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Experimental investigation on Fatigue and Impact Strength of MONEL 400 to AISI 304 joints by TIG welding

Jagwinderjit Singh Gill[1], Sukhwinder Singh Jolly[2], Charanjit Singh Kalra[3]
[1]Research Scholar, Sri Guru Granth Sahib World University, Fatehgarh Sahib, Punjab,
[2]ME Department, Sri Guru Granth Sahib World University, Fatehgarh Sahib, Punjab.
[3]ME Department, SUSCET, Mohali, Punjab, cskalra9988@gmail.com
*Corresponding Author: * Jagwinderjit Singh Gill*

Abstract: The objective of this experimental study is to investigate fatigue and impact strength dissimilar weld of MONEL 400 to AISI 304 joints by TIG welding. Five independent input parameters of TIG welding viz., welding current, V grove angle of joint, filler rod material, filler rod diameter and welding speed have used to explore the influence on fatigue strength and impact strength of joint. The regression equation, and ANOVA have developed using the experimental data and graphs were plotted to investigate the effect of process variables on response characteristics by using response surface methodology. It has observed that Fatigue Strength of welding joint is increases by increase both joint angle and welding current. The Impact Strength of welding joint is decrease by increasing diameter of filler rod.

Keywords: Dissimilar Weld, MONEL 400, AISI 304, Fatigue strength, Impact Strength, TIG welding

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I. INTRODUCTION

AISI 304 stainless steel is the most adaptable due to corrosion oxidation resistance at low cost. Monel-400 is a nickel-based alloy and has high strength, good corrosion resistance. AISI 304 stainless steel and Monel-400 both have common many applications like chemical processing equipment, marine fixtures and fasteners, boiler feed water heaters and other heat exchangers etc. **Bikash et al. (2016)** investigate mechanical and metallurgical characteristics of continuous wave CO_2 laser welded dissimilar couple of AISI 304 stainless steel and commercially pure copper sheets. They observed that the tensile stress found up to 201 MPa and the fracture has obtained outside the weld zone. **Srirangan, and Paulraj (2016)** optimization using grey relational analysis for Incoloy 800HT welded with TIG welding process. They find out that the optimal parameters combination as welding current at 110 A, voltage at 10 V and welding speed at 1.5 mm/s for welding of incoloy 800HT by TIG welding. **Atzori et al. (2008)** fatigue life assessments of welded joints have performed on the basis of the NSIFs, which are determined by setting the weld toe radius equal to zero and modelling the highly stressed regions as sharp V-notches. The design stress the elastic peak stress evaluated at the weld toe by means of a finite element analysis performed with a mesh characterised by a constant element size. By so doing, it is possible to take advantage of both the simplicity of a point-like method and the robustness of the NSIF local approach. **Cunha et al. (2016)** conducted with the pulsed TIG process in order to investigate welding current effect. They found that the weld penetration behaviour has closely related with mean welding current, while the weld width with the RMS value of the welding current. **Abid et al. (2013)** investigates the effect of different tip angles (30^0, 60^0, 90^0 and 120^0) on the arc and weld pool. The arc temperature at the tungsten electrode has found the maximum with sharp tip and decreases as the tip angle increases. **Marcelino et al. (2011)** investigated the effect of Gas Tungsten Arc Welding (GTAW) repairs on the axial fatigue strength of an AISI 4130 steel-welded joint. The fatigue strength decreased with the number of GTAW repairs, and has 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). They claimed that the impact strength of weldment made by GTAW has 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 experimental study is to investigate fatigue and impact strength dissimilar weld of MONEL 400 to AISI 304 joints by TIG welding.

II. EXPERIMENTATIONS

Various input process parameters varied during the experimentation have 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 have 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. Fatigue strength and impact strength have measured and studied for analysis the effect of TIG welding process parameters. The figure 1 shows the specimens after fatigue strength.

