Experimental and modeling studies on joining of aluminum 5052 to copper joints fabricated by friction stir spot welding

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Abstract

In the present study, lap joints of dissimilar 5052 aluminum alloy and pure copper were fabricated by friction stir spot welding process. The work was aimed to find effect of parameters such as tool rotary speed (1000, 1400 and 2000 RPM) and dwell time (5, 10 and 15s) on mechanical properties such as lap shear strength and microstructure characterization. Also, statistical models of the quality characteristics were developed based on response surface methodology for further understanding of the results. Research findings showed that to obtain sound joints with high lap shear strength tool rotary speed of 2000 rpm and dwell time of 5 s should be selected. It provides sufficient heat input and prevents the excessive material softening. On the other hand, to achieve maximum hardness, 2000 rpm tool rotary speed should be chosen to provide enough heat for formation of intermetallic compound and 10 s dwell time should be used prevent enough time for grain roughening and coarse microstructure. Also, from the statistical optimization by RSM approach, it was found that dwell time and tool speed are the significant factor for lap shear strength and hardness, respectively. Moreover, results of multiobjective optimization revealed that to attain simultaneous maximum strength and hardness, tool speed of 2000 rpm and dwell time of 8 s should be used. In such condition lap shear strength of 1755 N and hardness of 77 V are achieved with desirability of 85%.

Keywords: Friction stir spot welding; Lap joint configuration; Dissimilar joints; Mechanical properties; Intermetallic compound

1. Introduction

Dissimilar joining of copper and aluminum is applicable for industries such as electronic, aerospace, transportation industries and automobile [1]. The fabricated products have been supported by the need to offer a distinct combination of properties required to manufacture lighter, safer, more environmentally friendly and ultimately cheaper structures. Aluminum alloys are desirable in these fields due to its low density and cost. Also, copper is a promising materials because of their high specific strength, formability and excellent electrical conductivity.

However, fabrication of sound joints made of aluminum and copper by fusion processes like electrical resistance spot welding (ERSW) is difficult due to difference in chemical, physical, mechanical and metallurgical properties of these alloys [2]. In such condition, hard and brittle intermetallic compound are formed in weld cross section that drastically reduced mechanical properties of the joints. Therefore, solid state joining processes such as explosive welding [3], roll welding [4] and friction welding [5] have been considered as the qualified welding methods for these metals.

By emerging friction stir welding (FSW) process as a solid-state joining process, problems such as high heat affected zone, formation of brittle structures, melting and degradation of materials which were faced by fusion welding processes in dissimilar joining were overcome. Hence, researchers have focused on use of FSW for dissimilar joining of aluminum to copper. For first time, Murr et al [6] reported joining of aluminum to copper by FSW. They found that defect free joints are difficult to be fabricated by use of this method. Ouyang et al [1] performed an experimental study to join aluminum 6061-T6 to copper by FSW. They showed that complex microstructure with several intermetallic compounds are observed in weld nugget. Xue et al [7, 8] studied effects of FSW main parameters and tool offsetting on mechanical properties of dissimilar AA1060 and Cu. They showed that the properties of fabricated joints significantly influenced by formation of intermetallic compounds and corresponding thickness. Tan et al [9] performed experimental work to find relationship between microstructure and mechanical properties of Al-Cu dissimilar joints. They found that by increasing heat generation caused by reduction of travel speed, large amount of copper particles is dispersed in upper surface of the weld nugget zone and causes formation of composite like surface that improves mechanical properties. Li at al [10] analyzed microstructure and mechanical properties of the Cu-AA1350 dissimilar butt joints. The research findings showed that vortex-like pattern and lamella structure are formed in the microstructure of the weld nugget. Also, the hardness distribution was higher in copper side than that of aluminum side. Galvao et al [11, 12] analyzed influence of tool offsetting on the morphology and structure of dissimilar aluminum 6082 to copper. They found that welding with tool offsetting formation of intermetallic compounds is prevented but metallurgical inconsistencies in the vicinity of advancing side are formed that have detrimental effect on weld strength. Muthu et al [13] analyzed effect of travel speed from 50 to 90mm/min with 10mm/min increment on mechanical properties and microstructure of the joints. They showed that travel speed of 70 and 80mm/min result to appropriate heat input to form sound welds. Also, various researchers showed feasibility of joining of aluminum to copper in lap configuration by friction stir welding by use a long weld line. Saeid et al. [14] used FSW to joint aluminum to copper sheets in lap configuration. They showed that increase in welding travel speed restricts formation of microcracks and intermetallic compound. Zhang et al. [15] applied water cooling method to FSW of lap Al-Cu joints in order to restrict excessive heat input that caused formation of intermetallic compound.

However, fabrication of lap joints of Al-Cu by friction stir spot welding (FSSW) has hardly been reported in the literatures. Hence, the present study focuses on the effect of the FSSW main parameters such as tool rotary speed and dwell time on the microstructure characterization, weld nugget formation, intermetallic compound and relevant mechanical properties. Also, response surface methodology is utilized here to identify which factors has great influence on tensile strength and hardness and to find optimum parameter setting regarding simultaneous maximization of tensile strength and hardness.

1. Materials and methods

The materials used to fabricate joints were made of AA5052 and pure copper with different chemical composition and material properties. Table 1 presents mechanical properties of parent material which obtained through tensile testing and Vickers microhardness analysis. Samples of aluminum and copper were prepared with dimensions of 1×20×100 mm^3 and secured in proper position by used of a hand-made clamping system. A hot worked tool made of AISI H13 was machined to form cylindrical tool with tapered like pin profile

Table 1 Mechanical properties of pure copper and AA5052

Type	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Hardness (Vickers)
Pure copper	180	270	39	125
AA5052	131	190	21	82

All the experiments were carried out on TBARIZ 4301 milling machine with 15hp power that was modified by FSSW attachment. After conducting experiments, lap shear testing was carried out by use of SANTAM universal testing machine with speed of 2mm/min. The hardness of welded cross section were also measured by means Vickers Mitutoyo microhardness tester.

To analyze microstructure of the weld nugget, welded samples were cross-sectioned and polished with emery papers and Al_2O_3 suspension. An optical microscope was utilized to observe the morphology and microstructure of weld samples. In addition, X-ray diffraction analysis was utilized to find dispersion of parent metal in weld nugget and to find material characterization in friction stir processed zone

To analyze effects of tool rotary speed (1000, 1500 and 2000 RPM) and dwell time (5, 10 and 15s) mechanical properties and material characterization, number of 9 experiments were conducted and values of tensile strength, hardness along with microstructural characterization were measured and observed through aforementioned equipment's. During the experiments, plunge rate and plunge depth were kept constant at the values of 20mm/min and 0.5mm respectively.

3. Results and discussion

3.1. Analyzing weld strength

Fig. 1 illustrates interaction effect of tool rotary speed and dwell time on lap shear strength of Al-Cu joints. It is seen in the figure that at 1000 RPM rotary speed, an increase in dwell time from 5 to 15s causes an 8.3% increase in weld strength. While at 1500 RPM speed, the weld strength firstly increases about 14% by increment of dwell time from 5 to 10s; but, by further increment of dwell time from 10 to 15s the weld strength decreases about 16.5%. on the other hand, when the tool rotary speed is 2000 RPM, it is seen from the fig. 1 that as dwell time increases, the weld strength decreases continuously about 27%.

