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Effect of Friction Stir Welding Parameters on the Ultimate Tensile Strength of Al-Cu Tailor Welded Blanks

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Abstract: In the present study, the parameters of tool rotation speed, tool travel speed and tool offsetting with different levels were used in the friction stir welding (FSW) of aluminum-copper tailor welded blanks (TWBs). The FSW of pure copper to 5052 aluminum alloy was carried out by varying tool rotation speeds from 800 rpm to 1200 rpm, tool travel speeds from 40 mm/min to 80 mm/min and tool offsettings from 1 mm to 2 mm. The L9 orthogonal array of Taguchi was used to design 9 experimental tests and each test was repeated three times. The uniaxial tensile test based on the ASTM-E8 was used for mechanical properties extraction of TWBs. The tool rotation speed of 1200 rpm, tool travel speed of 60 mm/min and tool offsetting of 1.5 mm resulted in the optimum range of heat input to form a stir zone with good quality. Using these FSW parameters caused the formation of thin intermetallic layers which stopped the motion of dislocation in the tensile test and resulted in higher tensile strength and joint quality. The scanning electron microscope (SEM) was used to scan the tensile fracture surface of TWBs.

Keywords: TWBs, FSW, Mechanical properties, Ultimate tensile strength, Microstructure.

1. Introduction

Al–Cu dissimilar joints are one of the dissimilar materials which are widely used in the industry, especially electric power industry, as transition pieces. There are different welding processes such as fusion welding to join materials together. Because of material incompatibility, it is difficult to use fusion welding process for the fabrication of Al-Cu dissimilar joints. Using this method for aluminum-copper welding caused the formation of thick intermetallic layers at the interface of the weld. The friction stir welding (FSW) is the best alternative welding process for this purpose. The FSW previously was used by Malarvizhi and Balasubramanian [1] to joint dissimilar materials like aluminum to magnesium or aluminum to steel by Watanabe et al. [2]. Parente et al. [3] investigated the effect of weld line orientation on the formability of aluminum TWBs. They used friction stir welding to join aluminum TWBs which consist of AA 6061 and AA 5182 with equal thickness as base metals. Their results showed that the formability of aluminum TWBs will decrease by increasing the weld line orientation. Safdarian et al. [4] investigated the effect of Nd: YAG laser welding parameters on the weld quality and mechanical properties of steel TWBs. They suggested the optimum welding parameters being joined to steel TWBs. Safdarian et al. [5] investigated the formability and weld line movement in the TWBs forming. Their results showed that the weld line movement increased by thickness ratio and strength ratio increasing of TWBs.

There are many different welding parameters which influence the quality of the FSW joint. One of these parameters is tool travel speed. The effect of the tool travel speed on grain growth in the FSW of AA 2095 aluminum was investigated by Attallah and Salem [6]. They concluded that the tool travel speed can influence the strength and ductility of the joint. Muthu and Jayabalan [7] used different tool travel speeds

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from 50 mm/min to 90 mm/min for the FSW of aluminum and copper. Increasing the tool travel speed to 80mm/min caused lower intermetallic thickness and resulted in higher tensile strength and joint efficiency. Safdarian [8] investigated the effect of FSW parameters on the formability of aluminum TWBs. Their results showed that the weld quality and formability of aluminum TWBs increased by increasing the tool's rotational speed. Genevois et al. [9] used tool offsetting for friction stir welding of 1050 aluminum alloy to commercially pure copper plates. They used full offsetting towards the aluminum side and concluded that no mechanical mixing was observed between the base materials. Xue et al. [10] investigated the effect of tool offsetting towards the aluminum side on the mechanical and morphological properties of Al-Cu friction stir welding. They found that using large values of tool offset (between 67 pct and 83 pct of the pin radius) improved the quality and soundness of the welds. Sinha, Kundu, and Chatterjee [11] used different tool rotation speeds for welding similar and dissimilar FSW joints of aluminum and pure copper. Intermetallic compounds of Al_4Cu_9, AlCu, Al_2Cu, and Al_2Cu_3 were observed in the stir zone of dissimilar Al-Cu FSW joints. Zhang, Gong, and Liu [12] used different welding parameters in the FSW of 1060 aluminum alloy and pure copper sheet. The best quality of the weld was obtained at the rotation speed of 1050 rpm and travel speed of 30 mm/min. Dhondt et al. [13] studied the durability of Al-Cu-Li 2050 alloy welded samples which were produced by the FSW. The intergranular stress corrosion cracking (IGSCC) behavior of the nugget region of 2050 welded samples were studied and a relation was established between microstructure heterogeneities, welding process and also IGSCC cracks propagation. Kordestani, Ghasemi and Mostafa Arab [14] studied the effect of welding parameters on the tensile and impact strength of polypropylene (PP) composite which had been welded by the FSW. Their results showed that tool linear speed of 8 mm/min, tool rotation speed of 2000 rpm and tilt angle of 6 degrees produced a weld with maximum tensile strength. Abdollah-Zadeh et al. [15] studied the microstructure and mechanical properties of the FSW of 1060 aluminum alloy into a commercially pure copper. Their results showed that Al4Cu9, AlCu, and Al2Cu are the main intermetallic compounds formed in the interfacial region. Galvao et al. [16] studied the effect of the shoulder geometry of the FSW tool on the formation and distribution of brittle structures in the welding of aluminum and copper .. Two types of FSW tools were scrolled and a conical shoulder was used in this study. Their results showed that the scrolled tool caused the formation of $CuAl_2$ in the mixing region, but the conical tool caused the formation of $CuAl_2$ and Cu_9Al_4 in the mixing region, with higher heterogeneity and lower intermetallic content. Heidarzadeh and Saeid [17] used response surface methodology based on a central composite design to investigate the effect of FSW parameters on the mechanical properties of copper joints. The rotational speed, travel speed, and axial force were selected as welding parameters. Their results showed that increase in the welding parameters resulted in increase in the tensile strength of the joints up to a maximum value. Li et al. [18] studied the FSW of pure copper to 1350 aluminum alloy sheet. The results showed that a better quality of the weld was produced by a rotation speed of 1000 rpm and a welding speed of 80 mm/min with no intermetallic compounds in the nugget. The microstructure of the fracture surface showed that the dissimilar joints fail with a ductile-brittle mixed fracture mode in the tensile test.

