1	
5	315.94	38.99	0.63	1.15	3.01	166.42	19610.4	1	

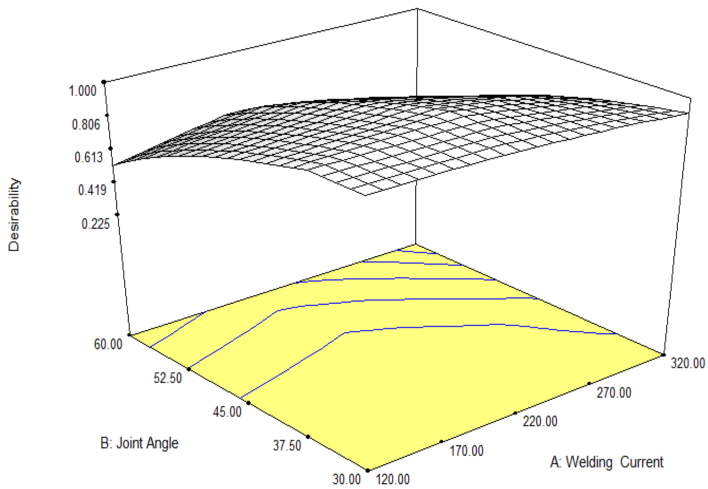

Fig 1: Desirability Graph in between Joint Angle and Welding Current

The Figure 1 shows a plot of desirability function distribution of both hardness and fatigue strength according to joint angle and welding current. It can be visualized that low level of welding current and middle level of joint angle favour of high hardness and high fatigue strength.

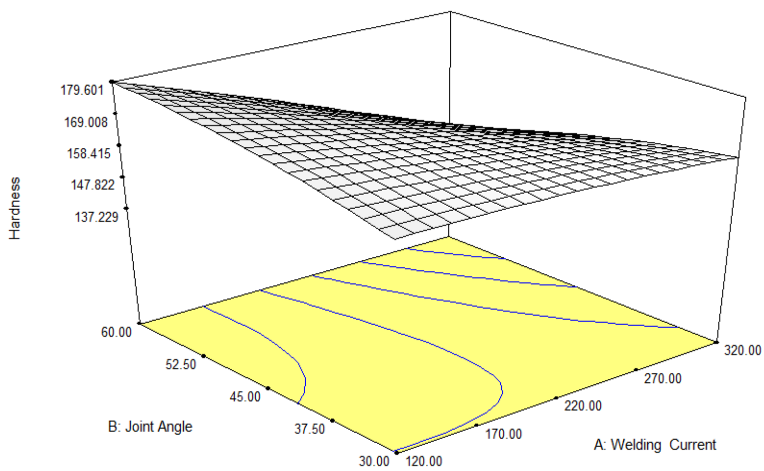

Fig 2: Interaction Graph in between Joint angle and welding Current for Hardness

The Figure 2 shows a plot of optimization of hardness of welding joint between joint angle and welding current. It can be visualized from graph that low level of welding current and high level of joint angle favour of high hardness of welding joint.

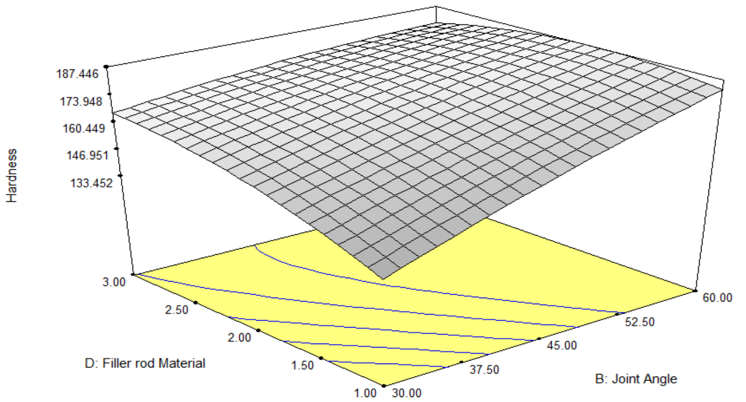

Fig 3: Interaction Graph in between Filler rod material and joint angle for Hardness

The Figure 3 shows a plot of optimization of hardness of welding joint between joint angle and filler rod material. It can be visualized from graph that high level of joint angle and high level of filler rod material are favour of high hardness of welding joint.