When the tool rotary speed is 1000RPM, the heat input in friction stir processed (FSP) region is relatively low [16]. In such condition, by increase in dwell time the concentration of the heat increases that provides enough thermal energy for plasticization and stirring action. Thus, defects such as tunnel due to insufficient heat input is eliminated that causes increase in weld strength. Furthermore, due to concentration of more thermal at higher dwell time, the copper metal is softened and its contribution in formation of FSP region enhances. Hence, the weld shear strength increases. Fig. 2 represents macrostructure and microstructure of FSP region that produced at rotational speed of 1000 RPM and different dwell time. It is seen from macrostructure that by increase in dwell time the defect eliminated from weld macrostructure. Also, it is found from the figure that increase in dwell causes formation of further copper particles in FSP region that yields higher weld strength.

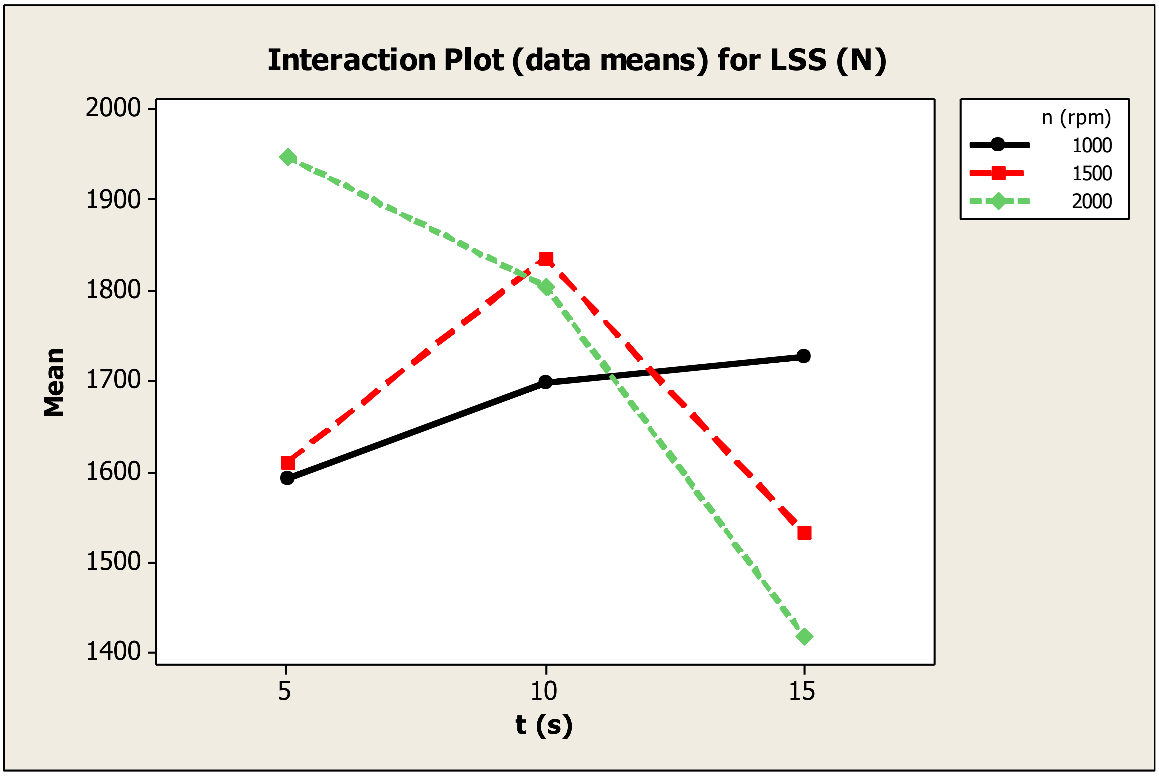


Fig. 1 Simultaneous effect of tool rotation speed and dwell time on lap shear strength

When the tool rotary speed is 1500 RPM, it is seen from the fig. 1 that by increase in dwell time from 5s to 10s the weld strength increases. As discussed, this improvement is due to providing enough heat input and sufficient material flow in FSP region that removes defect and enhances the weld strength. However, when the dwell time goes beyond a critical value of 10s, it is seen a drastic reduction occurs in lap shear strength. This decrease is because to the fact that at high dwell time, the thermal energy concentration is excessive that causes material softening. Therefore, by plunging force of the tool, the thickness of aluminum side decreases that results to a reduction in weld strength [17].

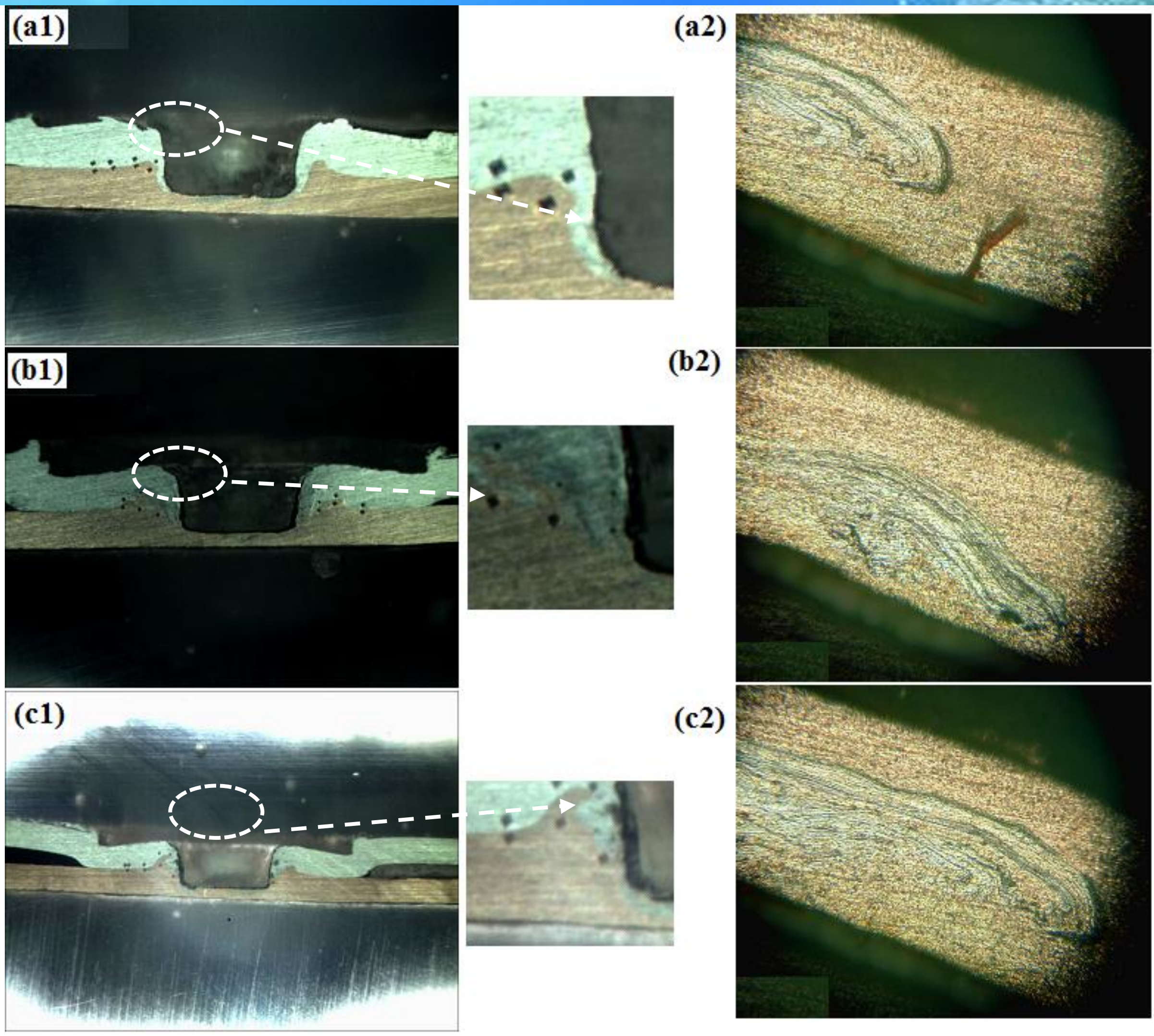


Fig. 2 Macrostructure and microstructure of FSP region at tool rotation of 1000 RPM and different dwell time (a) 5s (b) 10s (c) 15s