In the present study, the effects of the main parameters of the friction stir welding of 5052 aluminum alloy to commercially pure copper sheets on the mechanical properties are studied. The selected parameters are tool offset, tool rotation speed and tool travel speed with three levels for each one. Design of experiment (DOE) is used to study the effect of the parameters and also their interactions on the mechanical properties of welded samples. The uniaxial tensile test based on the ASTM-E8 is used to investigate weld quality.

2. Methodologies

2.1. Materials' properties

Commercial pure copper (99.9%) and 5052 aluminum alloy sheets with the thickness of 2 mm were used in the FSW process to produce tailor welded blank (TWB). The sheet of each material was cut into pieces with dimensions of 100 mm× 100 mm. The 5052 aluminum alloy had the yield strength and ultimate tensile strength of 147 MPa and 243 MPa, respectively. The pure copper had the yield strength and ultimate tensile strength of 98 MPa and 245 MPa, respectively. A milling machine with the maximum rotation speed of 2500 rpm and maximum power of 4.4 kW was used for the FSW of the samples.

A cylindrical FSW tool made of AISI H13 steel with a shoulder of 20 mm in diameter and a pin with the diameter of 6 mm and length of 1.8 mm was applied for the FSW of copper to aluminum. The tilt angle was 6° from the normal surface of the sheets. The welding tool and its dimensions have been shown in Fig. 1. The welds were made with a clock-wisely rotating pin at the rotation speed of 800–1200rpm and tool travel speed of 40-80 mm/min. Several pin offsets from 1mm to 2mm were used during the welding processes. The axial force was controlled by fixing the amount of tool penetration into the workpieces. The depth of shoulder penetration into the workpieces was 0.1 mm in all the experimental tests. Two different sheets of aluminum and copper were fixed in a fixture as shown in Fig. 2(a) to prevent the movement of the sheets during the FSW. More details about the welding parameters are presented in the next section.

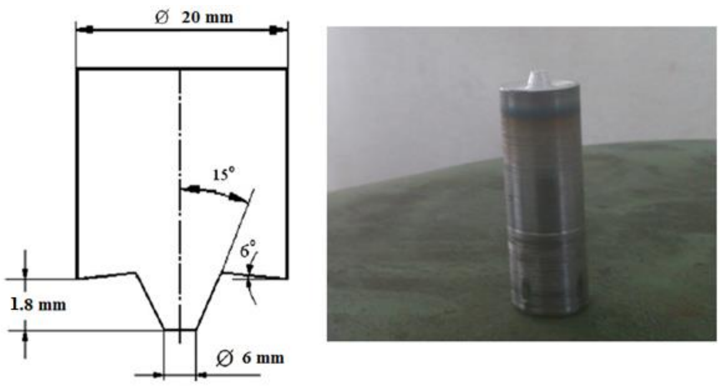
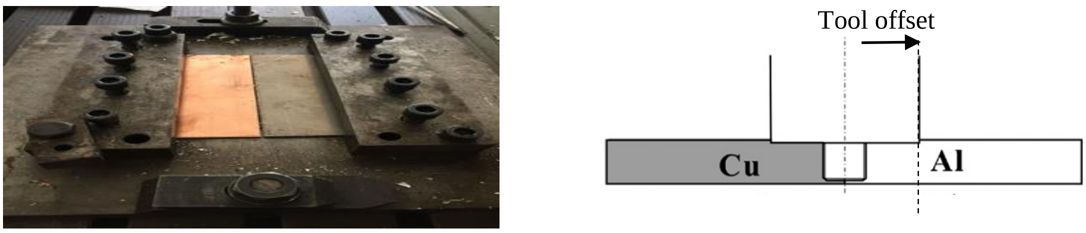


Fig. 1 welding tool.

