



Lap joining of aluminum 5052 to copper by optimum friction stir spot welding process

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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 simultaneous effect of parameters such as tool rotary speed (1000, 1500, and 2000 rpm) and dwell time (5, 10, and 15 s) on lap shear force (LSF), hardness, and microstructure evolution. Also, statistical models of the quality characteristics were developed to understand which parameter has dominant effect on quality characteristics. Research findings showed that to obtain sound joints with high lap shear strength, tool rotary speed of 1500 rpm and dwell time of 15 s should be selected. It provides sufficient heat input for mechanical interlocking and prevents the formation of coarse and thick intermetallic compounds (IMCs) in the stir zone. 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 to prevent enough time for microstructure refining. Moreover, from the statistical analyses, it was found that dwell time and tool speed are the significant factors for lap shear strength and hardness, respectively. In order to attain simultaneous maximum strength and hardness, tool speed of 1630 rpm and dwell time of 14 s should be used. In such condition, lap shear strength of 1980 N and hardness of 78 V are achieved with desirability of 86%.

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 and power systems [1]. The goal of addition of aluminum and copper is to achieve light and safe products which work more environmentally friendly and have cheaper cost. Each element of the fabricated joints can satisfy specific demand where aluminum is a low density and cheap alloy; also copper has desired formability and excellent electrical and thermal conductivities.

However, fabrication of sound joints made of aluminum and copper by fusion processes like electrical resistance spot

welding is difficult due to difference in physical chemical, chemical, metallurgical, and mechanical properties of these alloys. In such case, in order to achieve sound well, the process should be hybrid by external heating in order to compensate thermal defects [2]. Therefore, solid state joining of aluminum and copper can be used as successful method for welding of these alloys [3]. By emerging friction stir welding (FSW) process, problems such as high heat affected zone, formation of brittle structures, melting, and degradation of materials which were known as main problems of by fusion welding are covered by FSW. During last decades, several researchers attempted to use FSW for joining of aluminum to copper.

Tan et al. [4] performed experimental work to find relationship between microstructure and strength 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. Zhang et al. [5] reported that performing FSW under presence of water cooling prevents excessive heat input and subsequent formation

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of thick intermetallic compounds. Following to these modifications, mechanical properties of AA6061 and copper significantly enhance. Muthu et al. [6] analyzed effect of travel speed from 50 to 90 mm/min with 10 mm/min increment on mechanical properties and microstructure of the joints. They showed that travel speed of 70 and 80 mm/min results 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 of a long weld line.

Sahu et al. [7] performed a research to obtain sounds Al-Cu butt joints by FSW process. They revealed that placing the copper in advancing side and tool offset in aluminum side by amount of 1.5 mm leads to achieving strong joint with 95% strength of aluminum parent metal. Argesi et al. [8] used SiC nanoparticles to reinforce the Al-Cu joints fabricated by FSW. They exhibited that the sound joint can be achieved by selection welding speed of 50 mm/min rotary speed of 1000 rpm. The stirring action by the aforementioned setting results in uniform dispersion of nano-sized SiC in stir zone that reduces the grain size of aluminum and copper from 38.3 and 12.4 μm to 12.9 and 5.1 μm , respectively.

Khajeh et al. [9] used FSW for joining of aluminum 2024 to copper. The optimum values of ultimate tensile strength 142 MPa, elongation 5%, and electrical resistivity 33 n Ωm obtained by FSW at a rotational speed of 948 rpm and a traverse speed of 85 mm/min. They also revealed that IMCs and voids in the non-optimum joints were the origin of lower strength and ductility and higher electrical resistivity.

Friction stir spot welding (FSSW) has been also used for fabrication of the lap joints made of aluminum and copper [10]. Siddharth et al. [11] developed a processing window by selecting optimal FSSW parameter while joining of aluminum 5052 and copper C27200. They applied statistical methods to correlate rotational speed, plunge depth, and dwell time to lap shear force and hardness. However, they lack to provide exact physical meaning of variation by microscopic analysis. Li et al. [12] performed deep analyses to understand whether the joint mechanical properties, i.e., strength and hardness efficiency, are influenced by dwell time. Zhou et al. [13] in same research team performed a similar research to identify how the tool rotational speed influences the joint quality under constant values of dwell time. Nevertheless, they carried out valuable research in understanding the mechanism of weld nugget formation and IMCs generation, and they only analyzed influence of dwell time without consideration to other parameters such as tool rotational speed.

Therefore, according to these three recent publications, i.e., [11–13], and their mentioned drawbacks, the authors of the current work present a deep analysis to understand how the tool rotational speed and dwell time simultaneously influence joint properties of Al-Cu fabricated by FSSW process. Present investigation focuses on the effect of the FSSW main

Table 1 Mechanical properties of pure copper and AA5052

Type	YS (MPa)	TS (MPa)	E (%)	H (V)
Pure copper	120	151	39	85
AA5052	131	190	21	105

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 have great influence on tensile strength and hardness and to find optimum parameter setting regarding simultaneous maximization of tensile strength and hardness.

2 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 is obtained through tensile testing and Vickers microhardness analysis. Samples of aluminum and copper were prepared with dimensions of $1 \times 20 \times 100 \text{ mm}^3$ 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. The FSSW experiments for joining of aluminum to copper in lap joints were conducted on universal milling machine made of TBARIZ corporation. The machine was set up with a clamping system to restrict the elements in secured position.

Lap shear strength of the joints was measured by use of SANTAM universal testing machine with speed of 2 mm/min. The tensile test machine's grippers were designed in such way they can have lateral motion for lap shear test. Thus, during the shear test, the samples in both grippers remain parallel. To analyze microstructure of the weld nugget, welded samples were cut from their cross-sectioned and subjected to metallographic activities such as polishing and etching. The etchants were used in different sections

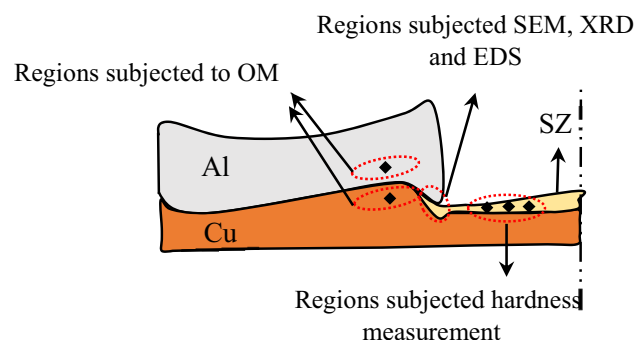


Fig. 1 A schematic diagram showing different regions of measurement and microscopic observations