Fig. 3 illustrates macrostructure of the weld region at 1500 RPM rotary speed and different dwell time. It is found from the figure that a 5s dwell time due to less concentration of thermal energy a tunnel like defect is formed between aluminum and copper in keyhole region. Also, it is found that at 10s dwell time the defect is eliminated and sound joint is fabricated. On the other hand, it is inferred from fig. 3c that at 15s dwell time due to excessive heat input material softening occurs that causes thickness reduction in aluminum side and formation of pin hole defect in keyhole region that restricts weld strength.

However, it is seen from the fig. 1 that at 2000 RPM tool rotation, by increase in dwell time the weld strength decreases, subsequently. When the tool rotation is 2000 RPM, the heat input is relatively high; hence, at 5s dwell time the sufficient thermal energy is provided that is enough for plasticization, stirring action and material flow. However, by increase in dwell time, due to excessive heat input, the material softening occurs in both aluminum and copper that causes a reduction in the thickness of the sheets. In such condition the strength of the lap configuration drastically decreases.

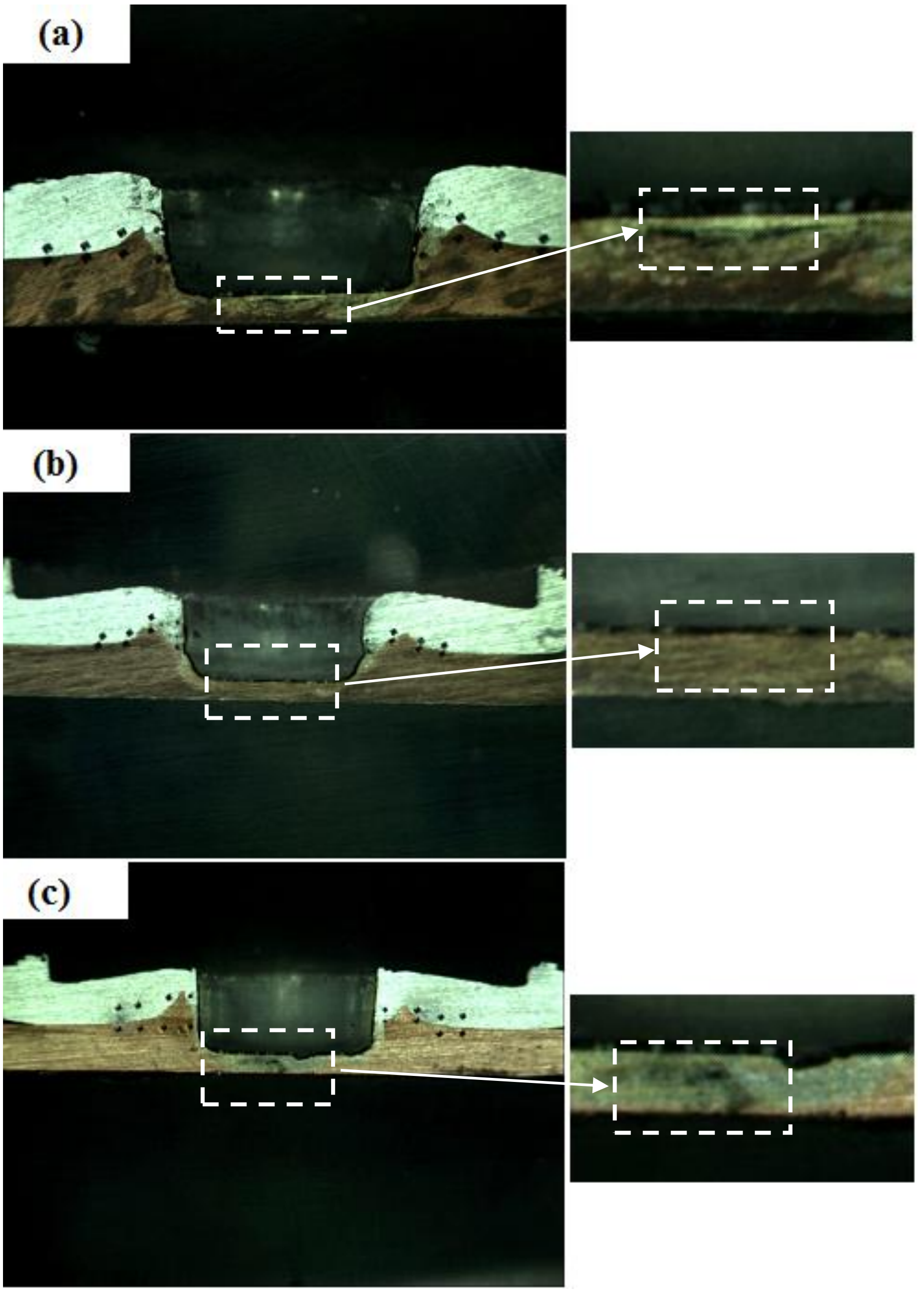


Fig. 3 Macrostructure of the weld region at rotation of 1500 RPM and different dwell time (a) 5s (b) 10s (c) 15s

The macroscopic image of weld cross section at 2000RPM rotary speed is visible in fig. 4 It is ascertained from the figure 4a that at 5s dwell time the macrostructure is free from defect and thinning in the thickness. While, at 10 and 15s dwell time due to excessive heat input and material softening, a sever thinning occurs in weld macrostructure that damages the joint strength.