Fig 1: TIG welding Specimens after Fatigue Testing

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. Fatigue strength and Impact 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 has incorporated in order to perform the experiments most effectively. RSM approach has taken as the basis for planning and conducting the experiments so that the appropriate data is collected, which has 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	Fatigue Strength	Impact Strength
1.	220	45	1.0	2	6.0	12661	5.3
2.	220	45	1.0	2	3.0	15265	5.6
3.	220	45	1.0	2	4.5	13688	5.6
4.	220	45	1.0	2	4.5	13658	5.6

5.	320	60	1.5	1	3.0	19585	6.6
6.	120	60	1.5	1	6.0	11864	5.5
7.	120	60	1.5	3	3.0	11178	5.4
8.	120	60	0.5	3	6.0	16852	5.8
9.	320	30	0.5	3	6.0	14236	5.4
10.	320	60	0.5	1	6.0	15661	6.2
11.	220	45	1.0	1	4.5	13865	5.9
12.	220	30	1.0	2	4.5	13847	5.6
13.	220	45	1.0	2	4.5	13646	5.7
14.	120	45	1.0	2	4.5	11585	5.1
15.	220	45	1.0	3	4.5	15864	5.8
16.	320	30	1.5	3	3.0	16178	6.8
17.	320	45	1.0	2	4.5	15852	5.1
18.	120	30	0.5	1	3.0	12236	5.2
19.	220	60	1.0	2	4.5	12647	6.3
20.	320	30	1.5	1	6.0	13265	4.9
21.	220	45	1.5	2	4.5	13685	5.6
22.	220	45	0.5	2	4.5	13718	6.1
23.	120	30	1.5	3	6.0	11585	5.2
24.	220	45	1.0	2	4.5	13864	5.7
25.	320	60	0.5	3	3.0	16877	4.8
26.	220	45	1.0	2	4.5	13852	5.7

3.1 ANOVA for Fatigue Strength

The pooled version of ANOVA for fatigue strength (Table 3) 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 3: 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 3, 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.

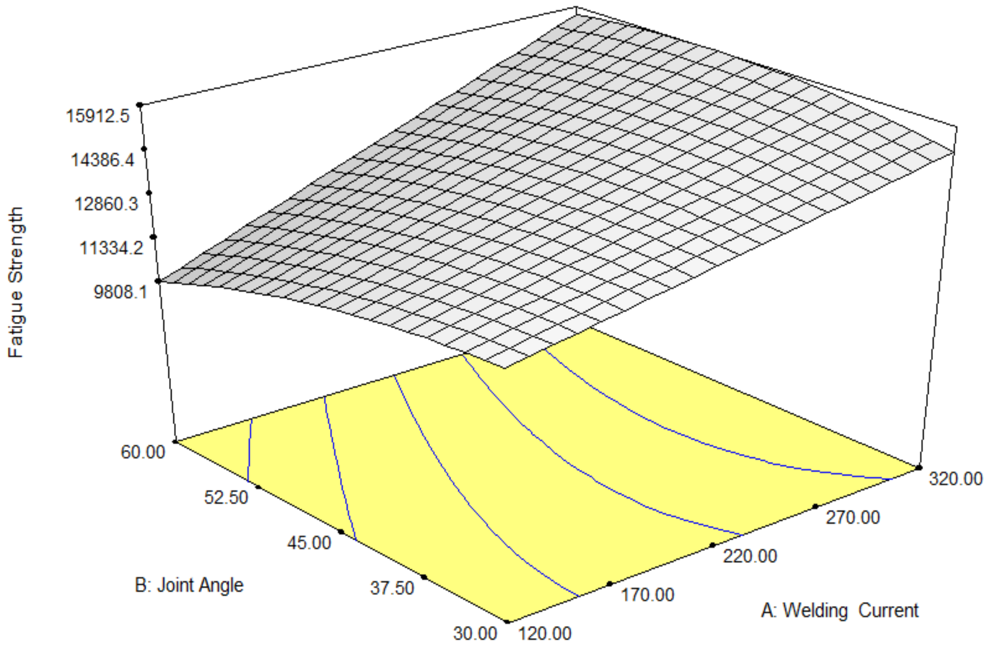

Fig 2: Interaction plots joint angle and welding current for Fatigue Strength of welding joint

Figure 2 shows the interaction between joint angle and welding current for Fatigue Strength of welding joint. It has observed that Fatigue Strength of welding joint is increases by increase both joint angle and welding current. Low joint angle between two-piece means less material of filler rod is solidify in gap so that there is tendency to generation of porosity and cracks in welding zone. By increase of joint angle between gap results, more metal has allowed to solidify in gap. At low welding current less metal has melt from base metal and it does not proper mixed in filler material and not proper filled the gap. By increasing, the welding current means more base metals is melt and uniformly mix with filler rod and filled the gap by solidify. Therefore, Fatigue Strength increases with increase in welding current and joint angle of weld specimens.