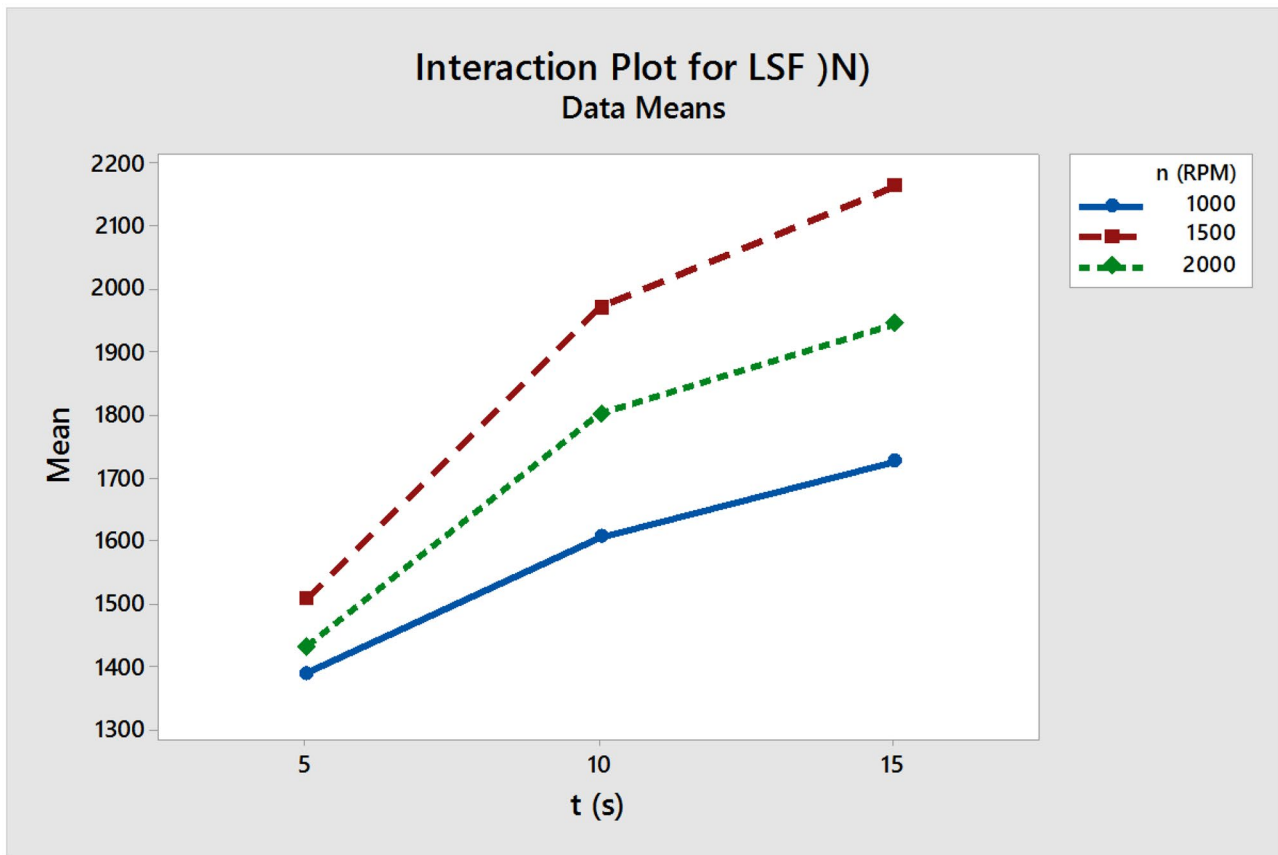


Fig. 2 Simultaneous effect of tool rotation speed and dwell time on lap shear strength

of the joint were selected based on composition of material. Macrographs and microstructures of weld nugget were observed by optical microscope MITUTOYO 1000 \times magnification) lined by quantitative image analyzer software. Also, to further study the microstructure alternation, TESCAN scanning electron microscope was utilized. Of the weld sample was utilized to observe the morphology and microstructure of weld samples. The electron dispersive spectrum (EDS) analysis was used to determine the composition of the various intermetallic formed in the Al–Cu weld interface. In addition, X-ray diffraction (XRD) examination was utilized to find dispersion of parent metal in weld nugget using STRESSTECH machine by CuK α radiation, 1.5406 $^{\circ}$ A wave length under a working voltage of 40 kV, and current of 40 A. The hardness of the samples was measured by microhardness tester (Shimadzu and Model: HMV-2 T) with penetration load 0.05 kg at 15 s exposure time.

The hardness and microstructure analyses were carried out on different regions including Al side, Cu side, and stir zone (SZ) as schematically demonstrated in Fig. 1. Also, the XRD and EDS analyses were carried out on SZ in order to identify the characteristics of intermetallic laminates in terms of

composition, thickness, and distributions. Figure 1 characterizes the different regions including the hardness measurement locations which were identified by black pyramids.

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

3 Results and discussion

3.1 Analyzing weld strength

Here firstly the effect of process factors on joint strength is discussed based on physic of the process, then microscopic analyses are provided to justify the results. Among the 9 fabricated samples, those with maximum and minimum lap shear force were taken into account for discussion

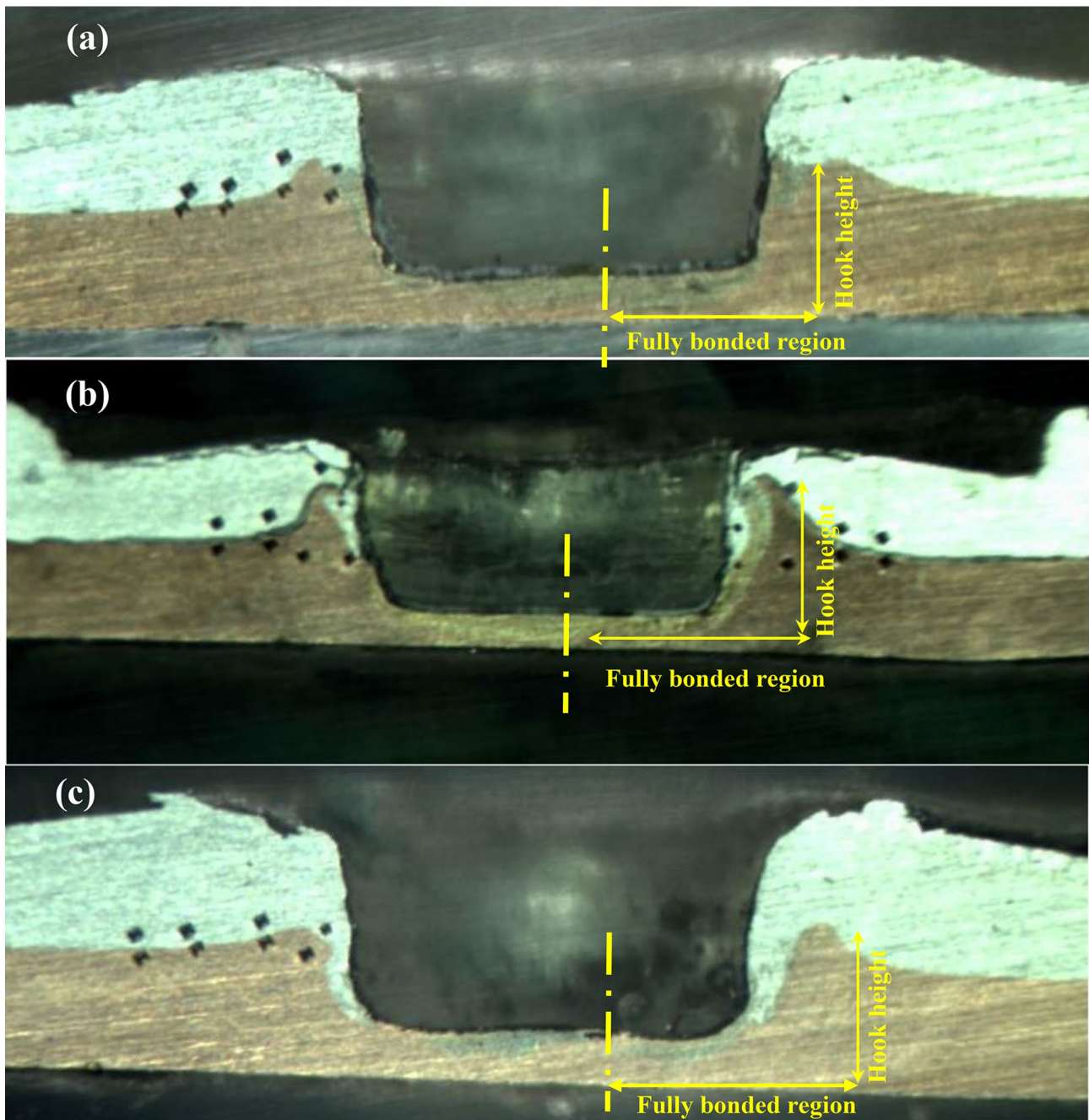


Fig. 3 Macrostructure of weld cross section for different samples: **a** N1000-t5, **b** N1500-t15, **c** N2000-t15