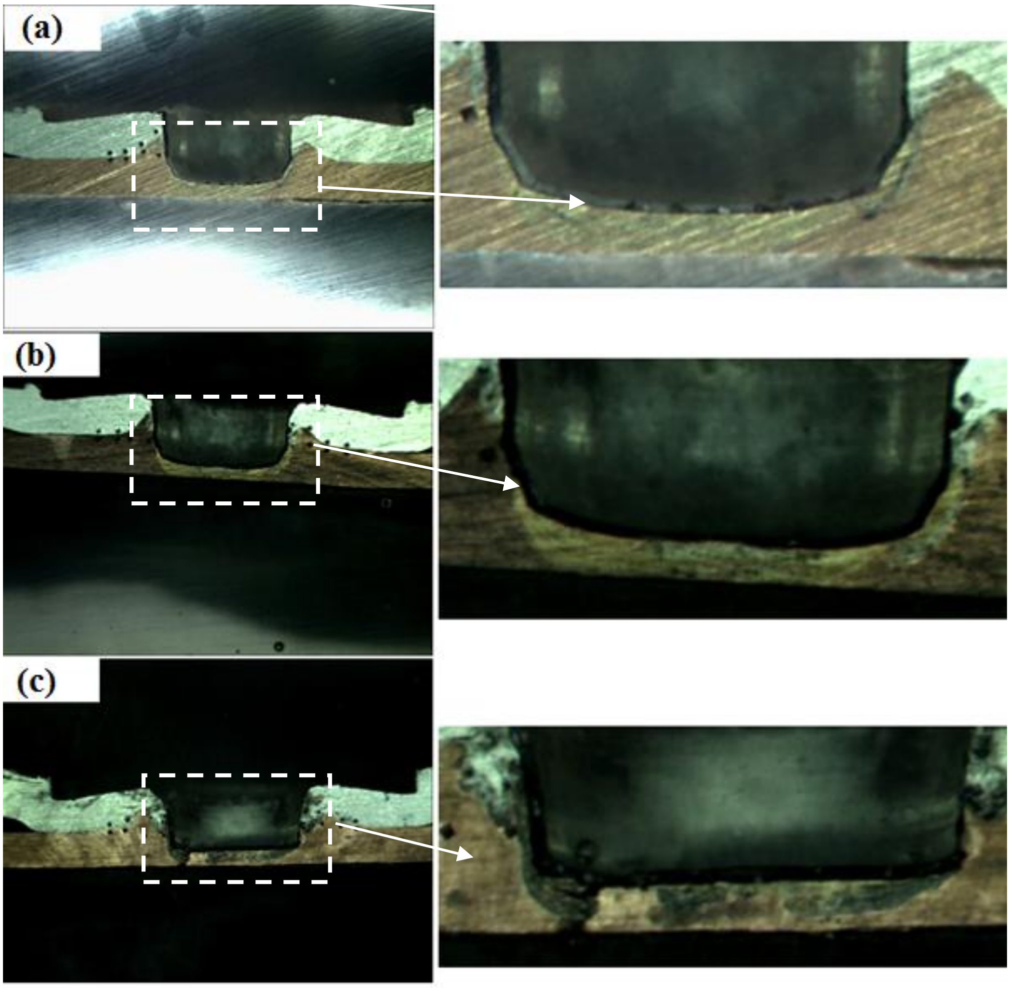


Fig. 4 Macrostructure of the weld region at rotation of 2000 RPM and different dwell time (a) 5s (b) 10s (c) 15s

3.2. Analyzing weld nugget hardness

In order to analyze the hardness of weld nugget. The cross section of the joint was prepared and the microhardness was measured in three locations of aluminum side, copper side and interface; then the average of microhardness for each weld sample was reported. Fig. 5 indicates effect of dwell time on hardness of the joint which were fabricated under different tool rotary speed.

It is seen from the figure that at 1000 RPM tool rotation, the hardness value decreases about 13.8% by increase in dwell time from 5s to 15s. Also, when the tool rotary speed is 1500 RPM, as the dwell time increases, the hardness of weld nugget increases about 16% and reaches to a maximum value at 15s. Moreover, at 2000 RPM rotation speed of the tool, the hardness value firstly increases about 12.6% by increase in dwell time from 5s to 10s; but, by further increase in dwell time from 10s to 15s, the hardness decreases about 10%.

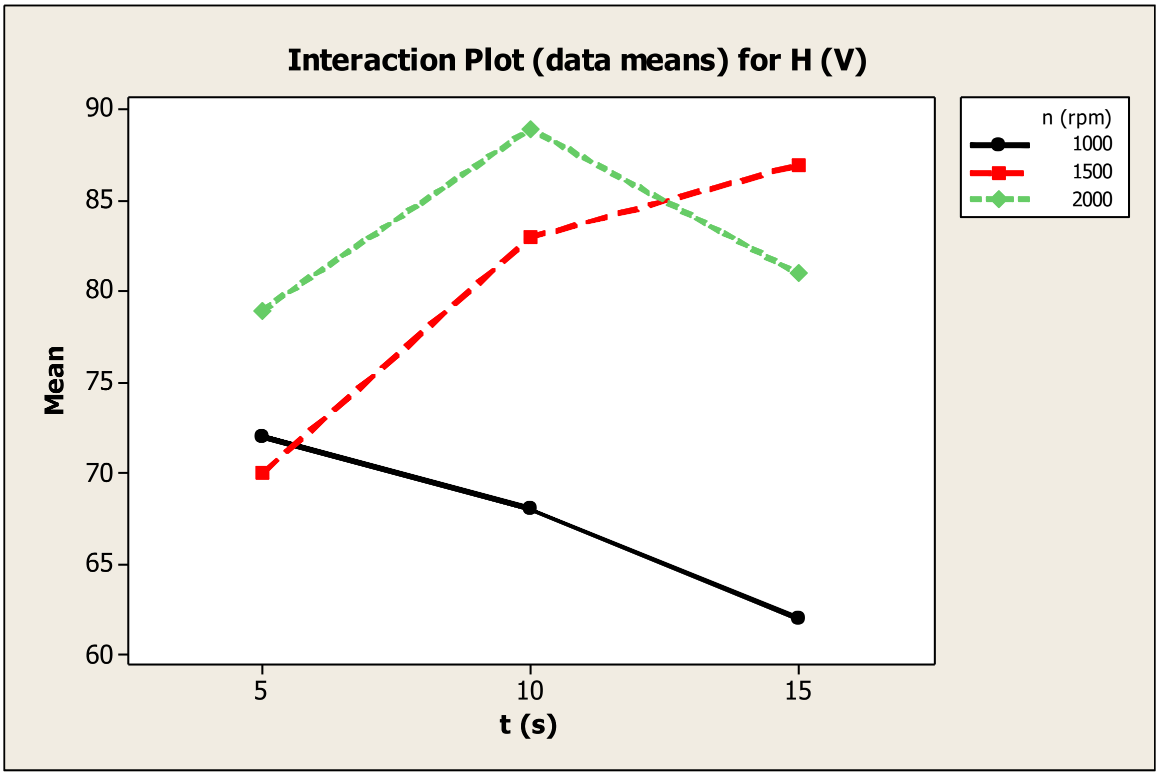


Fig. 5 Simultaneous effect of tool rotation speed and dwell time on weld nugget hardness

During welding of dissimilar materials. There are two important factors that significantly affect hardness of the weld nugget. One is size of microstructure and two is formation of intermetallic compounds [18]. According to Hall-Petch law, the finer microstructure results to higher hardness values. Also, intermetallic compound is type of ceramic material with high hardness and brittleness that formed under high heat input condition.

At 1000 RPM, tool rotary speed, the heat input is relatively low. Hence, sufficient heat for formation of intermetallic compound isn't provided. In such condition increase in dwell time provides enough time and heat for recrystallization and enlarging the grains in the microstructure. Therefore, the hardness of weld nugget decreases by an increase in dwell time due to formation of coarse microstructure in weld nugget. Fig. 6 illustrates XRD pattern and microstructure of the weld nugget at 1000 RPM tool rotation and different dwell time. It is inferred from the fig. 6a that no intermetallic compound is formed at 1000 RPM tool rotation and different dwell time. Also, from fig. 6b and 6c, it is seen that by increase in dwell time the microstructure of the weld nugget becomes coarser in both the aluminum and copper sides that reduce the hardness value.