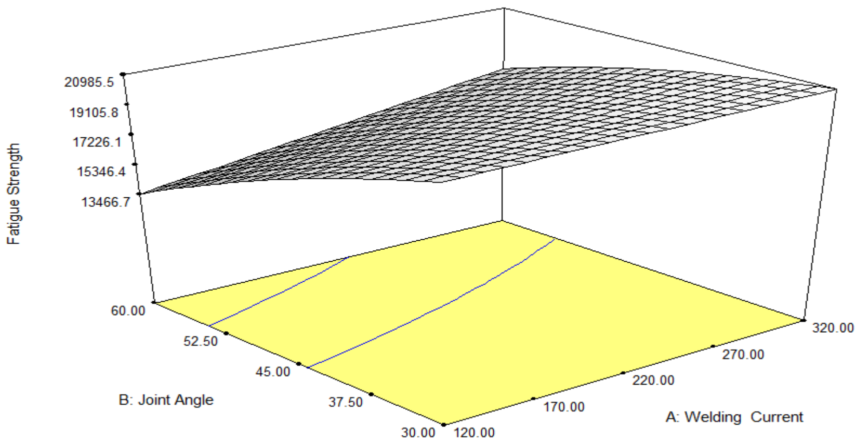

Fig 4: Interaction Graph in between Joint angle and welding Current for Fatigue Strength

The Figure 4 shows a plot of optimization of fatigue strength of welding joint between joint angle and welding current. It can be visualized from graph that high level of welding current and mid level of joint angle favours of high fatigue strength of welding joint.

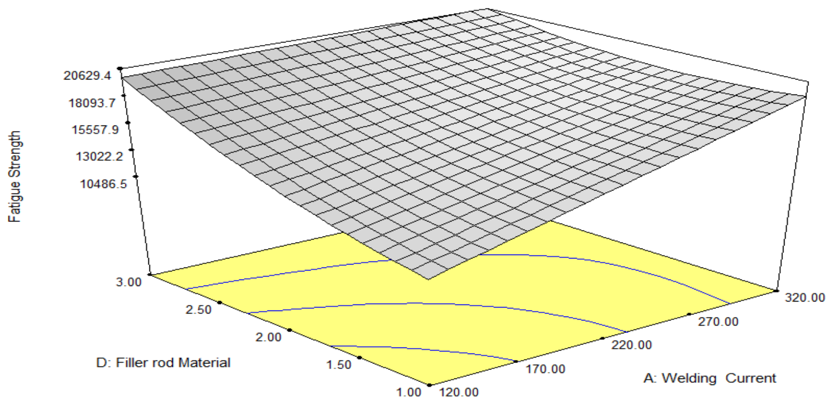

Fig 5: Interaction Graph in between filler rod material and welding Current for Fatigue Strength

The Figure 5 shows a plot of optimization of fatigue strength of welding joint between filler rod material and welding current. It can be visualized from graph that high level of welding current and high level of filler rod material favours of high fatigue strength of welding joint.

3.4 Ram Function and Bar Graph

The ramp function graph and bar graph drawn using Design Expert 6, show the desirability for hardness and fatigue strength of welding joint. Figure 6 shows the ramp function graph of desirability for hardness and fatigue strength of welding joint. The dot on each ramp reflects the factor setting or response prediction for those response characteristics. The height of the dot shows how much desirable it is. A linear ramp function is created the low value and the goal or the high value and the goal as the weight for each parameter was set equal to one.

Fig 6: Ramp Function Graph of Desirability for hardness and fatigue strength of welding joint

The Figure 7 shows the Bar graph of overall desirability function of the input parameters and responses (hardness and fatigue strength of welding joint). Desirability varies from 0 to 1 depending upon the closeness of the response towards target. The bar graph shows how well each variable satisfies the criterion.