through macroscopic and microscopic observation as well as the fractography analyses.

Figure 2 illustrates the lap shear force of the samples produced under different values of tool rotational speed and dwell time. According to the results presented in Fig. 2, it is seen that irrespective to the values of tool rotational speed, the joint strength increases by increasing the dwell time. As result of increase in dwell time, under constant values of tool rotational speed, the temperature

in the interface of sheets increases that results in material softening and enhancement of material flow [14]. In such condition, the stirring action enhances and results in formation of stronger bond between the aluminum and copper. As results of sufficient heat input, a hook and fully bonded regions which are formed from copper side and extended into aluminum region are significantly bigger (as shown in Fig. 3). This leads to interlocking between the Al and Cu that yields greater joint strength [12]. On the

other hand, Al_4Cu_9 intermetallic compounds are formed and uniformly distributed in stir zone that increases the joint strength.

It can be also seen from Fig. 2 that irrespective to the dwell of time, the joint strength increases when the tool rotational speed reaches up to certain limit (i.e., 1500 rpm). On the other hand, as result of further increase in tool rotary speed, the joint strength is reduced. Tool rotational speed corresponds to heat generation in FSW process. Once the tool rotary speed increases from 1000 to 1500 rpm, as result of further heat generation, the material in both the aluminum and copper sides is softened and enhances the stirring action. In such condition as result of heterogeneous mixing, interlocking phenomenon due to hook and fully bonded regions formation increases (Fig. 3b) that yields further joint strength [13]. On the other hand, when the tool rotary speed reaches to 2000 rpm, as result of excessive heat input, shape of stir zone is changed and results in reduction of hook height due to curling action (Fig. 3c) [12]. On the other hand, as result of excessive heat input, the intermetallic compound is coarsened; accordingly, as result of formation of thick and coarse brittle intermetallic compounds (that is shown in Fig. 4c), the cracks are formed in line with this layer and deteriorate the joint strength.

3.2 Microscopic analysis

In order to justify the results by, macroscopic images of joint cross sections, microscopic image of joint interface, and the XRD and EDS analyses of IMCs have been provided and presented in this section. The samples which were considered for these analyses are those that have minimum and maximum joint strength, i.e., those fabricated by tool rotational speed of 1000 rpm and dwell time of 5 s (i.e., N1000-t5) and tool rotary speed of 1500 rpm and dwell time of 15 s (i.e., N1500-t15). Furthermore, a sample with excessive heat input condition, i.e., tool rotary speed of 2000 rpm and dwell time of 15 s (i.e., N2000-t15), was also taken into consideration. Through these selections, conditions of insufficient heat input, sufficient heat input, and excessive heat input can be understood.

3.2.1 Macrostructure

Figure 3 demonstrates the macroscopic image of weld cross section under different above-mentioned conditions. It is seen from Fig. 3a that for the sample fabricated by N1000-t5, as result of insufficient heat input, material softening is limited and plastic flow occurs only in small scope that leads small stir zone and subsequent low joint strength. For the sample fabricated by N1500-t15 (Fig. 3b), as result of

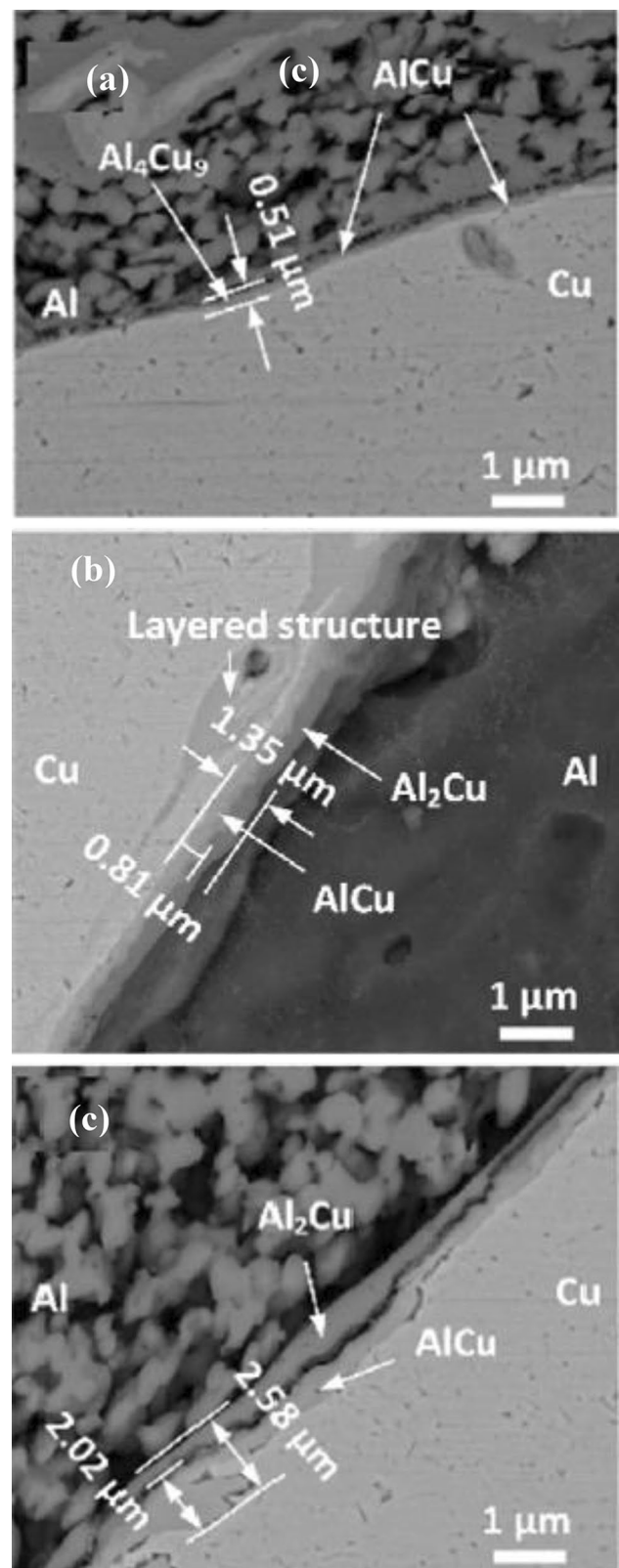


Fig. 4 SEM micrographs of interface of Al-Cu for different samples: **a** N1000-t5, **b** N1500-t15, **c** N2000-t15

