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Research Article

Examination of the parameters effect on Al-Cu FSW welded butt joints using formability consent

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ABSTRACT

In most applications, joining aluminum to copper using friction stir welding (FSW) is a primary manufacturing process followed by secondary forming processes. The aim of this study is to investigate the effect of FSW process parameters (speed and feed rate) on the formability of Al-Cu joints. Aluminum and copper blanks were welded at three different rotational speeds, i.e., 910, 1280, and 1700 rpm, and three different feed rates, i.e., 16, 29, and 44 mm/min. The base metals used in this study were aluminum (Al-1050) and copper in two states, i.e., as received and annealed. The mechanical properties of the base metals and the produced compounds were evaluated by tensile and hardness tests. The aluminum-copper joints were drawn into flangeless U-shape and cup shape using FSW to examine the formability of the joints. The maximum tensile load, punch load, and forming index were obtained when Al was at 1700 rpm and 16 mm/min, i.e., h. The welding was performed with annealed copper at the highest rotational speed and lowest feed rate due to work hardening of the joint. However, the ductility was highest at 1280 rpm and 44 mm/min, i.e., at medium rotation and highest travel speed. It can be depicted that when the FSW Al-Cu joint is further used in the forming process, moderate rotation and high feed speed should be adopted for welding to avoid work hardening and improve the ductility of the joint.

1. INTRODUCTION

Copper has excellent ductility, corrosion resistance, thermal and electrical conductivity, so, it is widely used to produce engineering parts such as electrical components, radiators, and electronic parts. Aluminum can be used as a substitute for copper since it is similar to copper in the above-mentioned properties. Replacing copper with aluminum has potential applications since similar electric properties can be achieved at a lower price and a lower density. Aiming at replacing copper with aluminum successfully [1-4]. Many attempts to weld aluminum with copper are carried out by using fusion welding but defects such as low penetration, spread area in the welding zone, and low mechanical properties are produced [5-6]. Aluminum and copper have problems when welded together because both metals are different in physical and mechanical properties, melting point, and microstructure [7-8]. Friction stir welding (FSW) is a promising technique for welding Al together with Cu, due to the good mechanical properties of the welded joint, no toxic fumes, no warping, and shielding issues, little distortion or shrinkage, and good welded joint appearance [9-12]. Friction stir welding is applied extensively in the automotive industry, especially vehicles of railway stations [13-16]. FSW is used to produce Al-Cu lap joints with excellent mechanical properties [17-18]. Other researchers used the FSW technique to weld dissimilar aluminum grades or dissimilar metals but joined with good mechanical and micro-structure properties [19-20]. Continuous attempts to simulate the effect of process parameters on the heat distribution, energy consumption, and temperature raising are reviewed for FSW of the dissimilar metal butt joints [21-22] and at dissimilar metal lap joints [23-24].

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The formability of welded joints from dissimilar metals [25-30] and dissimilar thicknesses [30-33] have been investigated thoroughly by many researchers, however, the formability Al-Cu tailored welded blanks with friction stir welding [7-8] has been not fully investigated and understood. Abdullah et al. [31] investigated the formability of Al-1051 welded joints using FSW under different thicknesses. It has been concluded that there is an optimal working condition at which the highest formability is reached.

Experiments were conducted using the lathe machine as a forming machine with the proposed tool[34]. The forming tool exerts pressure on the specimen as it rotates toward the die, driven by the lathe machine chuck, while the tool steadily advances towards the die. This process reduces the height of the specimen while increasing its diameter[35]. The process was performed on the lathe machine, with a data acquisition system in place to monitor and record the load applied during the process[36]

More research should be performed to determine the formability and mechanical behavior of Al-Cu joints welded by FSW under different operating conditions.

In this work, pure aluminum (Al) and copper (Cu) are welded using FSW under different operating conditions of rotational and traverse speeds. Aluminum and copper blanks are welded at three different rotational speeds that are 910, 1280, and 1700 rpm, under three different traverse speeds, which are 16, 29, and 44 mm/min. The tensile test is done for each welded joint to determine the maximum tensile load and ductility of the tested joint. The micro hardness of the upper and lower faces of the tested joints are measured. The formability of the welded joints is evaluated by drawing the specimen into U-shape and cup shape and measuring the formability load and calculating the formability index.

