Deformation Rate and Weld Time Influence on Optimized Dissimilar Metal Friction Welds of Pure Aluminium and Pure Copper

Pratyusha M[*1], Venkata Ramana P[2], Prasanthi G[3]

*Corresponding Author, email: pratyusha.sagi@gmail.com

[*1]Research Scholar, Dept. of Mechanical Engineering, JNTUA College of Engineering, Anantapuramu, Andhra Pradesh, India

[2]Professor, Dept. of Mechanical Engineering, Mahatma Gandhi Institute of Technology, Hyderabad, Telangana, India

[3]Professor, Dept. of Mechanical Engineering, JNTUA College of Engineering, Anantapuramu, Andhra Pradesh, India

Abstract- Welding of dissimilar metals such as pure aluminium and pure copper has been performed by a solid state welding through continuous drive rotary friction welding process. After carrying out the experimental work based on Taguchi L9 Orthogonal array, the factors Upset Force, Spindle Speed, Burn-Off and Friction Force were optimized. Tensile strength and shear strength are considered as responses. Design of Experiments and Analysis of Variance revealed that Upset Force and Spindle Speed are significant process parameters in controlling tensile strength and shear strength of the weld joint respectively. These strengths are correlated with deformation rate and weld time. Regression model was generated and validated by performing the experiments at optimized parameters.

Keywords: Dissimilar Metal Weld, Deformation Rate, Friction Welding, Optimization, Weld Time

1. Introduction

Weldability, electrical conductivity, corrosion resistance and machinability of some of the metals make them suitable in some applications particularly in the fields of automobile, aerospace and power transmission.These applications demand a dissimilar combination of metal welds especially Aluminium and Copper. Welding of these metals is difficult because of the prominent differences in their properties and also because of the formation of intermetallic compounds at the boundary which are brittle in nature.The process of joining Al and Cu by means of fusion welding process is complicated due tothe variation in thermal properties, metallurgical incompatibility, melting point,etc.*(S D Meshram et al., in [1])*.The mechanical properties of Al-Cu joints are considerably affected due to the brittle Intermetallic compound phases formed during the process of welding at the weld boundary*(Paul Kah et al., in [2]).*

In order to address this problem these specimens are welded using FW, a solid-state welding process in which one of the work pieces is rapidly rotated at high rpm and the other work piece is brought into contact at high forging pressure to get upset. *(Bekir s. Yilba et al.,in [3])* studied that in this welding process, the joint occurs at a temperature which is lower than work metal's melting point. Good joint efficiency with combination of metals with great differences in their mechanical and metallurgical properties can be achieved by friction welding *(M Aritoshi et al.,in [4]).* Apart from these, *(Sandeep Kumar at al.,in [5])* added other advantages of using this process like low heat input, eco-friendly and low cost. *(AG. Wahyu Wibowo et al.,in [6])* have studied that this process can produce a joint with high quality compared to other welding processes. Dissimilar metal welding of pure Al and pure Cu employing continuous drive rotary friction welding process was carried out along with optimization of process parameters to evaluate mechanical properties like shear andtensilestrengths of their joints.

2. Welding Materials and Method

FW was conducted using 99.9% pure rods of pure Al and pure Cu. Diameter of the rod was 10 mm whereasthe length is 60 mm. Fig. 1. shows the machine employed in carrying out friction welding. The parameters used in this process are Burn-Off (mm), Upset Force (kN),Spindle Speed (rpm) and Friction Force (kN). A typical weld design and assembly is shown in the Fig. 2. The parameters will be indicated in the manuscript as follows: Friction Force - FF, Spindle Speed - SS, Burn-Off - BO and Upset Force – UF.