2.2. Design of experiment (DOE)

The welding parameters have great influence on the weld quality and its mechanical properties in the FSW process. Therefore, the main parameters of this process with different values were selected to investigate their effect on the weld quality. Tool offsetting, tool rotation speed and tool travel speed with 3 levels were selected as welding parameters. Three different values of 800 rpm, 1000 rpm, and 1200 rpm were considered for tool rotation speed and three values of 40 mm/min, 60 mm/min and 80 mm/min for tool traveling speed. In order to study the effect of tool offsetting on the weld quality, three values of 1, 1.5 and 2 mm were selected for this parameter. As Fig. 2(b) shows the tool offsetting is toward the aluminum side of TWBs. The L9 orthogonal array of Taguchi was used for the design of experiment and 9 tests were designed with different welding parameters as shown in Table 1. Each test was repeated three times for increased accuracy. The last column of Table 1 shows the ultimate tensile strength of the welded samples and the base metals after the uniaxial tensile test which will be discussed in the results part. Since each test was repeated three times, every value in this column is the average of the three values.



(a) (b)

Fig. 2. (a) Fixture to prevent sheets movement during the FSW, (b) Tool offset scheme.

Table 1. Parameters of Al-Cu FSW tests.

Run	Sample Num.	Rotation speed (RPM)	Travel speed (mm/min)	Tool offset (mm)	UTS (MPa)
1	1,2,3	800	40	1	139.3
2	4,5,6	800	60	1.5	132
3	7,8,9	800	80	2	57.3
4	10,11,12	1000	40	1.5	117
5	13,14,15	1000	60	2	105.7
6	16,17,18	1000	80	1	62
7	19,20,21	1200	40	2	124.3
8	22,23,24	1200	60	1	147.7
9	25,26,27	1200	80	1.5	149
Al-base metal		-	-	-	243
Cu-base metal		-	-	-	245

3. Results

3.1. Morphological analysis

The visible effect of the FSW parameters on the welded samples is the quality and soundness of the weld surfaces. Figure 3 shows the weld's surface samples of three runs with different FSW parameters. The welding parameters of these runs have been presented in Table 2. One of the differences between these three runs was tool offsetting. The tool offsetting for run 3 (sample 9) and run 6 (sample 18) was 1 mm and 2 mm, respectively, but for run 9 (sample 25) it was 1.5mm. The very rough surface with crack happened for samples which had been welded with parameters of run 3 and run 6, but the samples of run 9 had smooth surfaces. According to the studies of Galvao et al. [16, 19] the formation and irregular distribution of intermetallic-rich structures over the weld surfaces was the main reason for obtaining very poor surface finishing. The last column of Table 2 shows that for run 3, run 6 and run 9 the UTS was 57.3, 62 and 149 MPa, respectively.

(a) (b) (c)

Fig. 3. The weld surface of three different FSW tests (a) Sample 9 (run 3), (b) Sample 18 (run 6) and (c) Sample 25 (run 9).

3.2. Microstructure of Al−Cu TWBs

Figure 4 shows the SEM image of the tensile fracture surface of three samples of 7, 11 and 25 which were welded with different FSW parameters. Figure 4(a) shows the SEM of sample 7 where there is no dimple on the fracture surface, and this means that the fracture of this sample is the brittle fracture. Figure 4(b) shows mainly quasi-cleavage fracture, with smooth faces without evidence of great plastic deformation and also the presence of cracks indicating the presence of hard and brittle structures, such as intermetallic compounds. The tensile strength of sample 7 which had been selected from run 3 was 28 MPa.

As Fig. 4(c) and (e) for samples 11 and 25 show, the finely populated dimples were formed on the fracture surface of the welded samples. The tensile strength of samples 11 and 25 is 117 MPa and 149

MPa, respectively, which are the highest values among other samples. The interfaces between the aluminum matrix and copper particles acted as crack initiation sites during the tensile loading. This confirms the fact that the weld joint failed in the ductile mode of failure [7].