2. EXPERIMENTAL WORK

2.1 The Base Materials

In this work, all specimens are prepared from pure aluminum and pure copper strips with dimensions of 160 mm in length, 75 mm in width and 2 mm in thickness. The mechanical properties of the material used are tested and given in Table 1. Half of the copper strips is annealed by heating the base metal Cu until 650oC and keeping it at this temperature for an hour, and then cooling it in the outside air.

TABLE I. MECHANICAL PROPERTIES OF AL AND CU BASE METALS.

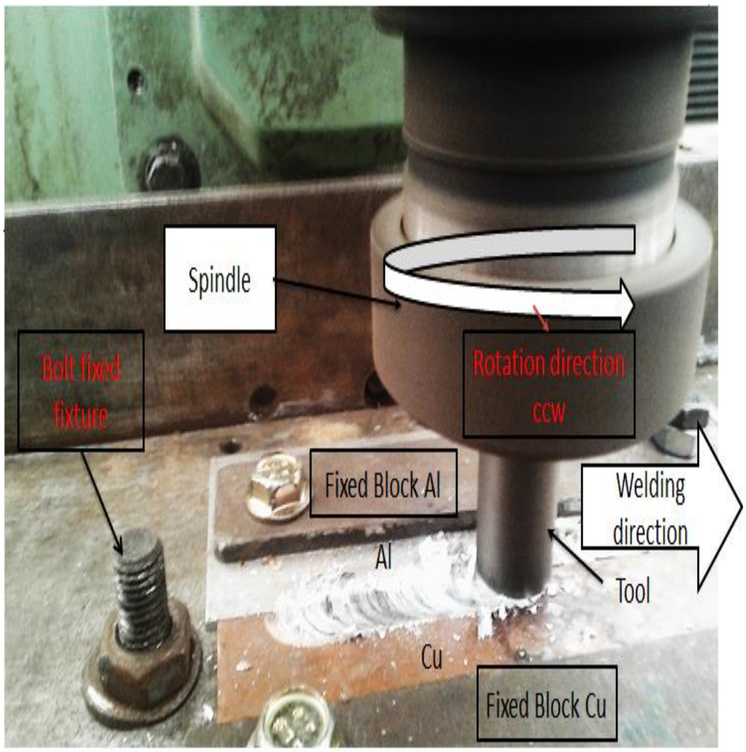
Material	Mechanical properties		
	Tensile strength (MPa)	Elongation (%)	Vickers Hardness (kg/cm^2)
Aluminum (as received)	152	25.60	27
Copper (as received)	164	32.94	52
Copper (annealed)	158	44.55	45

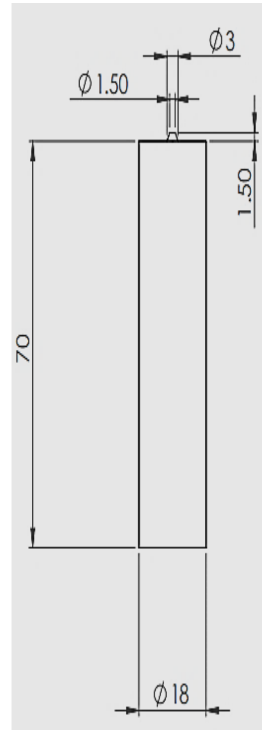
2.2 The Tool Setup

The fixture plate with 20 mm thickness, 350 mm length, and 150 mm width. It has two holes with a diameter of 17 mm to fix the fixture plate into the machine bed. Another eight holes with a diameter of 10 mm are used to fix the Al and Cu stripes into the fixture plate. Al and Cu strips are tightened together using the fixture shown in Fig. 1. The welding tool is also shown in Fig. 1, and it is made from tool steel with an 18 mm diameter flat shoulder. The welding tool has a tapered pin with a base diameter of 3 mm and a top diameter of 1.5 mm and 1.5 mm in height The welding tool is fixed into the milling machine chuck with a tilt angle of 2o to the axis perpendicular to the welding line in the forward direction. The tool dimensions and position are selected based on reference [38].