Fig. 1.Continuous drive friction welding machine

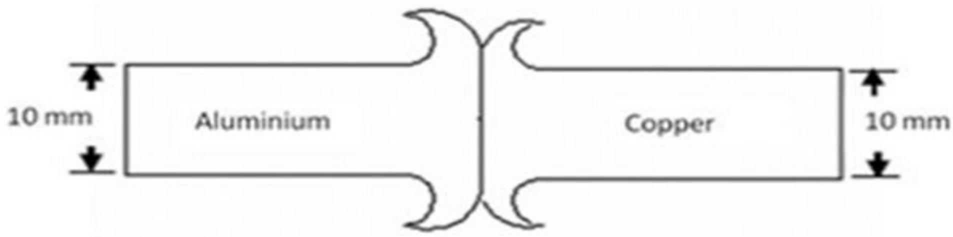

Fig. 2.Typical weld design and assembly for friction welding

2.1. Selection of Welding parameters and Levels

Dr.Genichi Taguchi proposed a design matrix which is a highly fractional orthogonal design. In these arrays, various parameters at different levels are considered equal. This method efficiently reduces both experimental time and cost*(Avinash S. Pachal at al.,in [7])*.Parameters which can be controlled and preset to appropriate valuesdetermine the weld quality obtained in the process of FW *(M. Maalekian et al.,in [8])*.The important process parameters in this processare SS, FF, UF, BO, Upset time and Friction time. *(Mumin Sahin in [9])* considered Torque also as process parameter in continuous drive friction welding.

The output characteristics of the joint get affected by the proper selection of process parameters*(Nada R. Ratković et al.,in [10])*. At least three levels of these process parameters are essential to get accurate values of responses. The process parameters are chosen in their workable range after carrying out a large number of trial runs using Al and Cu rods of specified dimensions and the selected factors and their levels are listed in Table 1.

Table 1.Parameters and their Levels

Factors	**Level 1**	**Level 2**	**Level 3**
SS (rpm)	1000	1050	1100
FF (kN)	6	8	9
UF (kN)	12	14	16
BO (mm)	4	6	8

2.2. Selection of Orthogonal array

In the Taguchi factor design, the initial step is the selection of appropriate Orthogonal Array.

		Number of Parameters(P)																													
		2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Number of Levels	2	L4	L4	L8	L8	L8	L8	L12	L12	L12	L12	L16	L16	L16	L16	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32
	3	L9	L9	L9	L18	L18	L18	L18	L27	L27	L27	L27	L27	L36	L36	L36	L36	L36	L36	L36	L36	L36	L36								
	4	L'16	L'16	L'16	L'16	L'32	L'32	L'32	L'32	L'32																					
	5	L25	L25	L25	L25	L25	L50	L50	L50	L50	L50	L50																			

Table 2.Taguchi Array Selector

The array selection will dependon the count of process parametersand their levels as shown in Table 2.

Because of four factors and three levels, L9 orthogonal array was selected and also cross verified by degree of freedom value. According to L9 array, a total 9 experiments were conducted with combined levels for process parameter as indicated in Table 3.

Table 3.L9 Array

Expt. No.	**SS (rpm)**	**FF (kN)**	**UF (kN)**	**BO (mm)**
1	1000	6	12	4
2	1000	8	14	6
3	1000	9	16	8
4	1050	6	14	8
5	1050	8	16	4
6	1050	9	12	6
7	1100	6	16	6
8	1100	8	12	8
9	1100	9	14	4

2.3. Mechanical Tests

Responses like tensile strength (TS) and shear strength (SHS) of all the welds and parent material were evaluated by carrying out mechanical tests. Plane tensile tests were carried out for all the welds on Instron 1185 UTM. Shear strength testing set up was used to conduct the tests at room temperature.For each condition three test specimens were tested for obtaining accurate values of both tensile and shear strengths.

2.4. Calculation of Deformation rate and Weld time

The machine which was used to carry out the welds by means of friction welding has a provision of measuring torque, weld time, axial position etc. A typical friction welding process chart which is obtained from the friction welding machine is shown in Fig. 3.