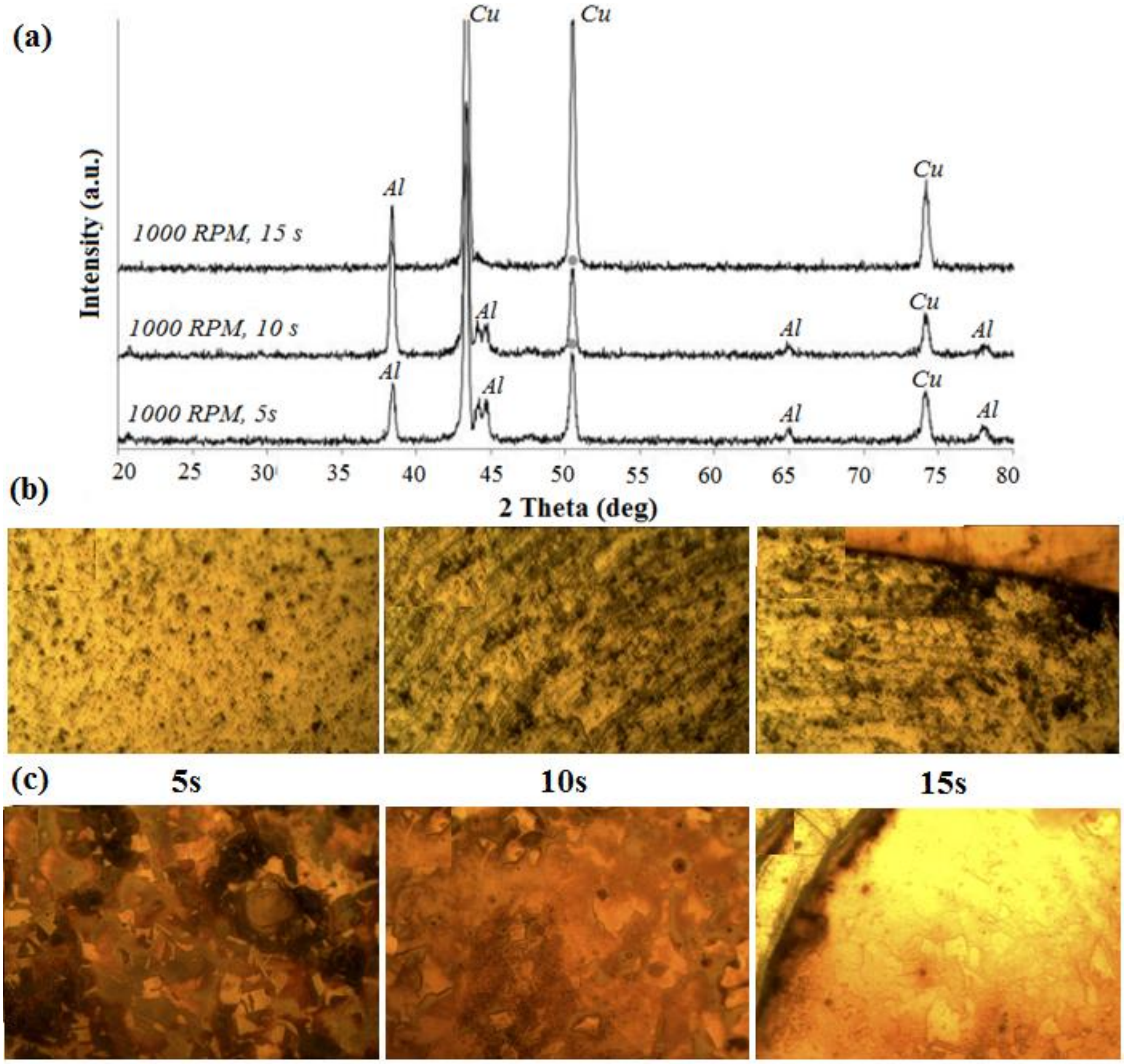


Fig. 6 (a) XRD pattern of the sample at 1000 RPM (b) Microstructure of the aluminum side (c) Microstructure of the copper side

It is also found from the fig. 7 that at 1500RPM tool rotation, the hardness increases by increase in the dwell time. When the tool rotation is 1500 RPM, enough heat for formation of intermetallic compound is provided. In such condition by increase in dwell time concentration of thermal energy enhances that causes formation of more intermetallic compound in weld nugget. Therefore, weld nugget hardness increases. Fig. 7 represents XRD pattern of the samples fabricated at tool rotation of 1500RPM under different dwell time. It is seen from the figure at 5s dwell time due to low heat input, no intermetallic compound is formed in weld nugget. Also, it is seen when the dwell time is 10s, compounds such as Al_2Cu and Al_4Cu_9 are seen in the XRD pattern. It is also seen that at 15s dwell time, number of peaks in XRD pattern is relatively higher showing more amount of intermetallic compound that exist in the weld nugget.

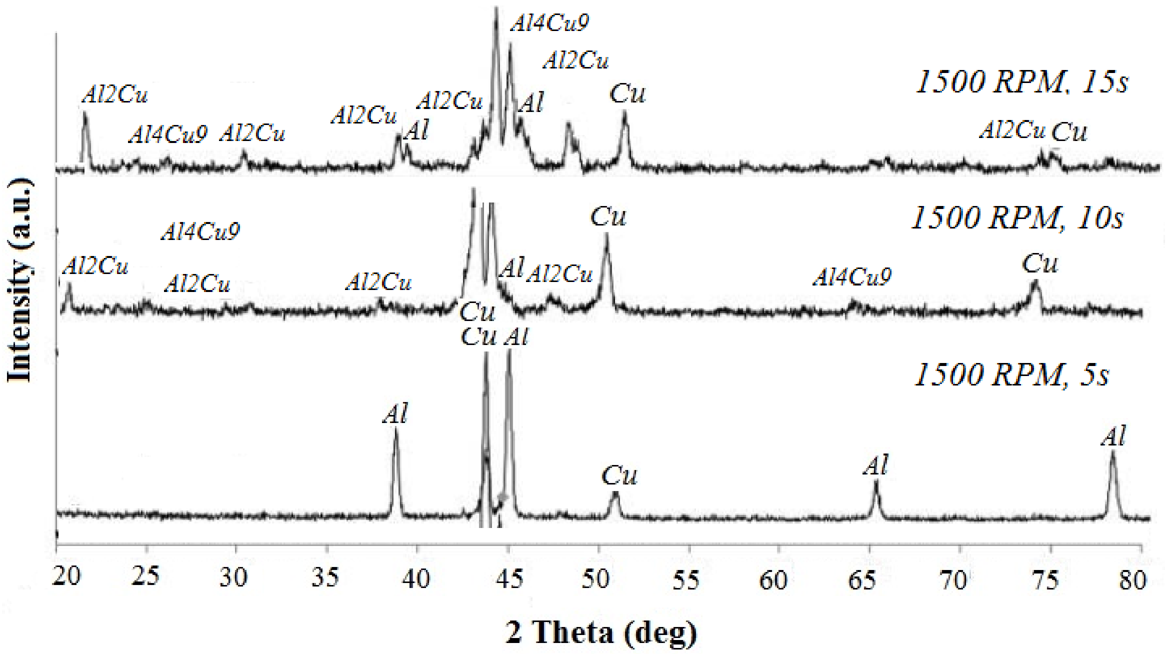


Fig. 7 XRD pattern of samples at 1500 RPM tool rotation under different dwell time

It is also ascertained from fig. 5 that at 2000 RPM tool rotation, the hardness value firstly increases as dwell time increases from 5 to 10s. This increase is due to formation another type of intermetallic compound like Al_2O_3 ceramic in weld nugget that significantly enhances the hardness value. It is further seen in the figure that as dwell time increases from 10s to 15s, the coarse and rough microstructure are formed in weld region. Nevertheless, the ceramic compound formed when dwell time is 15s, but the roughening effect of microstructure outperforms influence of intermetallic compound that causes low hardness value. Fig. 8 illustrates XRD patterns and microstructure change by dwell time at 2000 RPM rotation speed. It is seen from the fig. 8a at 10s and 15s dwell time a new type of intermetallic compound such as alumina is formed in the nugget. Therefore, the hardness increases. Also, from the fig. 8 b and c, it is observed that increase in dwell time causes coarse microstructure in both sides of aluminum and copper. Thus, a very rough structure damages the mechanical properties of weld nugget and decreases the hardness at 15s dwell time.