2.3 Working Conditions

The FSW process proceeded using a vertical milling machine (Model: milko-35r). The tool rotational speeds are 910, 1280, and 1700 rpm, and the welding traverse speeds are 16, 29, and 44 mm/min. The tensile and the formability tests were done at a computer-controlled servo-hydraulic universal testing machine (Model UH – 500 kN, Schematize™, Japan) with a crosshead speed of 5 mm/min for the tensile test and U- shape bending test, while it was 2 mm/min for the cup-drawing forming test. The micro hardness was measured from the top and bottom sides of the welding joint and linearly perpendicular to the welding direction at different positions including the stir zone (SZ), thermal mechanical affected zone (TMAZ), and heat affected zone (HAZ) of copper and aluminum sides. The micro-hardness test was carried out on a Vickers testing machine (VMH tester model number 1600-4981).





(a) (b)

Fig. 1. Vickers testing machine (VMH tester model number 1600-4981).

2.4 Formability Test

The formability test is based on two tests, which are (1) bending and (2) deep drawing of a cup. The bending test is performed based on the setup shown in Fig. 2.a, and it consists of fixed jaws, i.e. the die, and a punch. The punch is 50 mm wide, 150 mm long and 10 mm thick. The distance between the fixed jaws is 56 mm. The tested joint, i.e. the Al-Cu joint welded by FSW, is mounted over the fixed jaws and the punch presses over the joint to perform a U shape, as shown in Fig. 2.c. The die and punch used in the deep drawing test are shown in Fig. 2.b. The drawing process is performed with aid of a lubricant. The diameter of the punch is 72 mm, while the diameter of the die is 76 mm. The blank diameter D is calculated based on the following formula [31].

$$D = \sqrt{d^2 + d * h}, \quad (1)$$

where d is the punch diameter and h is the cup height. The shape and dimensions of the cup produced during the deep drawing test are shown in Fig. 2.d. In both tests, i.e. the deep drawing test and the bending test, the punch is operated by the universal testing machine, Model UH – 500 kN, Schematize™, Japan. The deep drawing tests were done on the Al-Cu welded joints that have the highest and lowest tensile strength for the sake of comparison, also, in case of annealed and non-annealed copper.