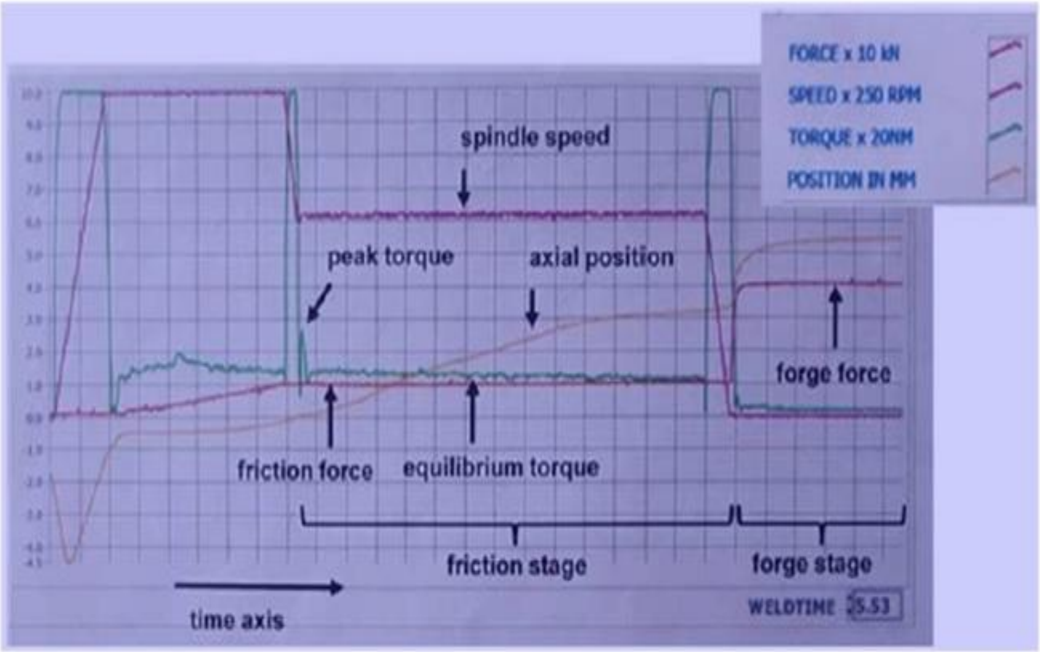

Fig. 3.Friction Welding Process Chart

It represents the variation of torque, spindle speed, axial pressure, loss of length etc. The deformation rate is calculated by taking the slope of the axial position curve. The slope of the curve in friction stage gives the magnitude of deformation rate in friction stage and slope of the curve in the forge or upset stage gives the deformation rate in upset stage. The weld time can be obtained from the x-axis of the graph.

3. Results and Discussion

Three sets each of nine joints produced by means of FWof pure Al and pure Cu are obtained by employing the combination of process parameters as presented in Table 3. Fig. 4 shows a set of welded joints through Taguchi L9 array.

Fig. 4.Friction Welded Joints

The selected responses tensile strength and shear strength are evaluated and shown in Table 4 and Table 5.

Table 4.Tensile strength values of the welds

Run (Expt.No.)	**SS (rpm)**	**FF (kN)**	**UF (kN)**	**BO (mm)**	**Tensile strength (MPa)**		
					T1	**T2**	**T3**
1	1000	6	12	4	183	176	179
2	1000	8	14	6	152	150	164
3	1000	9	16	8	165	163	155
4	1050	6	14	8	160	162	164
5	1050	8	16	4	145	147	164
6	1050	9	12	6	166	164	160
7	1100	6	16	6	162	164	163
8	1100	8	12	8	160	171	169
9	1100	9	14	4	171	173	163

Table 5.Shear strength values of the welds

Experiment No.	**SS (rpm)**	**FF (kN)**	**UF (kN)**	**BO (mm)**	**Shear strength (MPa)**		
					T1	**T2**	**T3**
1	1000	6	12	4	80	76	84
2	1000	8	14	6	95	91	99
3	1000	9	16	8	107	110	110
4	1050	6	14	8	110	104	114
5	1050	8	16	4	125	120	122
6	1050	9	12	6	106	109	103
7	1100	6	16	6	108	104	105
8	1100	8	12	8	105	101	102
9	1100	9	14	4	105	100	102

The welded joints subjected to shear strength test are shown inFig. 5

Fig. 5.Welded joints subjected to shear strength

3.1. Design of experiments

Design of experiments was conducted using MINITAB software so that influence of factors on the responses can be determined. Larger the better Signal to noise ratiohas been chosen to maximize responses. Tables 6 and 7 represent the response tables of S/N ratio of TS and SHS.