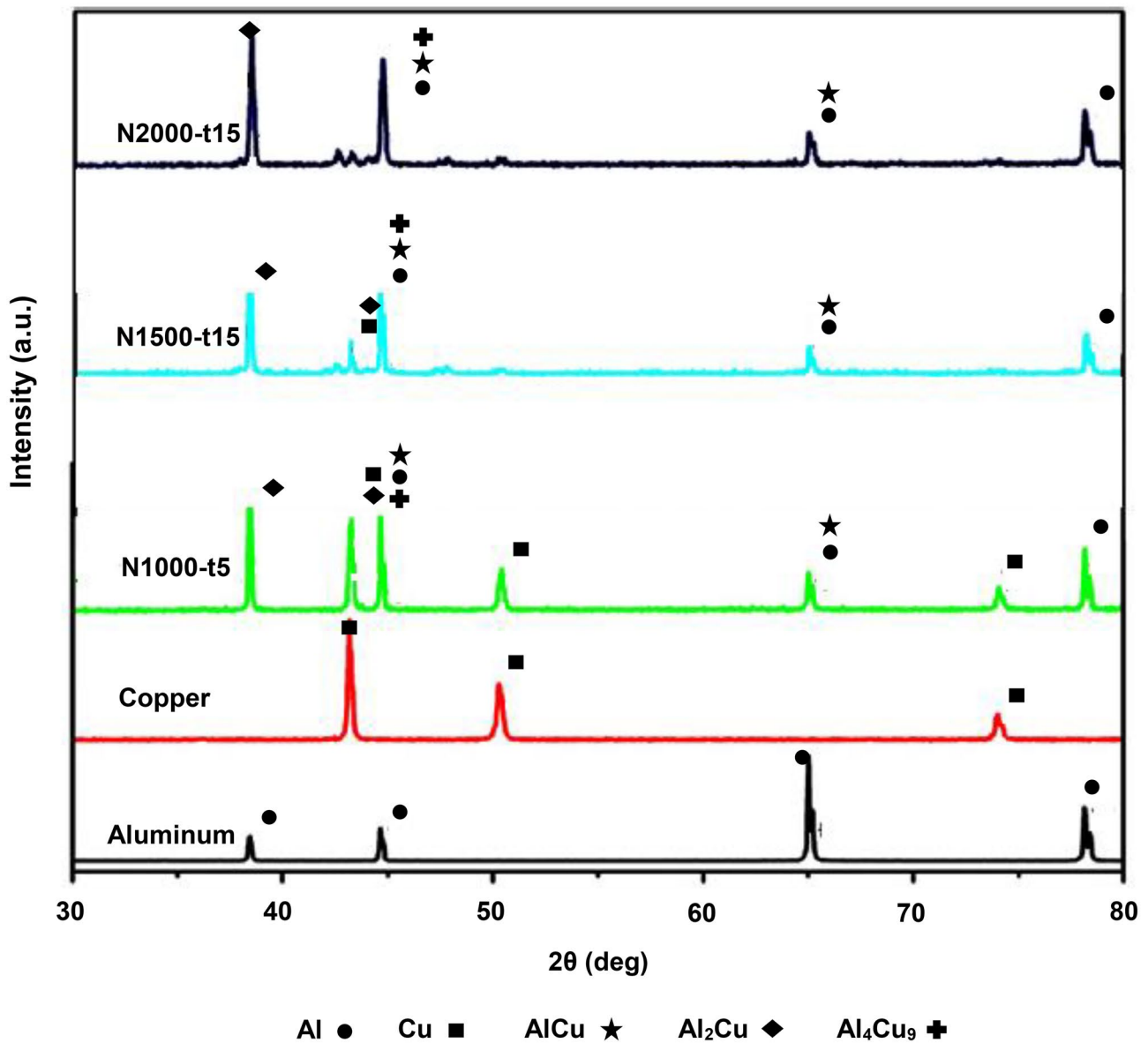


Fig. 5 XRD pattern showing phases formed for different samples

providing sufficient heat input, the size of stir zone is obviously increased. In such condition, Cu hook that is formed upward into Al sheet as result of extrusion and sufficient stirring action is visible. In addition, a fully bonded region is also formed in the stir zone. The formation of hook and fully bonded region enhances the mechanical interlocking and yields further joint strength. For the sample produced by N1000-t5 (Fig. 3a), it is seen that the height of hook is very short and width of fully bonded region is very narrow. On the other hand, for the sample fabricated by N2000-t15 (Fig. 3c), as result of excessive heat input, the Cu hook is curled and results in reduction of joint strength.

3.2.2 Microstructure

SEM images of the joint interface in stir region close to hook are presented in Fig. 4. It is clear from Fig. 4a–c that intermetallic layers are formed in the stir zone where aluminum meets copper. The XRD analysis of the interface shows that the intermetallic phases which were formed in the interface are AlCu, Al₂Cu, and Al₄Cu₉ as shown in Fig. 5. Generally, these types of compound are dispersed in the stir zone and produce composite-like structure. Their amount and distribution are determined by heat input and stirring action. As results of increased heat input, the Cu can be