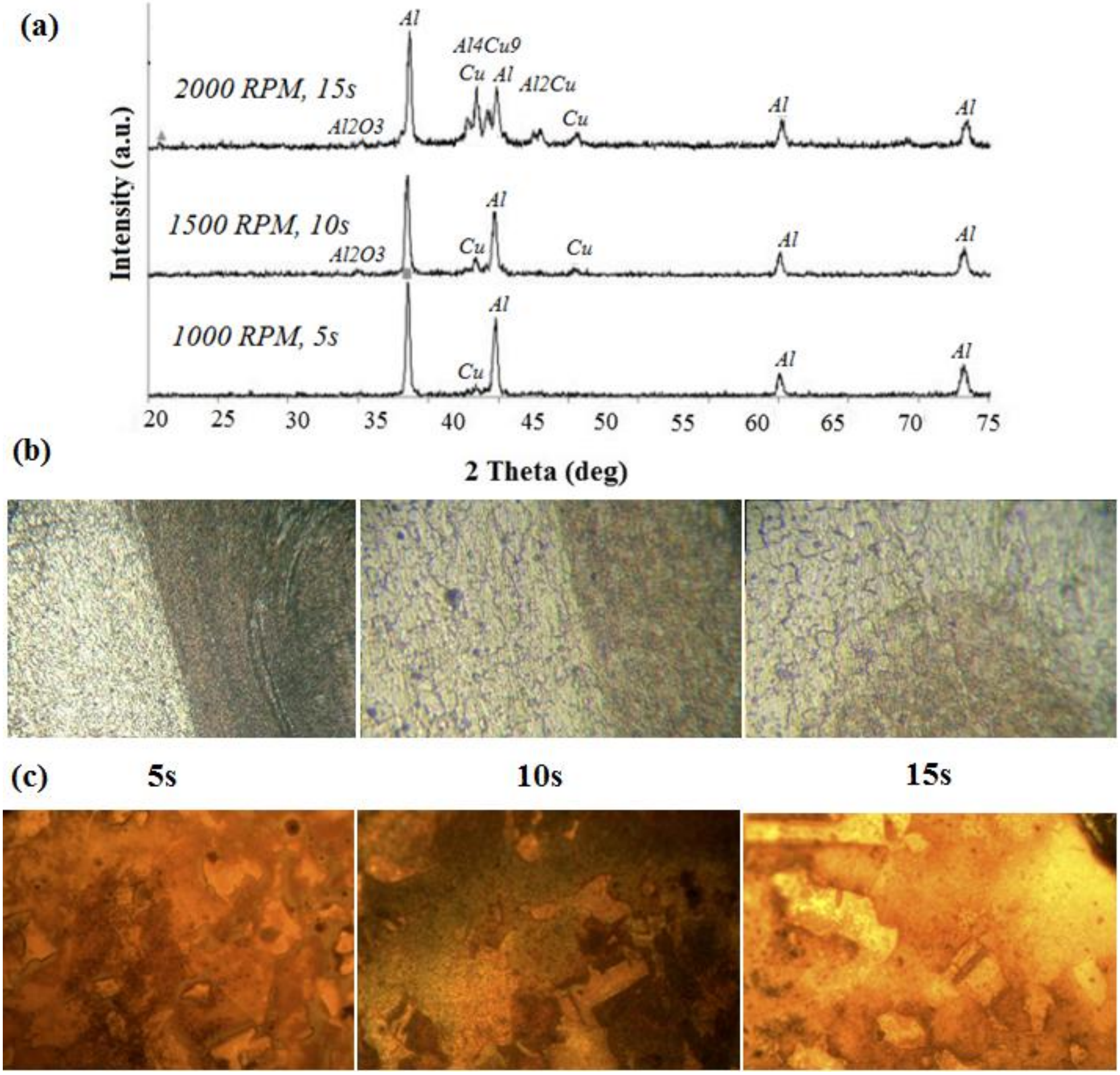


Fig. 8 (a) XRD pattern of the sample at 2000 RPM (b) Microstructure of the aluminum side (c) Microstructure of the copper side

3.3. Statistical analysis

In order to develop empirical relationship between tool rotation sped and dwell time to lap shear strength and hardness response surface methodology is utilized. The procedure of regression analysis was carried out in commercial statistical package Design Expert V7 software, and the validity of full quadratic models were evaluated by analysis of variances and coefficient of determination i.e. R^2. Analysis of variances is also used here to find which factor has greatest contribution on process quality characteristics. Second order polynomial model of responses including linear, interaction and quadratic terms of tensile strength and hardness are expressed in Eq. 1 and Eq. 2, respectively.

$$LSS(N) = 237.3 + 0.65N + 223.8t - 0066Nt - 7.017t^2 \quad (1)$$

$$H(V) = 9.25 + 0.075N + 1.09t + 0.001Nt - 0.137t^2 \quad (2)$$

To check the accuracy of developed models, analysis of variances of lap shear strength and hardness has been carried out and the results were presented in Table 1 and 2, respectively. It is seen from the tables that the values of Prob>F are lower than 0.05 that mean the model terms are significant. Also, the value for the term of lack-of-fit higher than 0.1 indicates that this term is insignificant. In addition, the coefficient of determination R^2 is in good agreement with adjusted R^2 and this implies high mathematical validity of regression functions [19]. According to the ANOVA results of tables 2 and 3, it is inferred that the dwell time and tool rotation are most influential factor for lap shear strength and hardness, respectively. Also, the contributions of the significant terms in developing mathematical models of lap shear strength and hardness are shown in Fig. 9. It is seen from the figure that in developing statistical model of the lap shear strength interaction of tool rotation and dwell time has significant influence; while for mathematical model of the hardness, the linear effect of tool rotation is the most significant term. According to ANOVA results, it is found that all the developed regression models are adequate and they are qualified enough to make compatibility between parameters and corresponding quality characteristics.

Thee developed RSM models can be used to analyze effect of process factors on lap shear strength and hardness. Hence, the response surfaces of process factors on aforementioned responses were drawn and presented in fig. 10. It is seen from the fig. 10a that the maximum lap shear strength is achievable by selection of 2000 RPM tool rotation and 5s dwell time. Furthermore, maximum hardness could be obtained when the tool rotary speed is 2000 RPM and dwell time is 10s. Hence, to simultaneously achieve maximum strength and hardness, multi-objective optimization should be performed. In other words, it is not possible to have maximum strength and hardness with as same parameter setting. Therefore, optimization should be carried out to find which parameter setting satisfies maximum strength and hardness.