Table 6.Response Table for Signal to Noise Ratios for tensile strength

Level	SS (rpm)	FF (kN)	UF (kN)	BO (mm)
1	44.33	44.5	44.58	44.41
2	44.02	43.94	44.18	44.1
3	44.41	44.31	43.99	44.25
Delta	0.39	0.56	0.6	0.3
Rank	**3**	**2**	**1**	**4**

Table 7.Response Table for Signal to Noise Ratios for shearstrength

Level	SS (rpm)	FF (kN)	UF (kN)	BO (mm)
1	39.44	39.76	39.59	39.99
2	41.00	40.50	40.16	40.17
3	40.30	40.48	40.99	40.58
Delta	1.56	0.75	1.40	0.58
Rank	**1**	**3**	**2**	**4**

It is known that signals indicate the average responses effected and noises indicate experiment outputdeviations *(M Jayaraman et al., in [11])*.Fig. 6. represent the main effects plot for S/N ratios of TS and Fig. 7. represent the main effects plot for S/N ratios of SHS.From these figures, it is evidentthat TS is maximum when the SS is at level 3 while FF, UF and BO are at level 1and SHS is maximum when SSand FF are at level 2 while UFand BO at level 3.

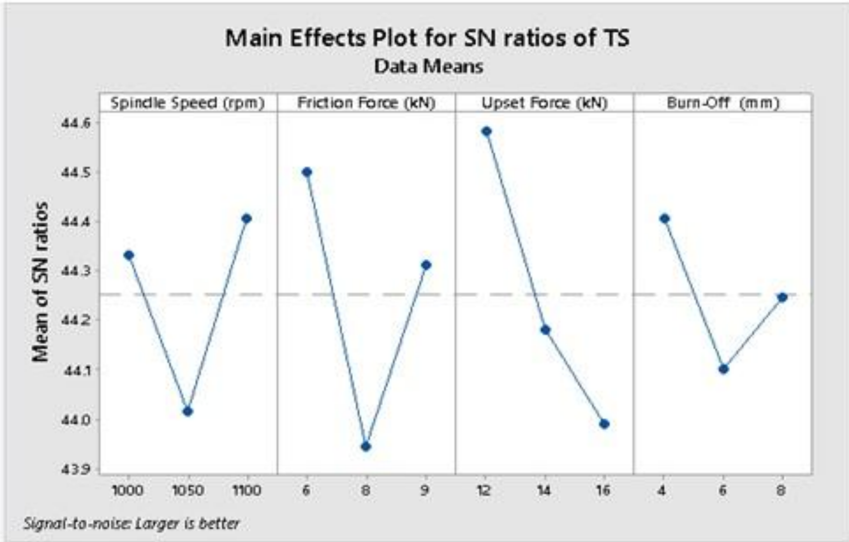

Fig. 6.Main Effects Plot for SN ratios of tensile strength

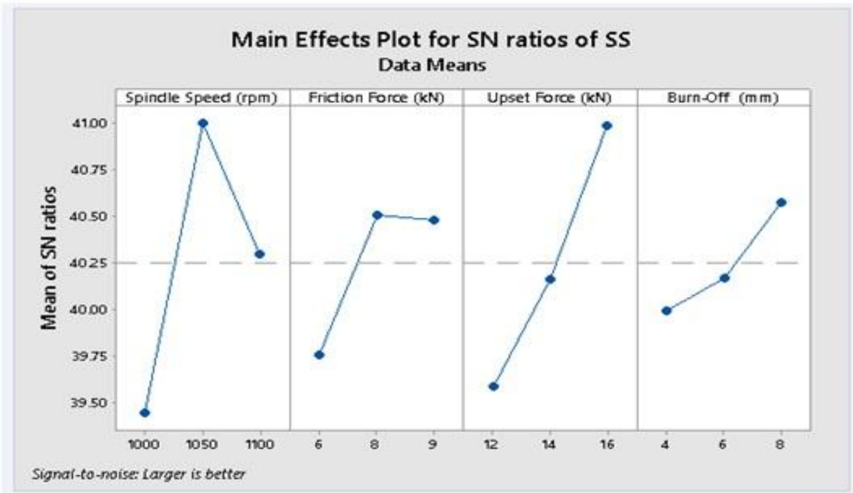

Fig. 7.Main Effects Plot for SN ratios of shear strength

3.2. Analysis of Variance (ANOVA)

ANOVA is a statistical practice that analyses each of the parameters to give a measure of confidence. It computes quantities such as sum of squares, degree of freedom, variance and contribution. The ANOVA results show that thefactors considered are highly significant effecting the TS and SHS of friction welded joints.