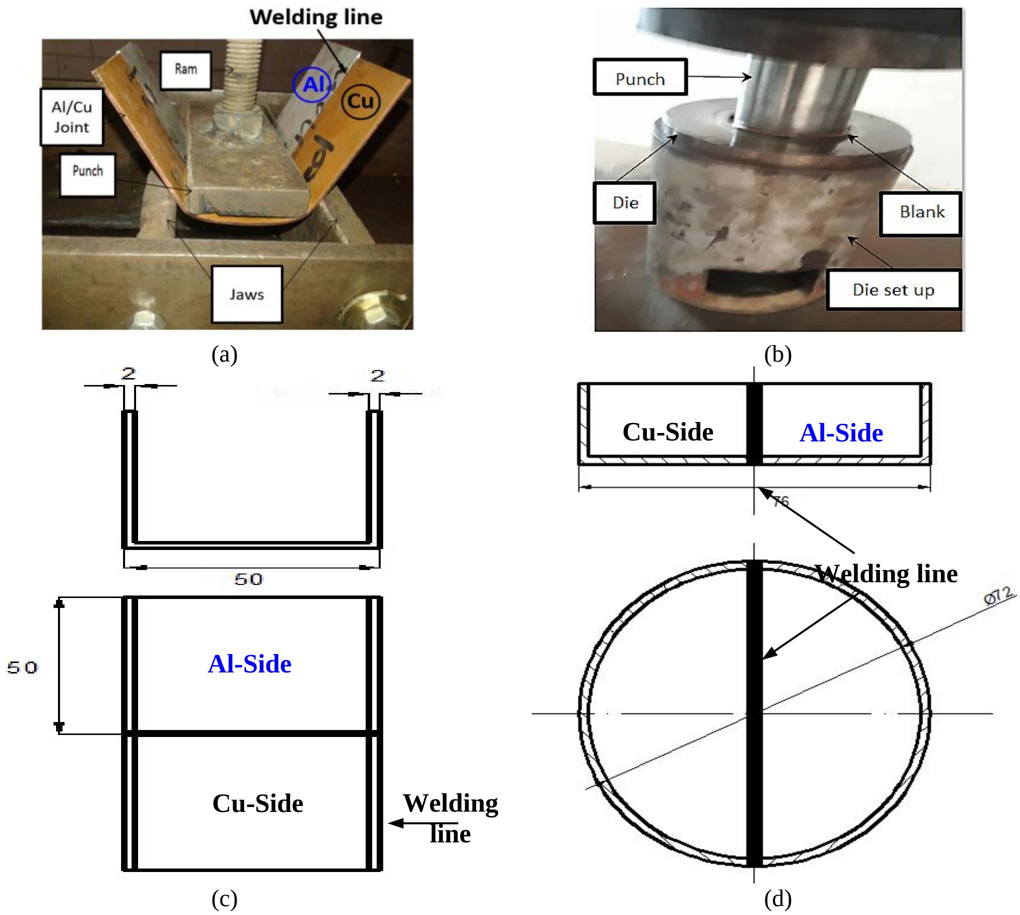
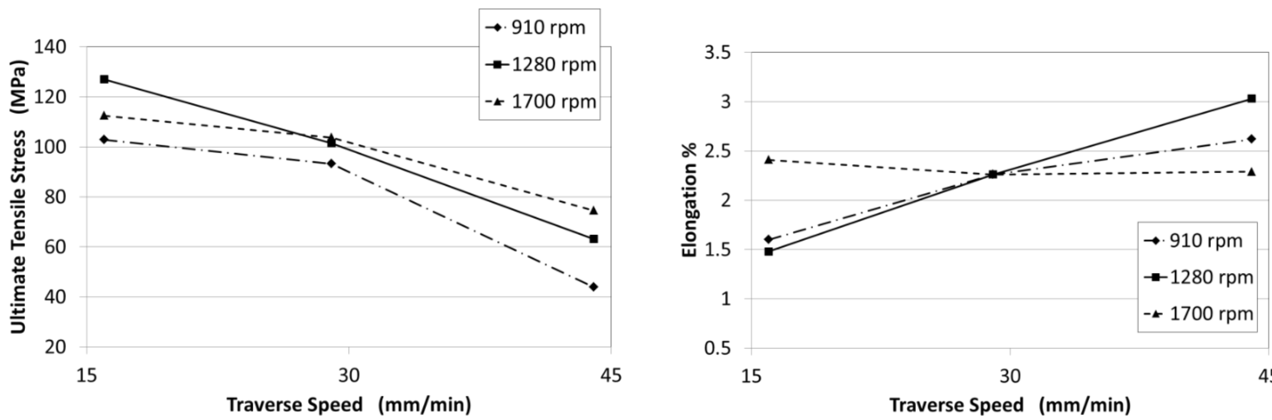


Fig. 2. The punch and die used in the bending test and the deep drawing of a cup are shown in (a) and (b), while the corresponding products are shown in (c) and (d), respectively. All dimensions are in mms.