Table 3 ANOVA results for lap shear strength

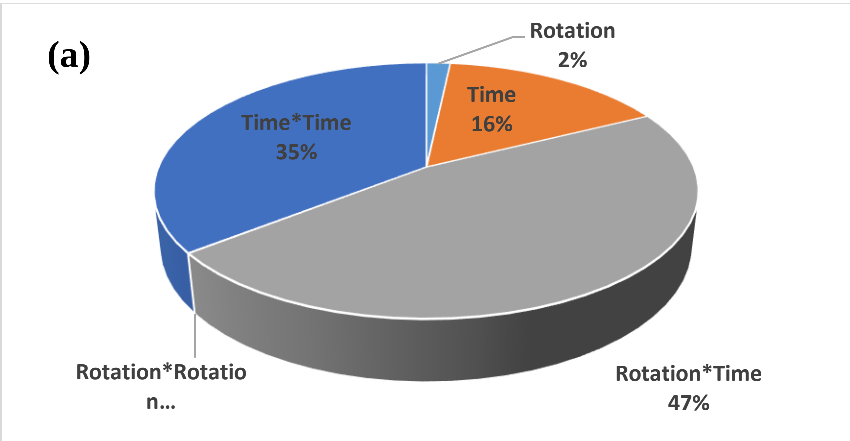
Source	Sum of squares	Degree of freedom	F-value	Prob>F
Model	246000	5	11.43	0.0029
N	3952.67	1	0.92	0.3699
t	37446	1	8.7	0.0214
$N\times t$	109600	1	25.45	0.0015
N^2	104	1	0.024	0.8839
t^2	83486	1	19.39	0.0031

R^2=0.93

Table 4 ANOVA results for hardness

Source	Sum of squares	Degree of freedom	F-value	Prob>F
Model	601.47	5	6.87	0.0125
N	368.17	1	21.03	0.0025
t	2.67	1	0.15	0.7
$N\times t$	36	1	2.06	0.1947
N^2	94.5	1	5.39	0.053
t^2	30.9	1	1.77	0.2259

R^2=0.96



(b)

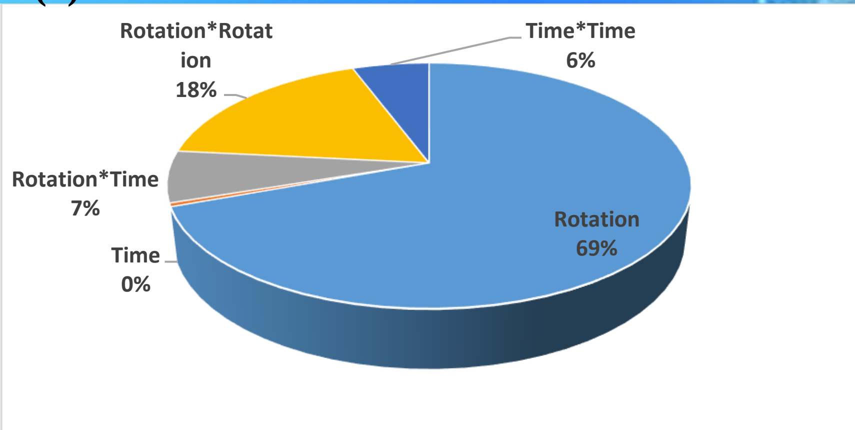


Fig. 9 Pie graphs showing contribution of model terms in (a) lap shear strength (b) hardness

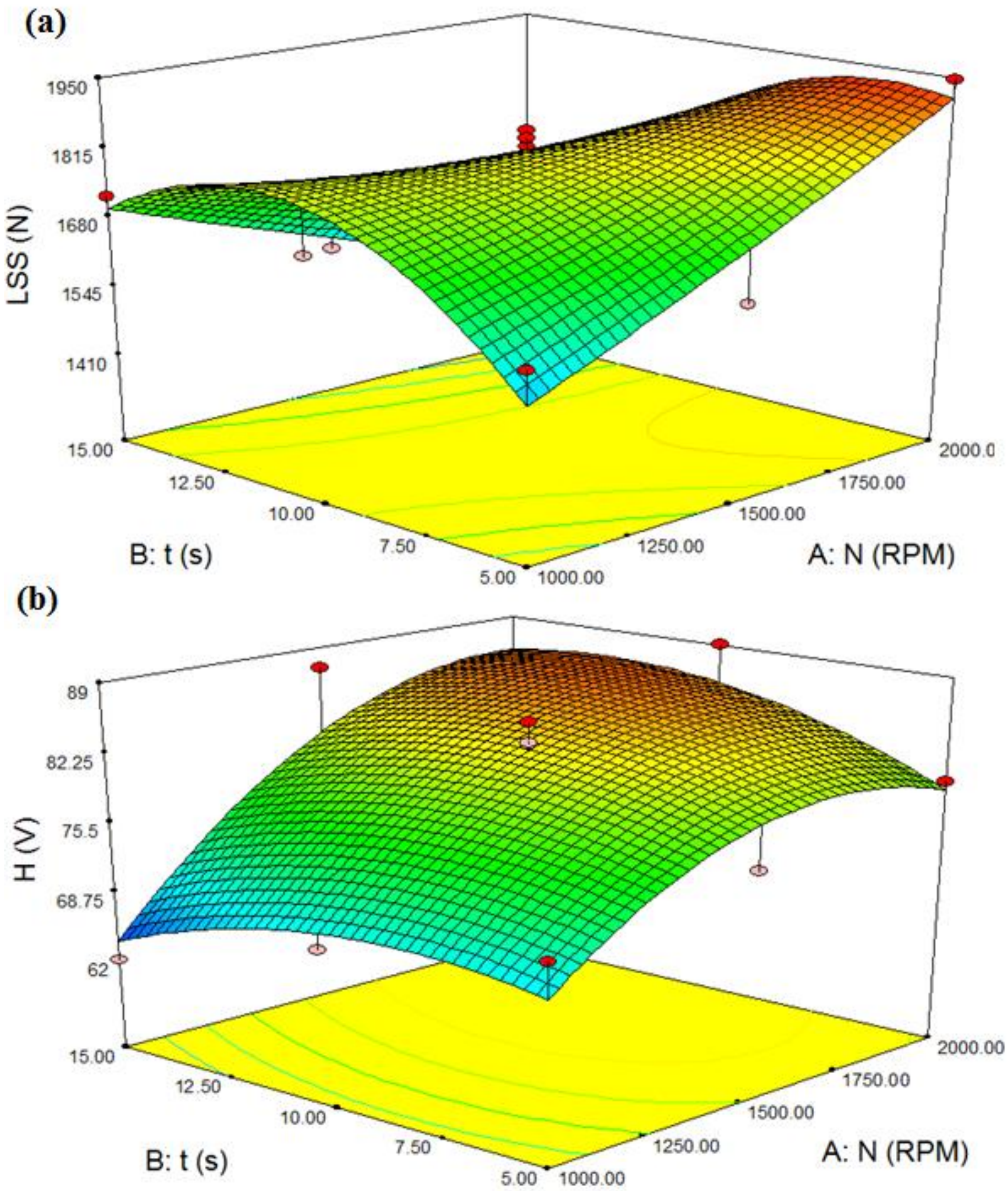


Fig. 10 Response surface of tool rotation and dwell time on (a) lap shear strength (b) hardness

In the present study, to find optimal parameter setting in a multi-objective optimization problem, desirability approach function was utilized. Solving such multiple-response optimization problems using this technique involves combining multiple responses into a dimensionless measure of performance called the overall desirability function [20]. The equation of desirability for goals of maximum along with overall objective functions is calculated by means of equations 3 and 4, respectively.

$$d_i = \begin{cases} 0 & Y_i < Low_i \\ \left(\frac{Y_i - Low_i}{High_i - Low_i}\right)^w & Low_i < Y_i < High_i \\ 1 & Y_i > High_i \end{cases}$$

(3)

$$D = \left(\prod_{i=1}^{n} d_i^{r_i}\right)^{1/\sum r_i}$$

(4)

Where *Y* is the given response and *Low* and *High* are the minimum and maximum value of the response, respectively. *r* is the number of response and *w* is the weight factor which varied over the range of 0.1 to 1.