As Taguchi method of experiment cannotdetermine the contribution of individual parameters on the total process, the % contribution obtained by using analysis of Variance is employed to balancethis effect. In order to decrease the deviation the % contribution of each parameter can be determined as it shows the influence of a parameter*(S. Kannan et al.,in [12]).* A littledeviationfor a parameter with a high percent contribution will have major influence on the performance.Table 8 and Table 9 show the ANOVA analysis of tensile and shear strengths respectively.

Table 8.ANOVA analysis of tensile strength

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
SS (rpm)	2	266.7	12.93%	266.7	133.37	4.24	0.031

FF (kN)	2	471.6	22.86%	471.6	235.81	7.49	0.004
UF (kN)	2	582.3	28.23%	582.3	291.15	9.25	0.002
BO (mm)	2	175.4	8.50%	175.4	87.7	2.79	0.088
Error	18	566.7	27.47%	566.7	31.48		
Total	26	2062.7	100%				

Table 9.ANOVA analysis of shear strength

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
SS (rpm)	2	1440.1	42.98%	1440.1	720.04	71.47	0.000
FF (kN)	2	377.0	11.25%	377.0	188.48	18.71	0.000
UF (kN)	2	1193.4	35.62%	1193.4	596.70	59.23	0.000
BO (mm)	2	158.7	4.74%	158.7	79.37	7.88	0.003
Error	18	181.3	5.41%	181.3	10.07		
Total	26	3350.5	100.00%				

From the Tables 8 and 9, it was clear that the considerable parameter affecting the TS is UF with p-value 0.002 and FF, SS with p-values less than 0.05. The results are compared with S/N ratios of TS (Table 6) from which it can be concluded that UF is notable parameter followed by others. The most significant factors influencing theSHSare SS, UF and FF with p-Values 0.000 followed by BO whose p-Value is 0.003. The results are compared with Signal to noise ratios of SHS (Table 7) and it can be concluded that SS is the notable process parameter followed by the others.

3.3. Regression equation

The Regression analysis was conducted on the data obtained from the friction welding process in order to relate the dependent variables (Responses) to the independent variables (Parameters). The equations derived from the regression analysis are presented as follows:

Tensile strength (MPa) =
[0.5237 X1 - 42.3 X2 – 18.60 X3 + 54.2 X4-0.0671 X1 * X4+ 1.883 X2 * X3+ 2.038 X2 * X4]

Shear strength (MPa) =
[-0.644 X1 - 159.2 X2 + 171.1 X3 – 55.7 X4 + 0.2297 X1 * X2 - 0.1106 X1 * X3 + 0.0544 X1 * X4– 5.83 X2 * X3]

Where X1 is SS (rpm); X2 is FF (kN); X3 is UF (kN) and X4 is BO (mm).
SHS and TS of the welded joints are a function of above said parameters. MINITAB software is used to generate these regression equations and the model summary of tensile and shear strengths are presented in Table10.

Table 10.Model summary of tensile strength and shear strength

Responses	S	R-sq	R-sq (adj)	R-sq (pred)
Tensile strength	5.66287	99.91%	99.88%	99.85%
Shear strength	6.53857	99.72%	99.61%	99.51%

Fig. 8. shows the normal probability plots of the residual for the mechanical properties tensile strength and shear strength. The plots show linear fit, which recommend the regression models are satisfactory to predict the responses TS and SHS forcompleterange of data.