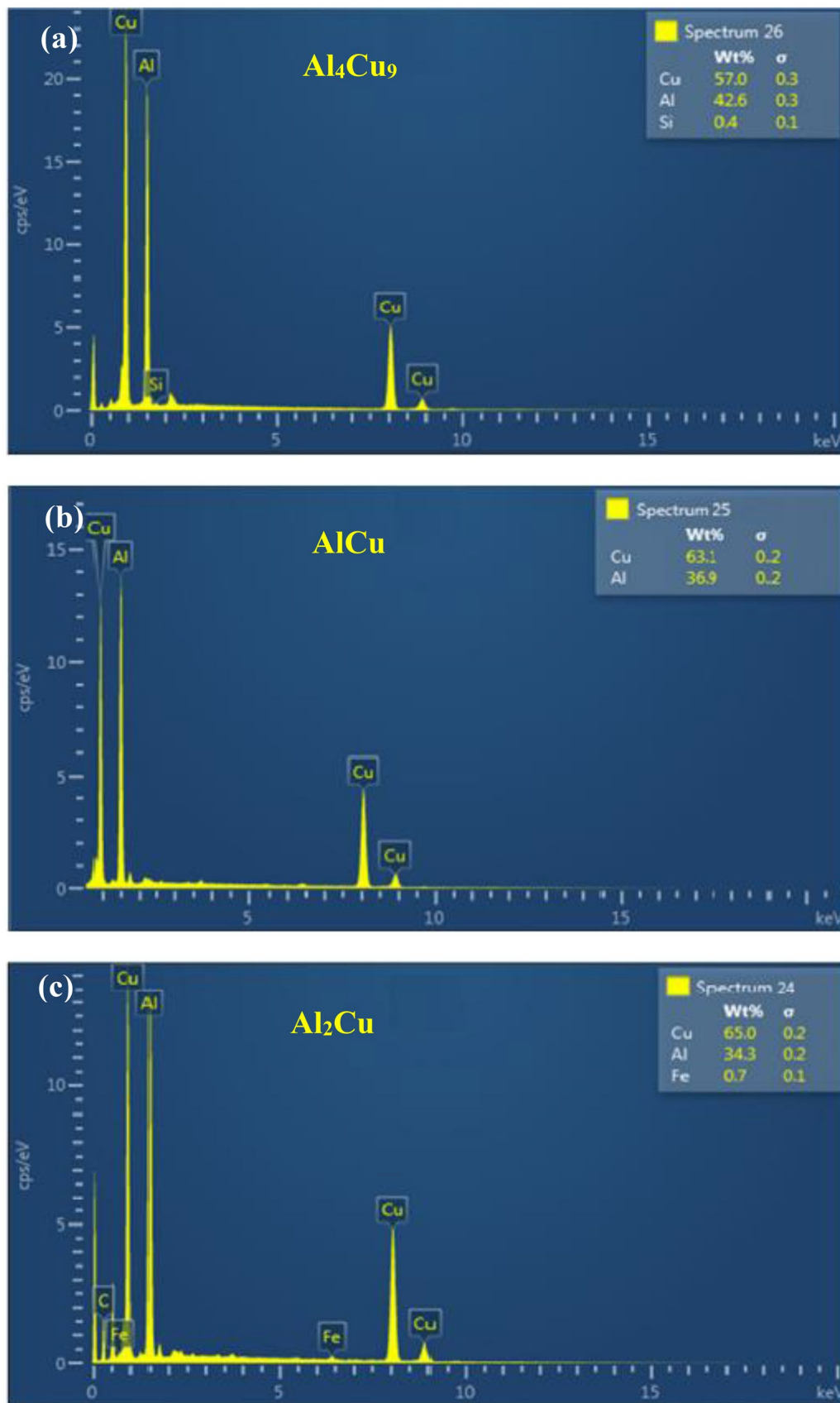
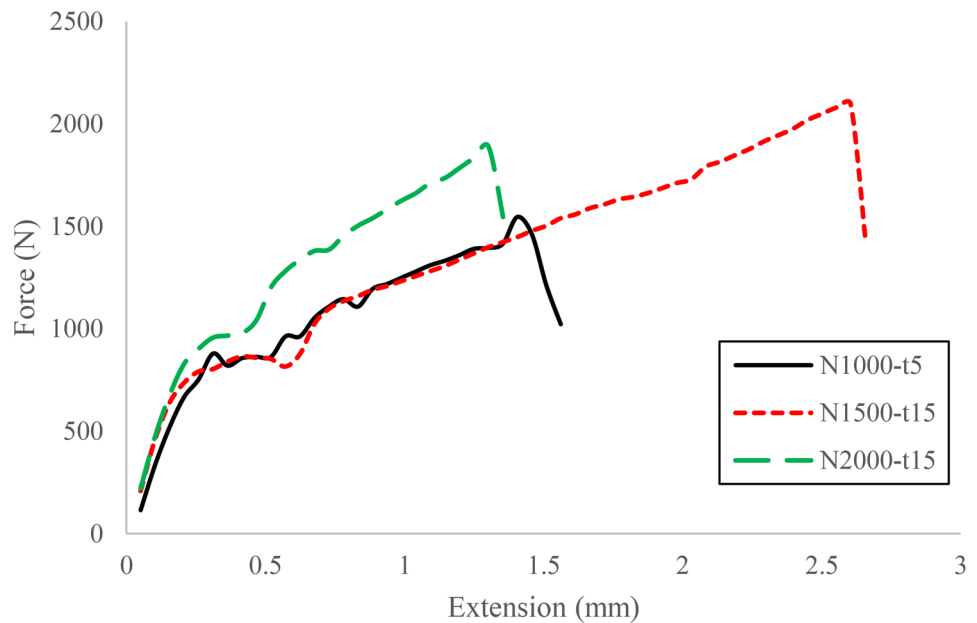


Fig. 6 EDS analysis of IMCs for **a** Al_4Cu_9 , **b** AlCu , and **c** Al_2Cu

Fig. 7 Force-extension curve showing tensile properties of the selected joints



softened and contribute more into the formation of IMCs. Furthermore, as result of thermomechanical load (further tool rotational speed and dwell time) in the interface, the distribution of these compounds enhances and results in further joint strength and hardness. Figure 6a, b, c demonstrate the EDS analysis of the IMCs Al_4Cu_9 , $AlCu$, and Al_2Cu that formed in the interface shown in Fig. 4a, b, c, respectively.

3.2.3 Tensile properties and fracture location

Figure 7 demonstrates the force-extension curves of the samples fabricated by N1000-t5, N1500-t15, and N2000-t15. According to this figure, it is seen that the maximum joint strength and elongation belong to the sample that is fabricated by N1500-t15. The fracture location in this sample is located at joint interface and the SEM image of the fracture surface in both aluminum and copper sides can be found in Fig. 8b. It is seen from the figure that the fracture location in copper side comprises the dimples that confirm good bonding strength between the Al and Cu. The dimpled surface also reveals that the sample has elongated during tensile testing that is completely in agreement with high elongation values presented in Fig. 7 [15]. As result of sufficient heat input, mechanical interlocking and uniform and fine dispersion of IMCs in the stir zone result in fabrication of the sound joint with high strength and ductility. The sample that is fabricated by N1000-t5 has minimum joint strength, but its elongation value is a bit further than that fabricated by N2000-t15. For the sample fabricated by N1000-t5, as result of insufficient heat input mechanical interlocking as result of hooking action of copper into aluminum side is very limited

that results in low joint strength. Furthermore, because of insufficient heat input, amount of brittle IMCs in stir zone is restricted that results in further ductility (compared to the sample fabricated by N2000-t15). Thus in the fracture region of this sample that is located in the interface, both the aluminum and copper comprise partial dimples in flat area (Fig. 8a). For the sample fabricated by N2000-t15 as result of formation of thick IMCs, the fracture mechanism (that is located in joint interface) seems brittle (Fig. 8c). The surface is completely flat with very limited dimples that confirm that type of fracture is more brittle than ductile. The information obtained by fractography analysis are completely matched with the force-extension curves of the samples after tensile shear testing.

3.3 Analyzing weld nugget hardness

In order to analyze the hardness of weld nugget, the cross section of the joint was prepared and the microhardness stir zone which is demonstrated in Fig. 1 was measured in three different locations and the mean value was reported as hardness. Figure 9 simultaneously effect illustrates effect of tool rotational speed and dwell time on weld nugget hardness. It is seen from the figure that when the tool rotary speed is 1000 and 1500 rpm, the hardness increases with increase of increase of dwell time. When the tool rotary speed is 2000 rpm, the stir zone hardness increases by increase of dwell time from 5 to 10 s. By further increase of dwell time (reaching to 15 s) at 2000 rpm tool rotational speed, the hardness dramatically decreased.