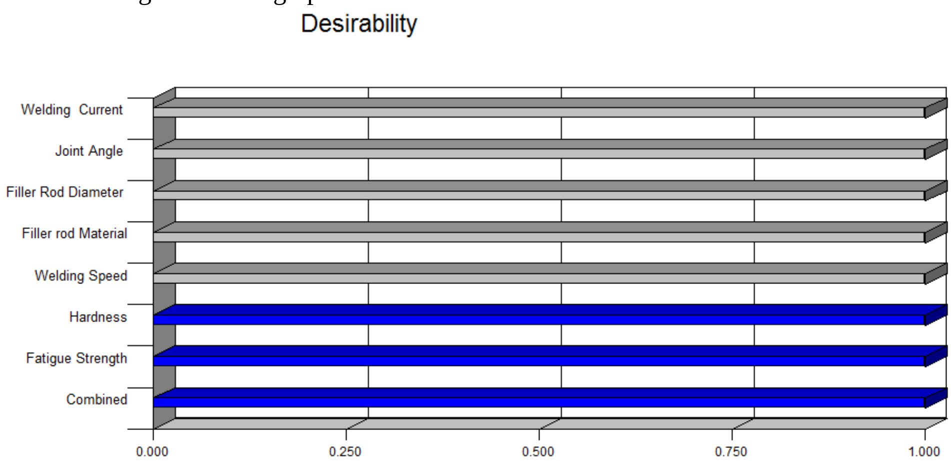

Fig 6: Bar Graph of Desirability for hardness and fatigue strength of welding joint

IV. Conclusions

In present work, the experimental study during the TIG welding of dissimilar weld of MONEL 400 and AISI 304 alloy. A total 26 experiments were conducted to identify the best possible welding characteristics to maximize the hardness and fatigue strength of welding joint. The conclusions were as follows.

1. From the experimental data of RSM, empirical model were developed and the confirmation experiments were performed, which were found within 95% confidence interval.

2. Hardness = 75.79 + 0.44 x welding current + 3.86 x joint angle – 231.32 x Filler rod Diameter + 69.13 x filler rod material – 11.73 x welding speed – 1.45E-004 x welding current^2 – 0.01 x joint angle^2 + 44.16 x Filler rod diameter^2 – 6.45 x Filler rod material^2 – 6.26E-003 x welding speed^2 + 0.11 x welding current x filler rod diameter – 0.09 x welding current x filler rod material + 0.29 x Joint angle x filler rod diameter – 0.60 x joint angle x filler rod material + 14.93 X filler rod diameter x filler rod material + 12.79 x filler rod diameter x welding speed -1.60 x filler rod material x welding speed
3. Fatigue strength = 21840.80 + 64.13 x welding current – 484.78 x joint angle + 5597.23 x Filler rod Diameter + 4077.08 x filler rod material – 5129.78 x welding speed – 2.39 x joint angle^2 + 1079.69 x Filler rod material^2 + 0.52 x welding current x joint angle – 8.29 x welding current x filler rod diameter – 3.97 x welding current x filler rod material – 3.97 x welding current x welding speed + 81.87 x Joint angle x filler rod diameter + 103.86 x joint angle x welding speed – 3813.94 x filler rod diameter x filler rod material + 207.68 x filler rod material x welding speed
4. Optimal setting for hardness of welding joint are 126 amp welding current, 59^0 joint angle, 1.5 filler rod diameter, MONEL 400 filler rod and 5.89 mm/sec welding speed.
5. Optimal set for fatigue strength of welding joint are 120 amp welding current, 30^0 joint angle, 0.95 filler rod diameter, MONEL 400 filler rod and 3.01 mm/sec welding speed.
6. Optimal setting for multi response characteristics means for both hardness and fatigue strength of welding joint are 124 amp welding current, 35^0 joint angle, 0.52 filler rod diameter, MONEL 400 filler rod and 3.40 mm/sec welding speed.

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