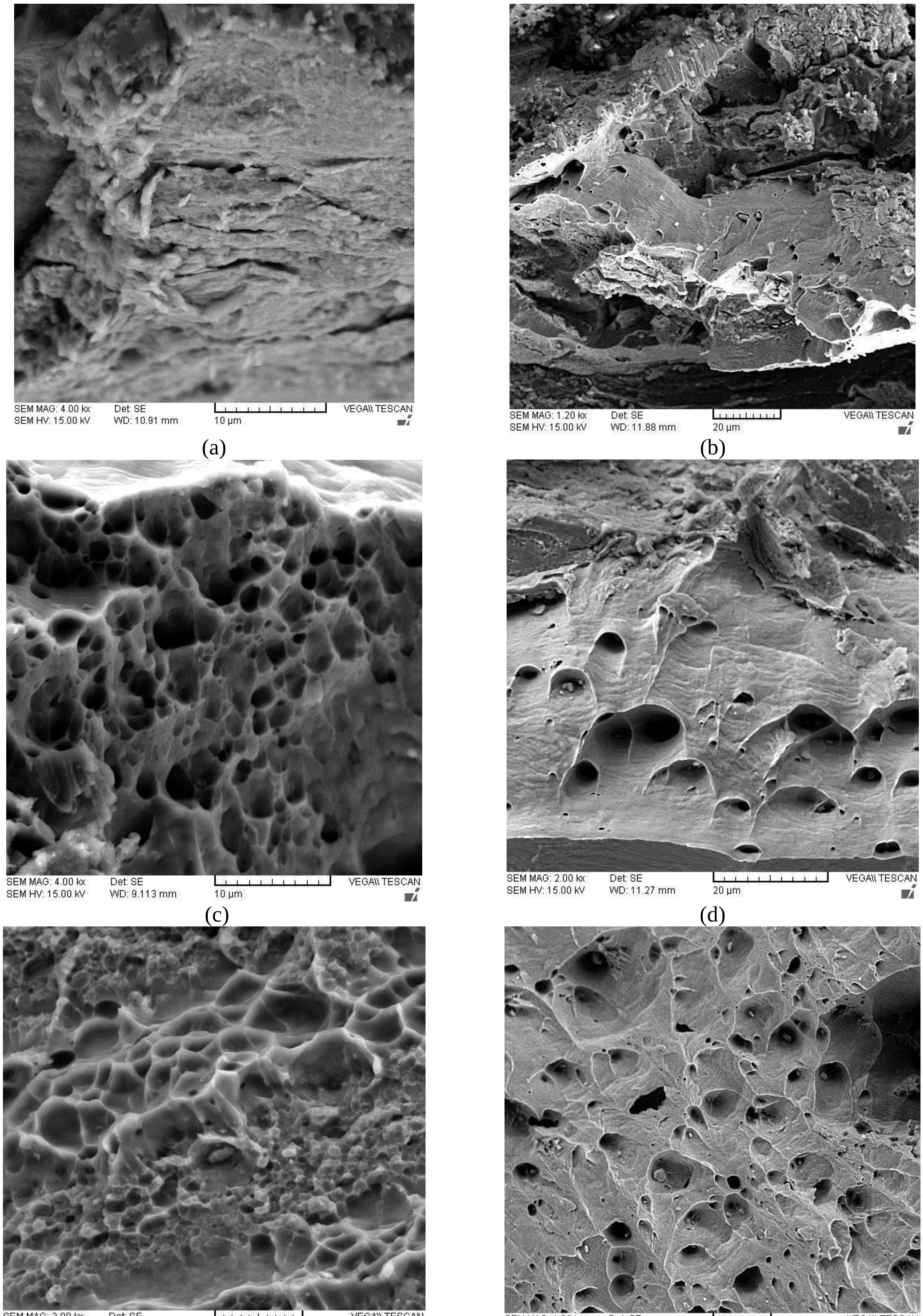
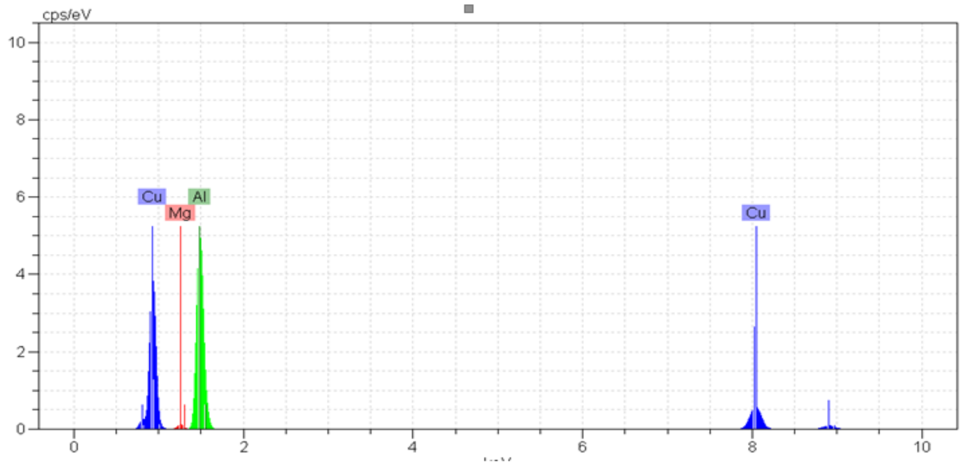


Fig. 4. The SEM images showing tensile fracture surface for (a) sample 7 (Al), (b) sample 7 (Al), (c) sample 11 (Al), (d) sample 11 (Cu), (e) sample 25(Al) and (f) sample 25 (Cu).