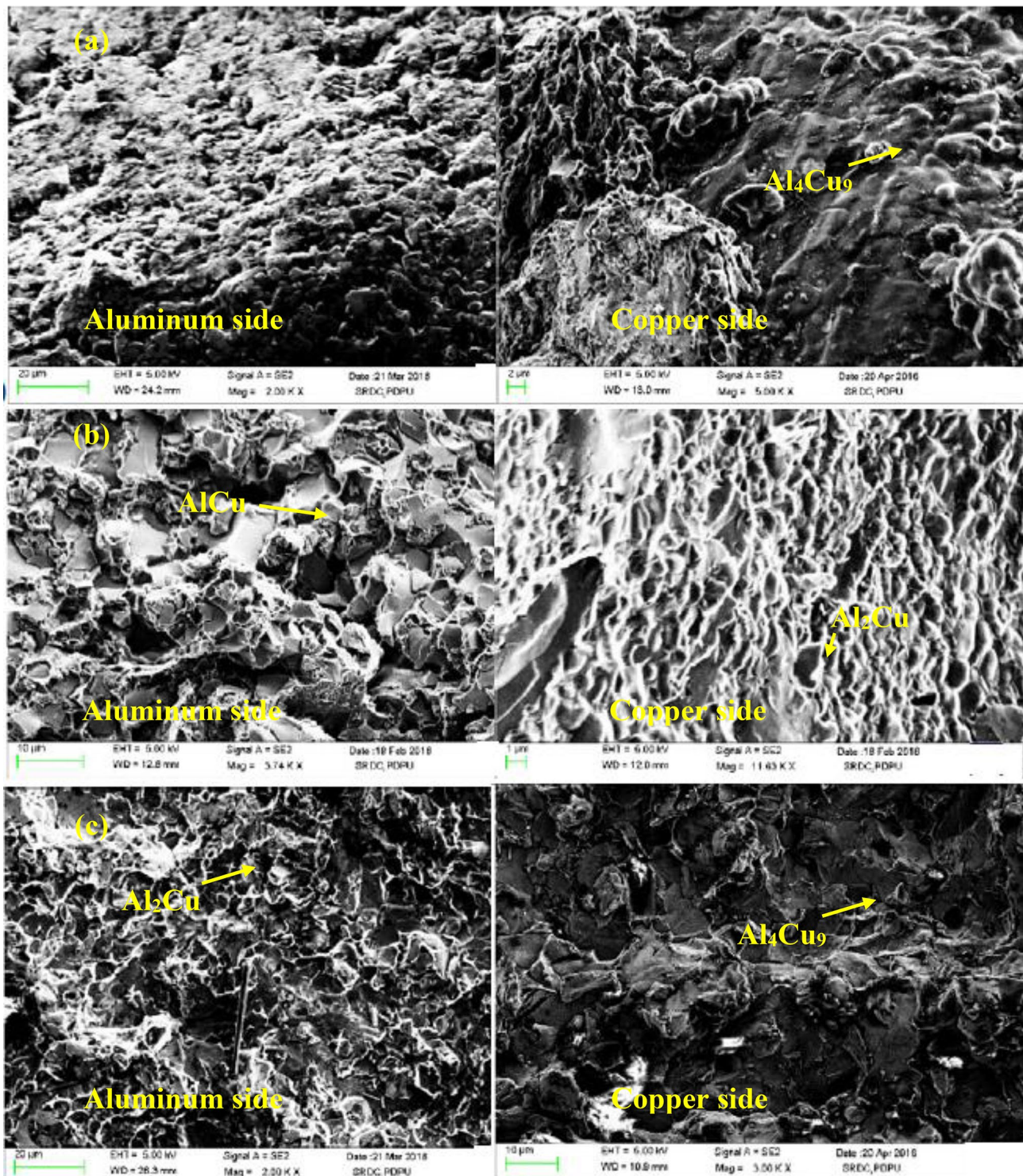


Fig. 8 Fracture location of the samples in both aluminum and copper sides: **a** N1000-t5, **b** N1500-t15, **c** N2000-t15

During welding of dissimilar materials, there are two important factors that significantly affect hardness of the weld nugget. The first is size of microstructure and second is formation of intermetallic compounds [14]. According to Hall–Petch law, the finer microstructure results to higher

hardness values. Also, formation of intermetallic compound up to desired amount and uniform dispersion results in increasing the hardness. As the FSW is a thermomechanical-based process, the stir action results in grain refinement compared to parent material. However, this improvement

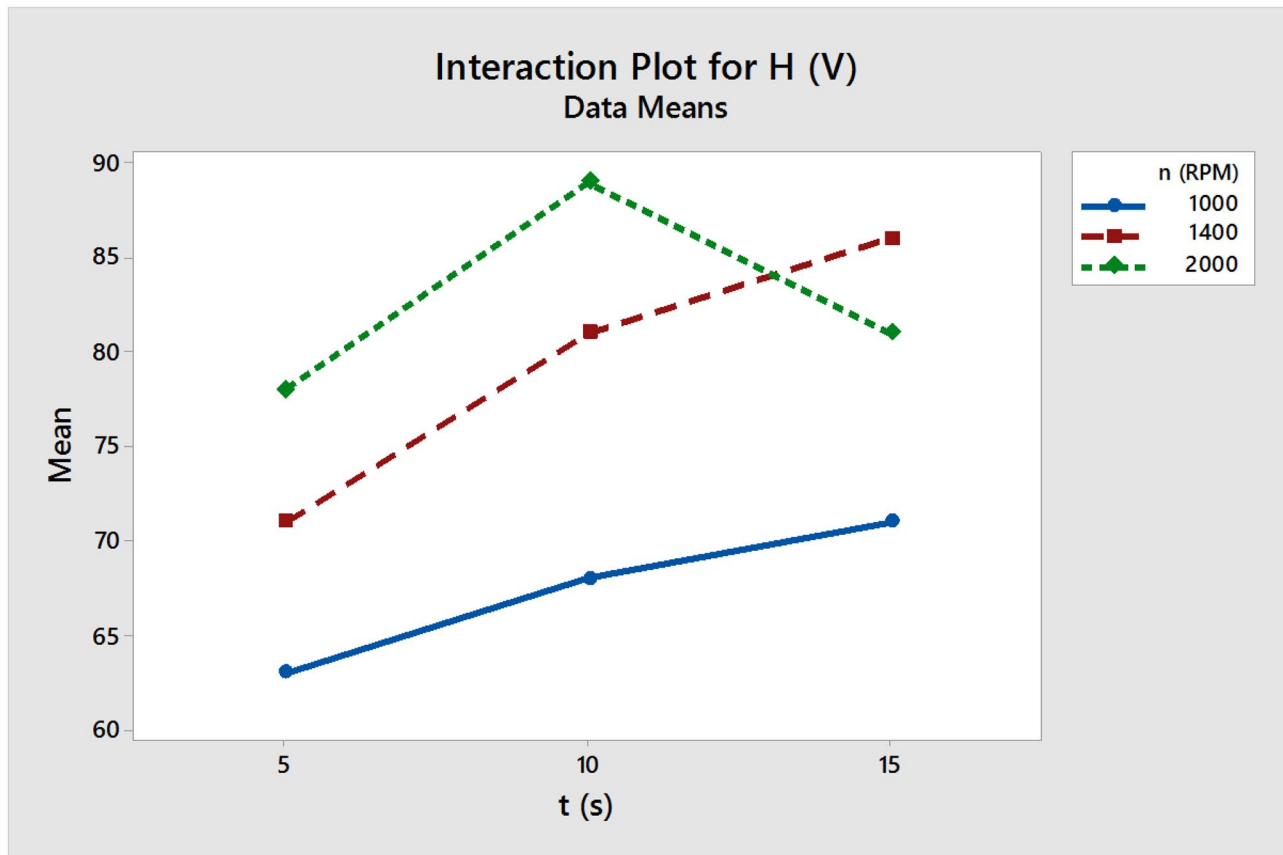


Fig. 9 Simultaneous effect of tool rotation speed and dwell time on lap shear strength

will be restricted by coarse microstructure and thick and non-uniform IMCs within the stir zone as result of excessive heat input [9].