To perform multi-characteristics optimization by desirability approach, firstly the optimization criteria should be identified. Table 3 presents the defined criterion for optimization. Design Expert statistical software was utilized here to find optimal results. Table 4 illustrates the optimum solution that obtained through desirability function. It is evident from the table that setting of 1972 RPM tool rotation and 8.38s dwell time is the most optimal solution that causes desirability of 85.6% with strength value of 1894N and hardness of 84V. The obtained solution should be experimentally verified to show applicability of proposed approach in optimization of FSSW process. The results of confirmatory experiment have been also presented in table 4. It is found from this table that the error values for both of lap shear strength and hardness are less than 8% that shows the excellent agreement with actual and predicted values.

Table 3 Optimization criterion

Factors/Responses	Criterion	Importance
Tool rotation (RPM)	In range of 1000-200	-
Dwell time (s)	In range of 5-10	-
Lap shear strength (N)	Maximize	*****(5)
Hardness (V)	Minimize	***** (5)

Table 4 Optimum parameter setting along with validation test results

Factor		Lap shear strength (N)			Hardness (V)			Objective
N (RPM)	t (s)	Experiment	Model	Error	Experiment	Model	Error	Desirability
1982	8.3	1803	1894	0.05	78	84	0.076	0.856

4. Conclusion

In the present study, lap joints of dissimilar 5052 aluminum alloy and pure copper were fabricated by friction stir spot welding process. Microstructural evolution and XRD pattern of fabricated samples were obtained to analyze the mechanical properties such as lap shear strength and hardness. Also, statistical analysis based on response surface methodology and analysis of variances were carried out to find contribution of significant terms and optimal parameter setting regarding desired quality characteristics. The obtained results can be summarized as follows:

- It is found from the results that sound joints with high lap shear strength is obtained when the tool rotation is 2000 RPM and swell time is 5s.
- The microstructure of the FSP region at 2000 RPM and 5s dwell time showed uniform dispersion of Cu in aluminum matrix and no metallurgical defect was observed in macrostructure.
- From the obtained microhardness results, it is found that tool rotation of 2000 RPM and dwell time of 10s causes highest hardness in weld nugget including aluminum side, copper side and interface.
- The types of intermetallic compound in the sample at 2000 RPM tool rotation and 10s dwell time were Al_2Cu, Al_4Cu_9 and Al_2O_3 than significantly increases the hardness.
- From statistical analysis, it was identified that dwell time and tool rotation are the most influential factor affecting lap shear strength and hardness, respectively.
- Multi-objective optimization of process parameters showed that achieving simultaneous maximum strength and hardness is possible by selection of 2000 RPM tool rotation and 8.3s dwell time. The desirability of optimum results was about 86% and the prediction error for the quality characteristics was less than 8%.

References

1. Ouyang, J., Yarrapareddy, E., & Kovacevic, R. (2006). Microstructural evolution in the friction stir welded 6061 aluminum alloy (T6-temper condition) to copper. Journal of Materials Processing Technology, 172(1), 110-122.
2. Sun, Z., & Karppi, R. (1996). The application of electron beam welding for the joining of dissimilar metals: an overview. Journal of Materials Processing Technology, 59(3), 257-267.
3. Kahraman, N., Gülenç, B., & Findik, F. (2005). Joining of titanium/stainless steel by explosive welding and effect on interface. Journal of Materials Processing Technology, 169(2), 127-133.
4. Abbasi, M., Taheri, A. K., & Salehi, M. T. (2001). Growth rate of intermetallic compounds in Al/Cu bimetal produced by cold roll welding process. Journal of Alloys and Compounds, 319(1), 233-241.
5. Uzun, H., Dalle Donne, C., Argagnotto, A., Ghidini, T., & Gambaro, C. (2005). Friction stir welding of dissimilar Al 6013-T4 to X5CrNi18-10 stainless steel. Materials & design, 26(1), 41-46.
6. Murr, L. E., Li, Y., Trillo, E. A., Flores, R. D., & McClure, J. C. (1998). Microstructures in friction-stir welded metals. Journal of materials processing and manufacturing science, 7, 145-161.
7. Xue, P., Xiao, B. L., Ni, D. R., & Ma, Z. Y. (2010). Enhanced mechanical properties of friction stir welded dissimilar Al–Cu joint by intermetallic compounds. Materials Science and Engineering: A, 527(21), 5723-5727.
8. Xue, P., Ni, D. R., Wang, D., Xiao, B. L., & Ma, Z. Y. (2011). Effect of friction stir welding parameters on the microstructure and mechanical properties of the dissimilar Al–Cu joints. Materials science and engineering: A, 528(13), 4683-4689.
9. Tan, C. W., Jiang, Z. G., Li, L. Q., Chen, Y. B., & Chen, X. Y. (2013). Microstructural evolution and mechanical properties of dissimilar Al–Cu joints produced by friction stir welding. Materials & Design, 51, 466-473.
10. LI, X. W., ZHANG, D. T., Cheng, Q. I. U., & ZHANG, W. (2012). Microstructure and mechanical properties of dissimilar pure copper/1350 aluminum alloy butt joints by friction stir welding. Transactions of Nonferrous Metals Society of China, 22(6), 1298-1306.
11. Galvão, I., Loureiro, A., Verdera, D., Gesto, D., & Rodrigues, D. M. (2012). Influence of tool offsetting on the structure and morphology of dissimilar aluminum to copper friction-stir welds. Metallurgical and Materials Transactions A, 43(13), 5096-5105.
12. Galvão, I., Leitão, C., Loureiro, A., & Rodrigues, D. M. (2012). Study of the welding conditions during similar and dissimilar aluminium and copper welding based on torque sensitivity analysis. Materials & Design, 42, 259-264.
13. Muthu, M. F. X., & Jayabalan, V. (2015). Tool travel speed effects on the microstructure of friction stir welded aluminum–copper joints. Journal of Materials Processing Technology, 217, 105-113.
14. Saeid, T., Abdollah-Zadeh, A., & Sazgari, B. (2010). Weldability and mechanical properties of dissimilar aluminum–copper lap joints made by friction stir welding. Journal of Alloys and Compounds, 490(1), 652-655.
15. Zhang, J., Shen, Y., Yao, X., Xu, H., & Li, B. (2014). Investigation on dissimilar underwater friction stir lap welding of 6061-T6 aluminum alloy to pure copper. Materials & Design, 64, 74-80.
16. Elangovan, K., & Balasubramanian, V. (2007). Influences of pin profile and rotational speed of the tool on the formation of friction stir processing zone in AA2219 aluminium alloy. Materials Science and Engineering: A, 459(1), 7-18.
17. Elangovan, K., Balasubramanian, V., & Valliappan, M. (2008). Influences of tool pin profile and axial force on the formation of friction stir processing zone in AA6061 aluminium alloy. The international journal of advanced manufacturing technology, 38(3-4), 285-295.
18. Rajakumar, S., Muralidharan, C., & Balasubramanian, V. (2011). Predicting tensile strength, hardness and corrosion rate of friction stir welded AA6061-T 6 aluminium alloy joints. Materials & Design, 32(5), 2878-2890.

19. Myers, R. H., Montgomery, D. C., & Anderson-Cook, C. M. (2016). Response surface methodology: process and product optimization using designed experiments. John Wiley & Sons.
20. Del Castillo, E., Montgomery, D. C., & McCarville, D. R. (1996). Modified desirability functions for multiple response optimization. Journal of quality technology, 28, 337-345.