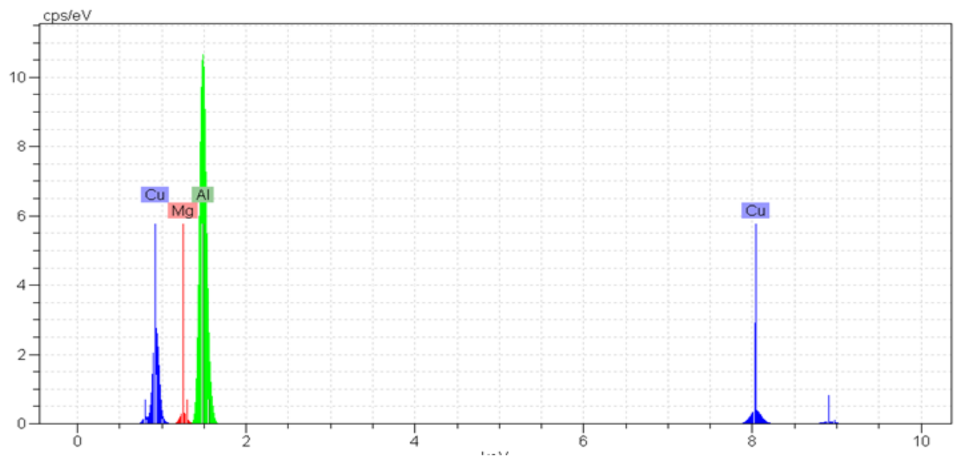
The electron dispersive spectrum (EDS) analysis was used to determine the composition of the various intermetallics formed in the Al–Cu weld interface of samples 7 and 25. Figure 5 shows the EDS of these samples from the center line of the weld region and also the atomic percent composition in this region. Considering Fig. 5, Al-Cu binary equilibrium phase diagram (Fig. 6) and using lever rule, it is possible to identify the intermetallic types and their percent in the weld region. For sample 7, the percent of aluminum and copper was 66.02 and 34.98, respectively. Therefore, the percent of $CuAl_2$ and CuAl for sample 7 was 88.35% and 11.65 %, respectively. For sample 25, the percent of aluminum and copper was 84.58 and 15.42, respectively. Therefore, this sample in the weld region was composed of solid solution (54.22 %) and $CuAl_2$ (45.78 %). Comparison of intermetallic percensts of samples 7 and 25 indicated that high values of these compounds caused the UTS decrease in sample 7.



Spectra: 7

Element	Series	norm. C [wt.-%]	Atom. C [at.-%]
Magnesium	K series	1.08	1.76
Aluminium	K series	43.63	63.87
Copper	K series	55.29	34.37

(a)



Spectra: 25

Element	Series	norm. C [wt.-%]	Atom. C [at.-%]
Magnesium	K series	2.14	2.86
Aluminium	K series	68.46	82.16
Copper	K series	29.40	14.98

(b)

Fig. 5. The EDS mapping of (a) sample 7 and (b) sample 25.

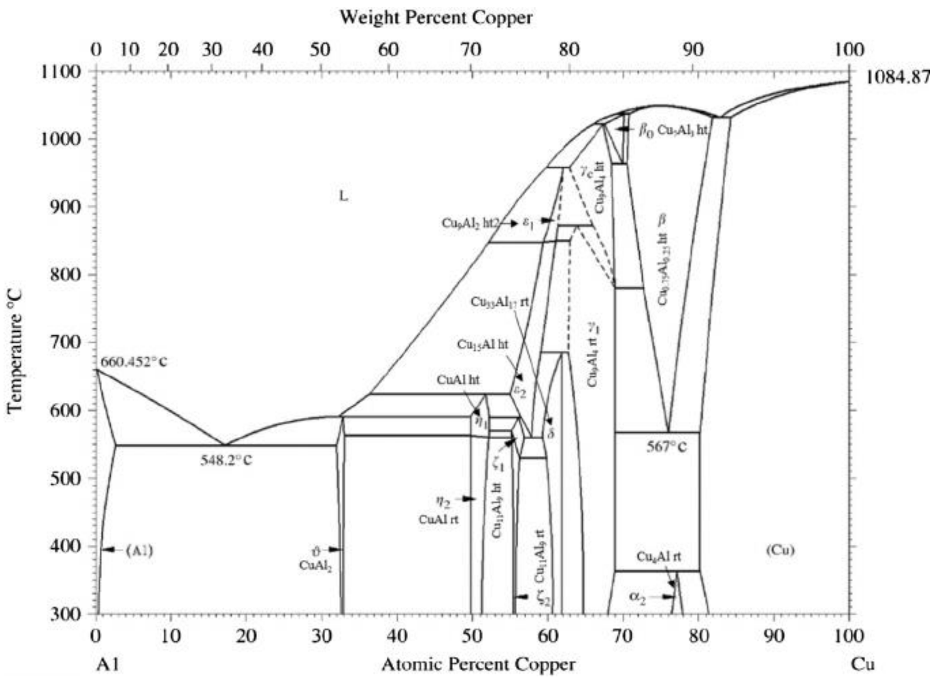


Fig. 6. Al-Cu binary equilibrium phase diagram.

3.3. Mechanical properties of Al−Cu TWBs

The uniaxial tensile test was used to investigate the mechanical properties of Al-Cu tailor welded blanks. The standard samples were extracted from all 27 welded samples and were used in the uniaxial tensile test based on the ASTM-E8 [20]. Figure 7 shows the samples after the uniaxial tensile test. As it is clear from this figure, the fracture line of samples 6, 7, 9, 23 and 24 had a zigzag and diagonal path. The results of the tensile test showed that these samples had the minimum value of the ultimate tensile strength (UTS) between the welded samples. For other samples, the fracture line was perpendicular to the tensile direction. The last column of Table 2 shows the UTS value of the welded samples.