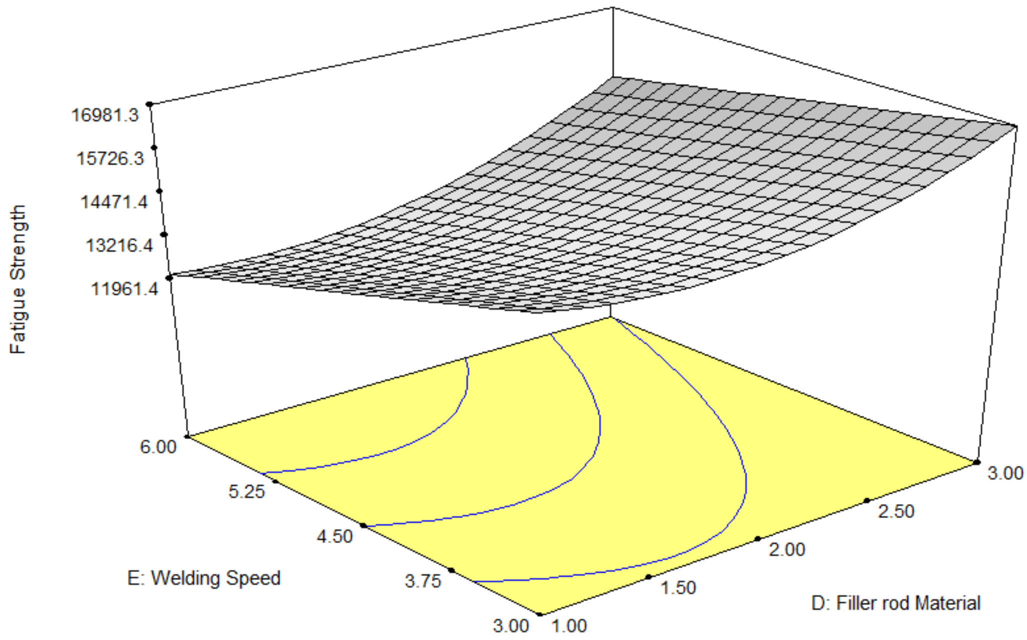

Fig 3: Interaction plots welding speed and joint angle for Fatigue Strength of welding joint

Figure 3 shows the interaction between welding speed and joint angle for Fatigue Strength of welding joint. The Fatigue Strength of welding joint is decrease by increasing welding speed. More welding speed means less time allowed to mixing the filler rod material with molten of base metal therefore Fatigue Strength is decrease by increasing the welding speed.

3.2 ANOVA for Impact Strength

To construct the pool ANOVA design expert 6.0 software was used. The aim of construction of pooled ANOVA is to pool the different factors together and test for significance. Table 4 represents Pooled ANOVA for impact strength of welding joint.

Table 4: Pooled ANOVA for Impact Strength

Source	Sum of Squares	DF	Mean Square	F Value	p-value Prob>F	
Model	5.82	16	0.36	162.33	<0.0001	Significant
A	5.135E-004	1	5.135E-004	0.23	0.6435	
B	1.28	1	1.28	569.45	<0.0001	
C	0.27	1	0.27	118.71	<0.0001	
D	8.216E-003	1	8.216E-003	3.67	0.0877	
E	0.13	1	0.13	57.06	<0.0001	
A^2	0.75	1	0.75	335.94	<0.0001	
B^2	0.21	1	0.21	95.46	<0.0001	
C^2	0.094	1	0.094	41.79	0.0001	
D^2	0.094	1	0.094	41.79	0.0001	
E^2	0.10	1	0.10	45.68	<0.0001	
AB	0.35	1	.035	158.24	<0.0001	
AC	1.31	1	1.31	582.97	<0.0001	
BC	0.046	1	0.046	20.54	0.0014	
BD	1.77	1	1.77	790.89	<0.0001	
BE	0.093	1	0.093	41.50	0.0001	
CD	0.50	1	0.50	222.13	<0.0001	
Residual	0.020	9	2.240E-003			
Lack of Fit	8.162E-003	5	1.632E-003	0.54	0.7406	Not significant
Pure Error	0.012	4	3.000E-003			