At 1000 and 1500 rpm tool rotary speed, increasing the dwell time provides more frictional heat for formation of IMCs as well as for grain refining of interface. Thus, as result of increase of dwell time, the hardness increases that can be attributed to formation of IMCs and its uniform dispersion in stir zone. Furthermore, the similar scenario is consistent at tool rotational speed of 2000 rpm when the dwell time increases from 5 to 10 s. At dwell time of 15 s, as result of

excessive heat input, the microstructure of stir zone becomes coarse and thick intermetallic layer is formed in the interface of the aluminum and copper (as demonstrated in Fig. 4c).

The formation of IMCs has been well discussed in “Sect. 3.2.” In order to study the simultaneous influence of tool rotary speed and welding speed on grain size, the microstructure of aluminum and copper close to the interface as shown in Fig. 1 was subjected to optical microscopy analysis. Accordingly, samples fabricated by N1000-t5 (representative of minimum hardness as result of insufficient heat input), N2000-t10 (representative of maximum hardness as result

Table 2 ANOVA results for lap shear force

Source	Sum of squares	Degree of freedom	F-value	Prob > F
Model	6.87×10^5	5	28.8	0.0002
N	34,656	1	7.29	0.0307
t	3.7×10^5	1	79.48	<0.0001
N × t	7832	1	1.65	0.2402
N ²	1.42×10^5	1	31.41	0.0008
t ²	28,482	1	5.99	0.0443
$R^2 = 0.9538$		$R^2_{\text{Adjusted}} = 0.9207$		

Table 3 ANOVA results for hardness

Source	Sum of squares	Degree of freedom	F-value	Prob > F
Model	601.47	5	6.87	0.0125
N	352	1	21.03	0.0025
t	112	1	0.15	0.7
N × t	6.25	1	2.06	0.1947
N ²	40	1	5.39	0.053
t ²	40	1	1.77	0.2259
$R^2 = 0.9591$		$R^2_{\text{Adjusted}} = 0.9289$		

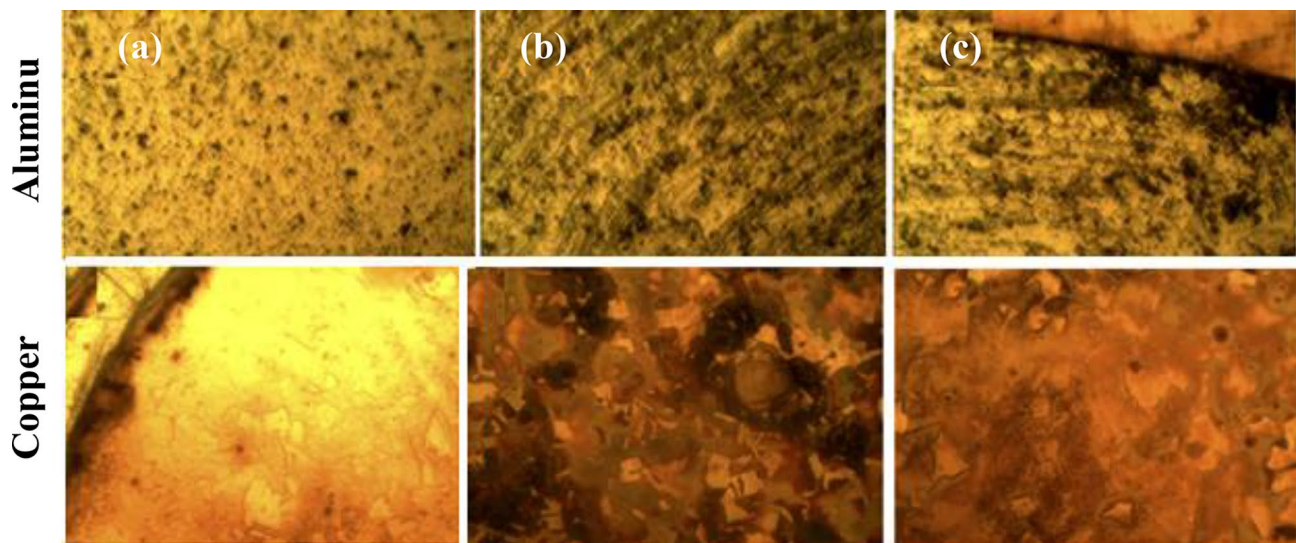


Fig. 10 Microstructure of aluminum and copper sides for different samples: **a** N1000-t5, **b** N2000-t10, **c** N2000-t15

of sufficient heat input), and N2000-t15 (representative of excessive heat input) were prepared to study the microstructure of copper and aluminum at the interface. Figure 9 illustrates microscopic images of fabricated samples for different aluminum and copper sides. It is clear from the figure that for the samples N1000-t5 as result of insufficient heat input metallurgical transformation, recrystallization and subsequent grain refining is very limited. The grain size is very coarse and the second phases were dispersed very heterogeneously in the aluminum and copper matrix. For the joint fabricated by N2000-t10 as result of sufficient heat input, severe plastic deformation as result of sufficing thermomechanical load occurs that results in grain refining in both of aluminum and copper sides. On the other hand, for the joint fabricated by N2000-t15, nevertheless, amount of thermomechanical load for severe plastic deformation and grain refining is provided, and due to excessive heat input, the grain size becomes partially coarser that can be found in both of aluminum and copper sides. Thus, the hardness dramatically decreases compared to sample fabricated by N2000-t10.

3.4 Statistical analysis

In order to develop empirical relationship between tool rotation speed and dwell time to lap shear strength and hardness, response surface methodology is utilized. Design Expert V7 software was utilized here for regression analysis. The analysis of variances (ANOVA) was also carried out to check the validity of developed quadratic model. It was also used to identify 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 is expressed in Eqs. 1 and 2, respectively.

$$LSF(N) = 1015 + 2.7N + 104t + 0.017Nt - 9.3 \times 10^{-4}N^2 - 4.06t^2 \quad (1)$$

$$H(V) = 7.54 + 0.076N + 4.67t - 5 \times 10^{-4}Nt - 1.53 \times 10^{-5}N^2 - 0.15t^2 \quad (2)$$

Analysis of variances of lap shear strength and hardness is presented in Tables 2 and 3, respectively. It is seen in ANOVA tables that the values of R^2 (i.e., coefficient of determination) are in close agreement with adjusted R^2 . It describes that the developed models are completely valid to navigate design space [16–19]. The models Prob > F value are less than 0.05 that implies model terms are significant. Also, the terms with Prob > F less than 0.05 have significant influence on performance measures, i.e., lap shear force and hardness [20–23]. Based on the analysis of variances, it is inferred that the dwell time and tool rotation are most influential factors for lap shear strength and hardness, respectively.