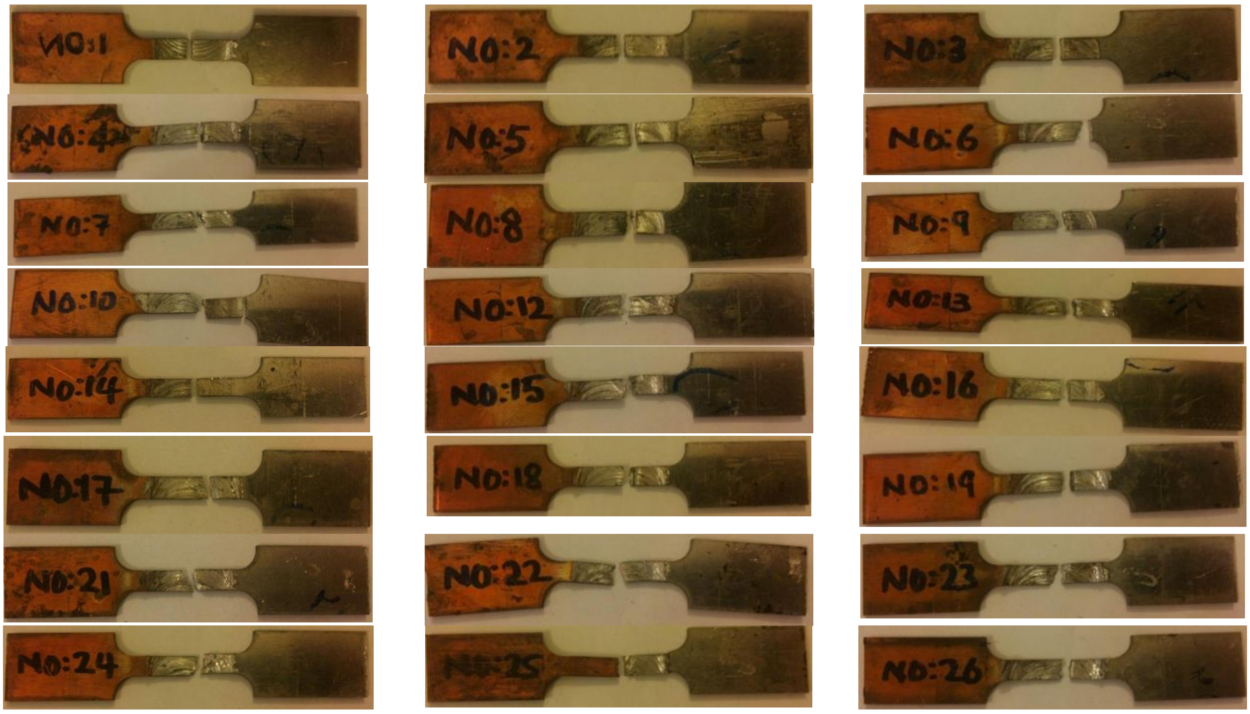


Fig. 7. Al-Cu TWBs after the uniaxial tensile test

The effect of the FSW parameters on the ultimate tensile strength of the welded samples has been shown in Fig. 8. Since each run of Table 2 was repeated three times, the average value of the UTS for each run was used in this figure. As this figure shows, increasing the tool rotation speed from 800 to 1200 rpm, increased the UTS of the welded samples. The inputted heat to the stir zone rose as the rotational speed increased. The high degree of temperature mixed up the materials in the interface of aluminum and copper and caused the formation of fine grains and low intermetallic thickness. Reduction of the grain size which was resulted from high temperature in the stir zone caused the formation of a large grain boundary. Therefore, the tensile strength of the welded sample was increased by the larger grain boundary. This result was concluded by [7, 21, 22]. The copper particles were fragmented from the copper side and distributed in the stir zone by stirring of the FSW tool. These fine particles caused the formation of hard brittle intermetallic which increased the strength of the weld region. This result was also mentioned by Muthu et al. [7]. The intermetallic layers during the tensile test stopped the dislocation motion and caused the UTS increase of TWBs, but increase in the intermetallic thickness decreased the UTS. The effect of the thickness of the intermetallic layers on the tensile strength was also reported by Borrisutthekul et al. [23] and Naotsugu et al. [24].

Figure 8 shows that the UTS of the welded samples increased with a slight slope by the tool travel speed variation from 40 to 60 mm/min, but the UTS decreased at a speed of 80 mm/min. This decrease in the UTS was related to the heat input value of the stir zone. The amount of the heat inputted to the stir zone decreased by increasing the tool travel speed, and this phenomenon limited the mixing of copper particles in the aluminum matrix.