Cor Total	5.84	25				
Std. Dev	0.047			R-Squared	0.9965	
Mean	5.63			Adj R-Squared	0.9904	
C.V.	0.84			Pred R-Squared	0.8991	
PRESS	0.59			Adeq Precision	52.257	

- The Model F-value of 162.33 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 B, C, E, A^2, B^2, C^2, D^2, E^2, AB, AC, BC, BD, BE, CD are significant model terms.
- Values greater than 0.1000 indicate the model terms are not significant.
- The "Lack of Fit F-value" of 0.54 implies the Lack of Fit is not significant relative to the pure error. There is a 74.06% chance that a "Lack of Fit F-value" this large could occur due to noise.

By using table 4, the regression equation for the impact strength of welding joint as a function of five input process variable has developed from the software (RSM) and has given below. The coefficients (insignificant identified from ANOVA) of some terms of the quadratic equation have been omitted.

Impact Strength = 0.56 + 0.02 x welding current + 0.09 x joint angle – 4.96 x Filler rod Diameter + 0.56 x filler rod material + 1.05 x welding speed – 1.54446E-006 x welding current^2 + 1.31357E-003 x joint angle^2 + 0.78 x Filler rod diameter^2 + 0.19 x Filler rod material^2 – 0.09 x welding speed^2 -2.00980E-004 x welding current x joint angle +0.01 x welding current x filler rod diameter – 0.01 x joint angle x filler rod diameter – 0.04 x joint angle x filler rod material – 7.65423E-003 x Joint angle x welding + 0.63 x filler rod diameter x filler rod material

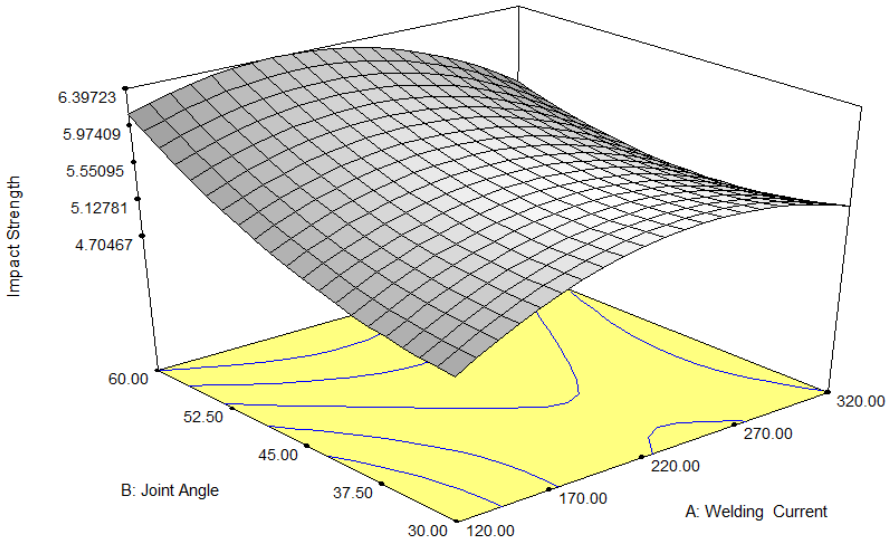

Fig 4: Interaction plots joint angle and welding current for Impact Strength of welding joint

Figure 4 shows the interaction between joint angle and welding current for Impact Strength of welding joint. It has observed that Impact Strength of welding joint is increases by increase both joint angle and welding current. Low joint angle between two-piece means less material of filler rod is solidify in gap so that there is tendency to generation of porosity and cracks in welding zone. By increase of joint angle between gap results, more metal has allowed to solidify in gap. At low welding current less metal has melt from base metal and it does not proper mixed in filler material and not proper filled the gap. By increasing, the welding current means more base metals is melt and uniformly mix with filler rod and filled the gap by solidify. Therefore, Impact Strength increases with increase in welding current and joint angle of weld specimens.