The developed empirical models can be also 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 Fig. 10a that the maximum lap shear strength is achieved by selection of 1500 rpm tool rotation and 15 s dwell time. Furthermore, maximum hardness could be obtained when the tool rotary speed is 2000 rpm and dwell time is 10 s. It is seen that the variation of lap shear strength and hardness by variation of process factors do not follow a similar trend. Thus, to achieve

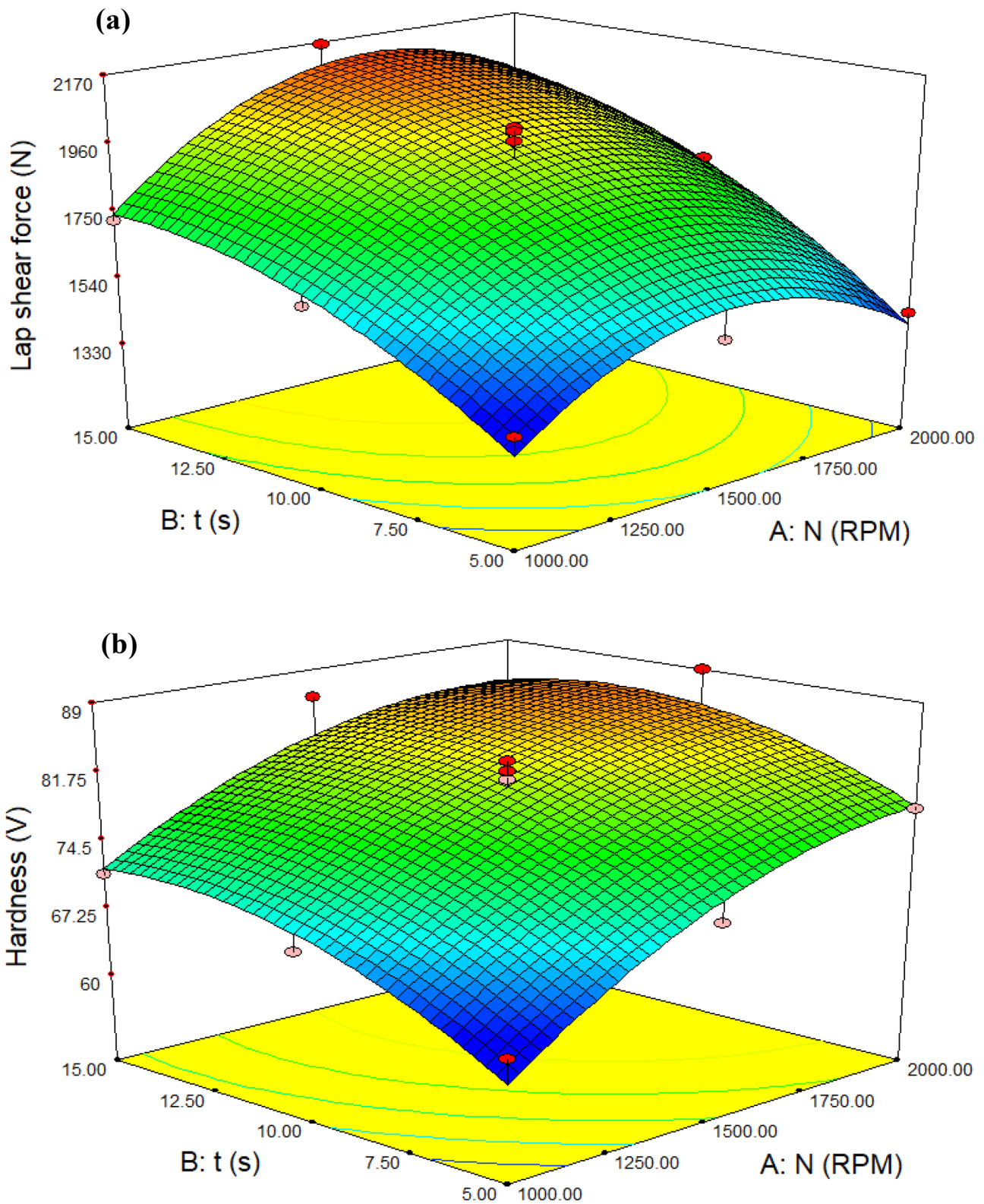


Fig. 11 3D surface showing interaction effect dwell time and tool rotary speed on **a** lap shear force and **b** hardness

Table 4 Optimization criterion

Factors/responses	Criterion	Importance
Tool rotation (rpm)	In range of 1000–2000	-
Dwell time (s)	In range of 5–10	-
Lap shear strength (N)	Maximize	***** (5)
Hardness (V)	Minimize	***** (5)

Table 5 Optimum parameter setting along with validation test results

Factor		Lap shear strength (N)			Hardness (V)			Objective
<i>N</i> (rpm)	<i>t</i> (s)	Experiment	Model	Error	Experiment	Model	Error	Desirability
1730	14.3	1978	2093	0.058	79	84	0.063	0.868

a unified result, it is required to find optimal result in a multi-objective optimization problem [24–26] (Fig. 11).

Multi-characteristics optimization was carried out by desirability function. Criteria must be defined for optimization of process based on the desired values lap shear force and hardness subjecting to limited range of process factors and presented in Table 4. By performing the optimization based on the numerical optimization method, the most optimal setting was identified and presented in Table 4. It is evident from the table that setting of 1730 rpm tool rotation and 14.3 s dwell time is the most optimal solution that causes desirability of 86.8% with strength value of 2093 N and hardness of 84 V. The obtained solution should be experimentally verified to show applicability of proposed approach in optimization of FSSW process. The results of confirmatory experiment are 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 5).

4 Conclusion

In the present study, lap joints of dissimilar 5052 aluminum alloy and pure copper were fabricated by friction stir spot welding process. Effects of process tool rotational speed and dwell time on lap shear force and hardness of stir zone were taken into study. The results were justified by microstructural using SEM, OM, XRD, and EDS pattern of fabricated samples. Also, statistical analyses were made to identify contribution of parameter in determining 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 are obtained when the tool rotation is 1500 rpm and dwell time is 15 s. Interlocking bonding

due to hooking action of copper into the aluminum plates and uniform distribution of intermetallic compounds such as AlCu and Al₂Cu were found as the main reason for enhancing the joint strength.

- From the obtained microhardness results, it is found that tool rotation of 2000 rpm and dwell time of 10 s cause highest hardness of stir zone. Fine microstructure due

to sufficient thermomechanical load and formation of composite-like structure as result of dispersion of IMCs Al₂Cu and Al₄Cu₉ in the stir zone correspond to the maximum hardness value.

- From statistical analysis, it was identified that dwell time and tool rotation are the most influential factors affecting lap shear force and hardness, respectively.
- Multi-objective optimization of process parameters showed that achieving simultaneous maximum strength and hardness is possible by selection of 1730 rpm tool rotation and 14.3 s dwell time. The desirability of optimum results was about 86% and the prediction error for the quality characteristics was less than 8%.

Author contribution Aydin Jadidi: 40% contribution in writing the paper and doing research; Reza Bagherian Azhiri: 30% contribution in analyzing the results and supervision; Amir Baghdadchi: 20% contribution in designing facilities; Abolfazl Salmani Bideskan: 10% contribution in providing materials and testing and editing the language.

Availability of data and materials It is confirmed that the data and materials can be available after publication on the basis of Springer Nature rights and access.

Declarations

Ethical approval It is approved that the paper is original and has been written based on authors own finding. All the figures and tables are original and every expression from other published works was acknowledged and referenced.

Consent to participate It is confirmed that all the authors are aware and satisfied from authorship order and correspondence of the paper.

Consent to publish All the authors are satisfied with authorship order in publication process.

Competing interests The authors declare no competing interests.

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