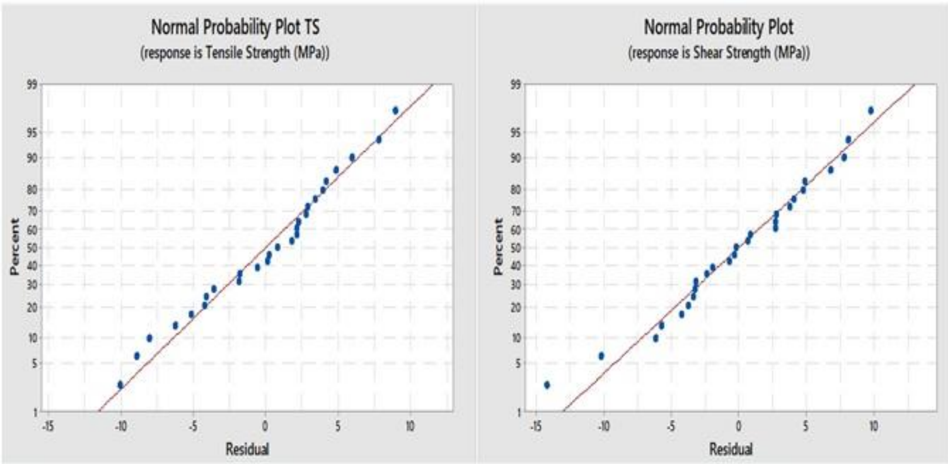

Fig. 8.Normal Probability Plots of tensile strength and shear strength

To validate the obtained regression model for the observed responses of friction welded dissimilar metal joints of pure Al and pure Cu, welding was performed with optimized process parameters i.e., with SS of 1100 rpm, FF of 6 kN, UF of 12 kN and BO of 4 mm for tensilestrength and with SS of 1050 rpm, FF of 8 kN, UF of 16 kN and BO of 8 mm for shear strength. By replacing the above values in the empirical equations developed, the predicted values for TS and SHS are 205 MPa (R-sq=99.92%) and 124 MPa (R-sq=99.72%) respectively. The values obtained are in agreement with values 198 MPa for TS and 122 MPa for SHS obtainedexperimentally.

3.4. Deformation rate and Weld time

The highest shear strength is for the joint obtained in the experiment no.5 (Table 5). This high shear strength can be attributed to the high deformation rate and low weld time (Fig.9 (a) and (b)).

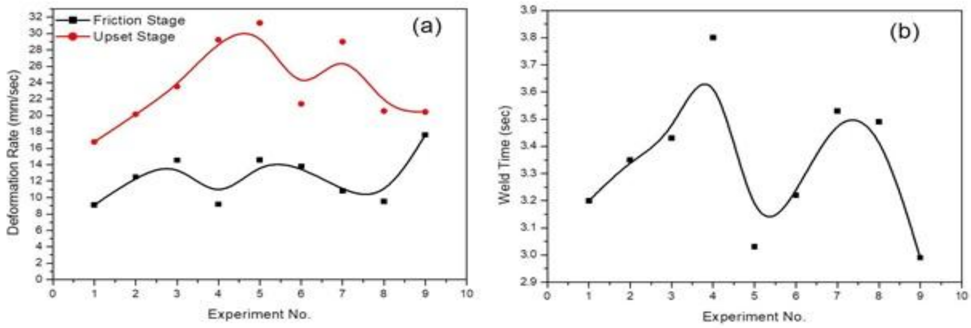

Fig. 9.Deformation Rate at Friction and Upset Stages

Due to shorter weld time, less amount of material is plasticized and due to the high deformation rate most of the plasticized material is pushed out of the joint interface by which the detrimental intermetallic compounds, if any, will be removed from the joint interface. This phenomenon will lead to better bonding at the joint interface. The wavy pattern of the weld line, as shown in Fig. 10 (a), also substantiates the high shear strength in the joint obtained in the experiment no.5. The length of the weld line is more compared to all other joints. Typical weld line of joint with lower shear strength is shown in Fig.10 (b).

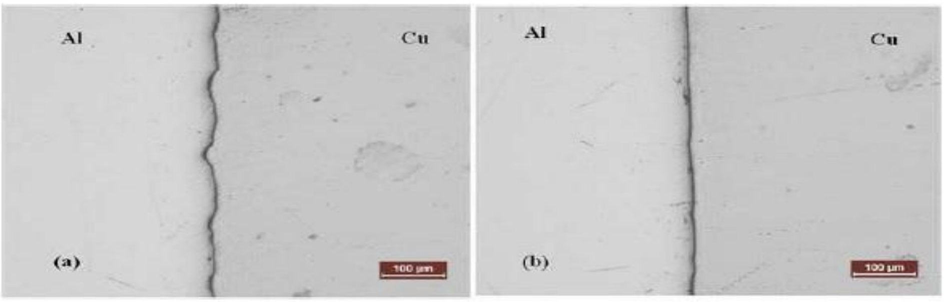

Fig. 10.Weld Line of the Joint

Though the deformation rate and weld time are low, the tensile strength of the joint obtained in experiment no.1 is high compared to that of all the other joints. This may be due to lesser effect of intermetallics as the load applied in tensile test is distributed across the cross-sectional area unlike in shear where the load applied is only in one plane along the weld line.The tensile property is influenced by a particular intermetallic layer thickness.