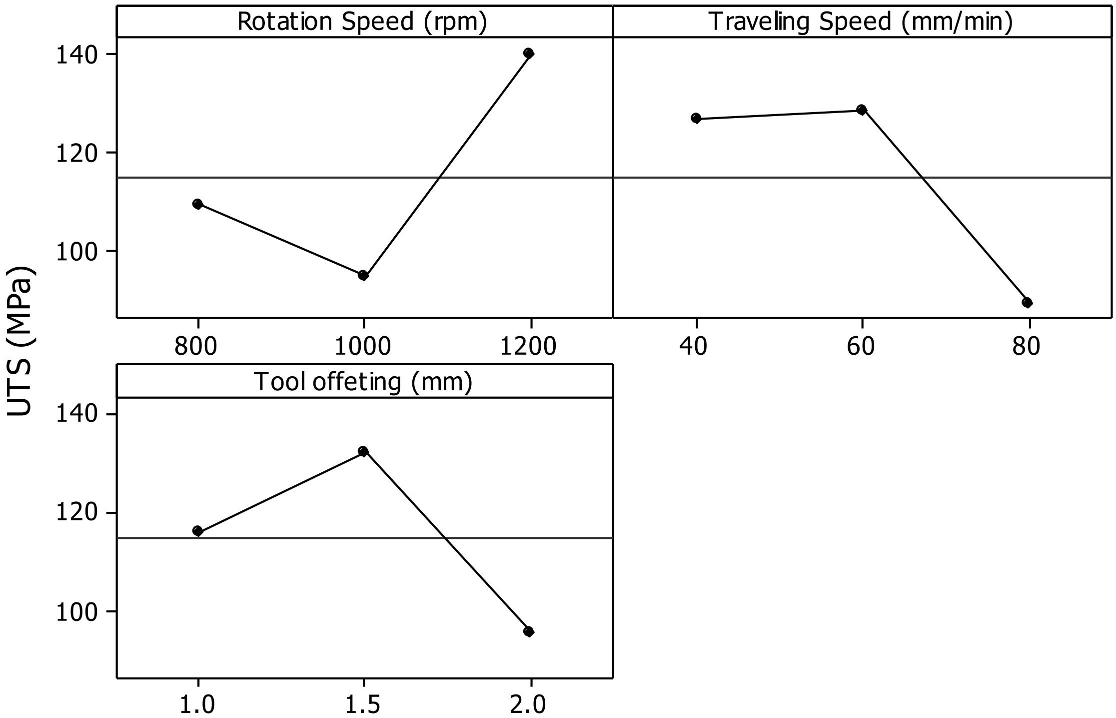


Fig. 8. Effect of welding parameters on the UTS.

Tool offsetting is another important parameter which its effect was investigated on the UTS of the welded samples in this study. In the present study, tool offsetting is toward the aluminum side of TWB with three values of 1 mm, 1.5 mm and 2 mm. As Fig. 8 shows, the UTS of the welded samples increased by increasing the tool offset from 1 mm to 1.5 mm, but it decreased by increasing the tool offset from 1.5 mm to 2 mm. The maximum of the UTS happened when the tool offsetting was 1.5 mm.

Interaction effect of the FSW tool travel speed and rotation speed on the UTS of Al-Cu TWBs has been shown in Fig. 9. As this figure shows, for two rotation speeds of 800 rpm and 1000 rpm, the UTS decreased as the tool travel speed increased, but it increased for the tool rotation speed of 1200 rpm. The amount of the heat inputted to the stir zone was not enough for two rotation speeds of 800 rpm and 1000 rpm. Thus the tensile strength decreased by increasing the tool travel speed. For rotation speed of 1200 rpm, enough heat was inputted to the stir zone resulting in the UTS increase. For this rotation speed, the UTS increased by the tool travel speed variation from 40 mm/min to 60 mm/min and the UTS was constant by increasing the tool travel speed to 80 mm/min. As this figure shows, the highest strength resulted in the tool rotation speed of 1200 rpm and the tool travel speed of 60 mm/min.

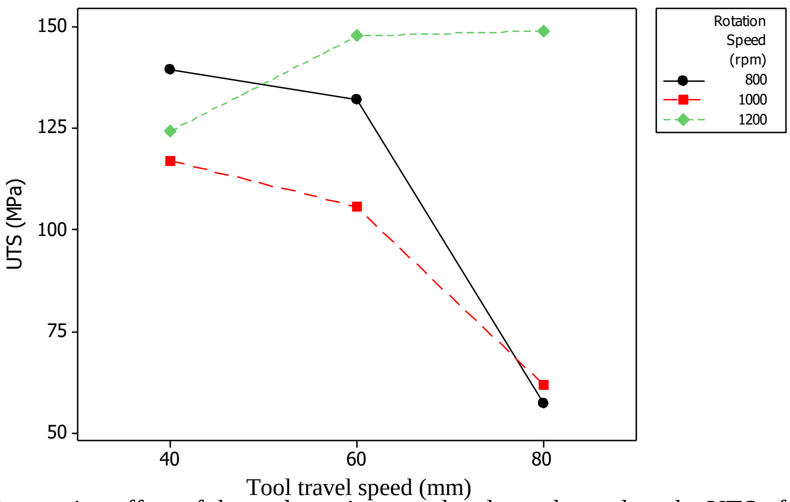


Fig. 9. Interaction effect of the tool rotation speed and travel speed on the UTS of TWBs.

Interaction effect of the tool rotation speed and tool offsetting on the UTS of Al-Cu TWBs has been shown in Fig. 10. As this figure shows, the tool rotation speed of 1200 rpm had the highest level of the UTS among other rotation speeds for different values of tool offsetting. The higher rotational speed caused temperature increase at the interface and increased the intermetallic compounds. The intermetallic layers hindered the dislocation motion and increased the UTS of TWBs in the tensile test. For the tool rotation speed of 1200 rpm, the UTS increased as the tool offsetting increased from 1 mm to 1.5 mm and then it decreased with the tool offsetting of 2 mm. As this figure shows, the best parameter of the FSW was the tool rotation speed of 1200 rpm and tool offsetting of 1.5 mm.