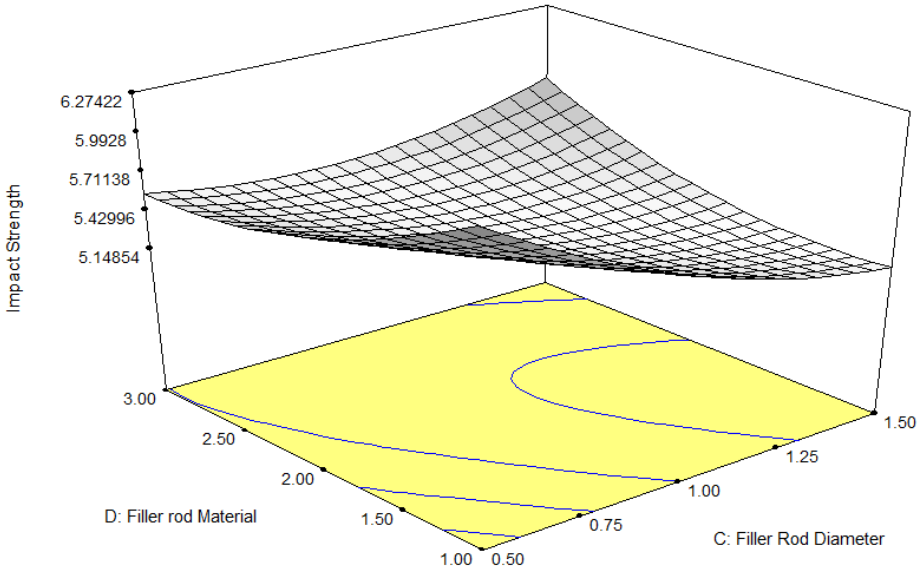

Fig 5: Interaction plots filler rod material and filler rod diameter for Impact Strength of welding joint

Figure 5 shows the interaction between filler rod material and filler rod diameter for Impact Strength of welding joint. The Impact Strength of welding joint is increase by changing the filler rod from AISI-304 to E-316. By further changing, the filler rod from E-316 to MONEL-400 the Impact Strength of welding joint is again increase. This is due to properties of MONEL-400 alloy it is harder than both AISI-304 and E-316 and more ever MONEL-400 filler rod is uniformly mixed with base metal, make strong welding joint and defect free joint.

The Impact Strength of welding joint is decrease by increasing diameter of filler rod. If diameter is, 0.5 mm of filler rod means all material of filler rod is melt and properly mixed with molten metal of base metal, and become strong and defects free 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. 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.
2. It has observed that Fatigue Strength of welding joint is increases by increase both joint angle and welding current. By increase of joint angle between gap results, more metal has allowed to solidify in gap. By increasing, the welding current means more base metals is melt and uniformly mix with filler rod and filled the gap by solidify.
3. The Fatigue strength of welding joint is higher using MONEL-400 alloy filler rod as compare to AISI-304 and E-316. MONEL-400 filler rod has uniformly mixed with base metal, make strong welding joint and defect free joint.
4. Impact Strength = 0.56 + 0.02 x welding current + 0.09 x joint angle – 4.96 x Filler rod Diameter + 0.56 x filler rod material + 1.05 x welding speed – 1.54446E-006 x welding current^2 + 1.31357E-003 x joint angle^2 + 0.78 x Filler rod diameter^2 + 0.19 x Filler rod material^2 – 0.09 x welding speed^2 -2.00980E-004 x welding current x joint angle +0.01 x welding current x filler rod diameter – 0.01 x joint angle x filler rod diameter – 0.04 x joint angle x filler rod material – 7.65423E-003 x Joint angle x welding + 0.63 x filler rod diameter x filler rod material
5. It has observed that Impact Strength of welding joint is increases by increase both joint angle and welding current. By increasing, the welding current means more base metals is melt and uniformly mix with filler rod and filled the gap by solidify.

6. The Impact Strength of welding joint is decrease by increasing diameter of filler rod. If diameter is, 0.5 mm of filler rod means all material of filler rod is melt and properly mixed with molten metal of base metal, and become strong and defects free joint.

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