4. Conclusions

Pure Al and pure Cu rods of specified dimensions were welded by means of friction welding usingTaguchi L9 array with fourfactors and three levels. The responses measured were tensile strength and shear strength.

- Optimization of process parameters was done.
- According to DOE, UF is the significant parameter for TS followed by FF, SS and BO.
- According to DOE, SS is the significant parameter for SHS followed by UF, FF and BO.
- TS is maximum when the SS is at level 3, FF, UF and BO are at level 1and SHS is maximum when SS and FF are at level 2, UF and BO are at level 3.
- ANOVA analysis is performed and the results are compared with Signal to noise ratios of tensile strength and shear strength.
- Regression equations were developed and could be used for real time prediction of the responses without requiring experimental testing.
- The difference in the values of joint strengths welded using optimized parameters and the values obtained from regression analysis was found to be less than 5%.
- Obtained shear strength and tensile strength values are in tune with calculated deformation Rate and weld Time.

References

[1]S.D.Meshram, T. Mohandas and G. Madhusudhan Reddy. 2007. Friction welding of dissimilar pure metals. Journal of Materials Processing Technology 184: 330-337.doi: 10.1016/j.jmatprotec.2006.11.123.

[2] Paul Kah, Cyril Vimalraj, Jukka MartiKainen and Raimo Suoranta. Factors influencing Al-Cu weld properties by intermetallic compound formation. International Journal of Mechanical and Materials Engineering: 1-13, 2015.doi: 10.1186/s40712-015-0037-8.

[3] Bekir s. Yilba, Ahmet Z. Sahin, Nafiz Kahraman and Ahmed Z. Al-Garni. Friction Welding of St-Al and Al-Cu materials. Journal of Materials Processing Technology: 431-433, 1995.

[4] M Aritoshi and K okita. Friction welding of dissimilar metals. Welding International 17: 271-275, 2003. doi: 10.1533/wint.2003.3112

[5] Sandeep Kumar, Rajesh Kumar and Yogesh Kumar Singla. 2012. To study the mechanical behavior of friction welding of aluminium alloy and mild steel. International Journal of Engineering and Robotics Research: 43-50. doi: 10.18178/ijmerr

[6] AG. Wahyu Wibowo, Rifky Ismail and J. Jamari. Microstructure analysis in friction welding of copper and aluminum. AIP Conference Proceedings1725: 1-6, 2016. 10.1063/1.4945549.

[7] Avinash S. Pachal and Amol Bagesar. Taguchi Optimization of Process Parameters in Friction Welding of 6061 Aluminum Alloy and 304 steel: A Review. International Journal of Emerging Technology and Advanced Engineering4: 229-233, 2013.

[8] M. Maalekian. Friction welding - Critical assessment of literature. Science and Technology of Welding & Joining 12(8): 738-759, 2007.doi: 10.1179/174329307X249333.

[9] Mumin Sahin. Joining of aluminium and copper materials with friction welding. The International Journal of Advanced Manufacturing Technology 49: 527-534, 2010.doi: 10.1007/s00170-009-2443-7.

[10] Nada R. Ratković, Dušan M. Arsić, Vukić N. Lazić, Ružica R. Nikolić, Branislav Hadzima, Peter Palček and Aleksandar S. Sedmak. Influence of Friction Welding Parameters on Properties of the Al-Cu Joint. FME Transactions 45: 165-171, 2017.

[11] M Jayaraman, R Sivasubramanian, V Balasubramanian and A K Lakshminarayanan. Optimization of process parameters for friction stir welding of cast aluminium alloy A319 by Taguchi method. Journal of Scientific and Industrial Research 68: 36-43, 2009.

[12] S.Kannan, S. Senthil Kumaran, and L. A. Kumaraswamidhas. 2016. Optimization of friction welding by Taguchi and ANOVA method on commercial aluminium tube to Al 2025 tube plate with backing block using an external tool. Journal of Mechanical Science and Technology 30: 2225-2235.doi:10.1007/s12206-016-0432-y.