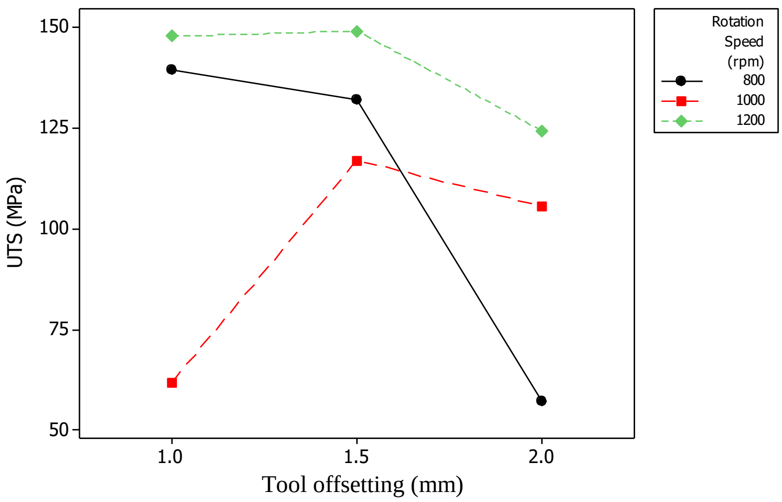


Fig. 10. Interaction effect of the tool offsetting and tool rotation speed on the UTS of TWBs.

4. Conclusions

The effects of the three parameters of tool travel speed, tool rotation speed, and tool offsetting on the mechanical properties of Al-Cu tailor welded blanks were investigated. Results of the present study can be summarized as follows:

1- Tool rotation speed of 1200 rpm produced higher tensile strength in the FSW of Al-Cu tailor welded blanks. The optimum heat inputted to the stir zone at the tool rotation speed of 1200 rpm caused the formation of thin intermetallic layers between Al and Cu which stopped the motion of dislocation and increased the UTS of TWBs.
2- Tool travel speed of 60 mm/min produced an Al-Cu TWB with higher strength in the present study. The amount of the heat inputted to the stir zone decreased by increasing the tool travel speed and this phenomenon limited the mixing of the copper particles in the aluminum matrix.
3- Tool offsetting was one of the effective parameters in the FSW of Al-Cu TWBs. This offsetting was toward the aluminum side of TWBs. The best value for tool offsetting was 1.5 mm.
4- Different orientations were observed for the fracture line of the tensile samples of TWBs. Samples with minimum tensile strength had a zigzag and diagonal path. For other samples, the fracture line was perpendicular to the tensile direction.
5- The interaction effect of the tool rotation speed and travel speed showed that the highest strength resulted in the tool rotation speed of 1200 rpm and the tool travel speed of 60 mm/min.
6- The interaction effect of the tool rotation speed and tool offsetting showed that the tool rotation speed of 1200 rpm and tool offsetting of 1.5 mm produced the best weld quality.
7- Results of the present study showed that the tool rotation speed of 1200 rpm, tool travel speed of 60 mm/min and tool offsetting of 1.5 mm were the best FSW parameters for Al-Cu TWBs.

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اثر پارامترهای جوشکاری اصطکاکی اغتشاشی بر روی استحکام کششی نهایی ورقهای ترکیبی آلومینیم-مس

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چکیده: در تحقیق حاضر پارامترهای سرعت چرخشی ابزار، سرعت پیشروی ابزار و افست ابزار با سطوح مختلف در جوشکاری اصطکاکی اغتشاشی (FSW) ورقهای ترکیبی مس-آلومینیوم مورد استفاده قرار گرفت. جوشکاری اصطکاکی اغتشاشی مس خالص و آلیاژ آلومینیوم 5052 با سرعت چرخش 800 تا 1200 دور در دقیقه، سرعت پیشروی ابزار 40 تا 80 میلی‌متر بر دقیقه و افست ابزار از 1 تا 2 میلی متر انجام شد. آرایه L9 تاگوچی برای طراحی 9 آزمایش تجربی استفاده شد و هر آزمایش سه بار تکرار شد. آزمون کششی یکسانی بر اساس ASTM-E8 برای استخراج خواص مکانیکی TWBs استفاده شد. سرعت چرخش ابزار 1200 دور در دقیقه، سرعت پیشروی ابزار 60 میلی‌متر در دقیقه و جابجایی ابزار 1/5 میلی متر باعث ایجاد محدوده مطلوب ورودی گرما برای ایجاد یک منطقه اغتشاشی با کیفیت خوب شد. استفاده از پارامترهای FSW باعث تشکیل لایه های بین فلزی نازک و توقف حرکت نابجایی در آزمون کشش شد و سبب افزایش مقاومت کششی بالاتر و بهبود کیفیت اتصال گردید. از اسکن میکروسکوپ الکترونی (SEM) برای بررسی سطح شکست ورقهای ترکیبی پس از آزمون کششی استفاده شد.

واژه های کلیدی: ورقهای ترکیبی، جوشکاری اصطکاکی اغتشاشی، خواص مکانیکی، استحکام کششی نهایی، ریزساختار ریز دانه.