3. RESULTS AND DISCUSSION

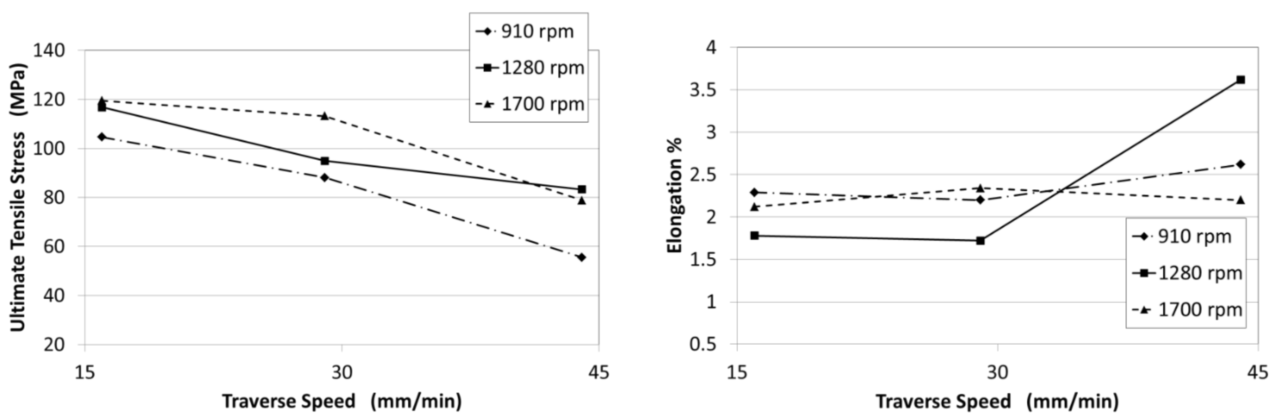
3.1 Tensile Strength and Elongation

The tensile strength and elongation % of the welded Al-Cu joints are presented in Fig. 3 in the case of non-annealed copper and in Fig. 4 in the case of annealed copper. The tensile strength and the elongation % are presented versus the traverse speed and as a function of the rotation speed. It can be seen from Figs. 3.a and 4.a that, as the traverse speed increases or the rotational speed decreases the strength of the joint decreases, and vice versa, which is in line with previous literature [8-12]. Increasing the traverse speed, i.e. the welding speed decreases the contact time between the tool and the workpiece, which decreases the energy input to the workpiece and consequently heating of the joint [37]. Decreasing the energy input to the joint i.e. heating of the joint, by increasing the traverse speed, decreases the strength of the joint. Also, decreasing the rotational speed decreases the heating of the joint which affects its strength of the joint. However, it can be seen from Figs. 3. b and 4.b. that as the traverse speed increases the elongation % increases, such that it can be concluded that the influence of increasing the traverse speed on the ductility of the joint is opposite to its effect on the tensile strength. This behavior can be attributed to the decrease in heat generation with the increase of the traverse speed or decrease of the rotational speed. Raising the welding temperature could improve the welding strength but on the other hand causes strain hardening, which affects the ductility of the joint. It can also be concluded from Fig. 3 that at the moderate traverse speed of 29 mm/min the elongation % is almost the same value for all rotational speeds, and the variation in the tensile strength is almost negligible, which indicates that the elongation% is dependent on the ultimate tensile strength such that if the ultimate tensile strength remains constant, irrespective of the welding conditions, the elongation percentage remains also constant.



(a) (b)

Fig. 3. Tensile strength (a) and elongation % (b) of the welded Al-Cu joint, versus the welding traverse speed and as a function of the rotational speed. The copper in this case is non-annealed.



(a) (b)

Fig. 4. Tensile strength (a) and elongation % (b) of the welded Al-Cu joint, versus the welding Traverse speed and as a function of the rotational speed. The copper in this case is annealed.

The joint efficiency is obtained as the ratio between the ultimate tensile strength of the Al-Cu joint to the ultimate tensile strength of Al base metal (the weaker part of the joint). The maximum efficiency of the Al- annealed Cu joint is 78.6% at 1700 rpm and 16 mm/min, i.e. at the highest rotational speed and the lowest Travers speed, while the minimum efficiency is 36.5% at 910 rpm/44 mm/min at the lowest rotation speed and highest Travers speed. The maximum tensile strength specimen is 83.6% at 1280 rpm -16 mm/min, which is not the highest rotational speed, while the minimum value is 29.6% at 910 rpm/44 mm/min. is the lowest rotational speed and highest Travers speed. It can be concluded based on **Figs. 3 and 4** and the joint efficiency that if the function of the joint is stress resistance, then the rotational speed should be maximum and the traverse speed should be minimum to enhance the joint strength, but if the welded joint will be used further in a forming process, then high rotational speeds with low traverse speeds should be avoided.

3.2 Specimen Fracture

The SEM image of the fractured surface of the 910/16 and 1700/16 specimen are shown in Fig. 5 and Fig. 6. respectively. The fracture occurred at the center of the welding line for the 910/16 specimen while it occurred at the aluminum side with an offset distance of 3 mm right to the welding line for specimen 1700/16. The 910/16 SEM images show the lamellar layers of aluminum mixed with the copper side while the intermetallic structure of Al_2Cu and inclusions of Cu are found on the aluminum side (Fig. 12). The fracture occurred for the 910/16 specimen looks like that occurred for brittle materials due to presence of intermetallic components (IMCs). The 1700/16 SEM image (Fig. 13) shows a good mixing between Cu and Al for both sides that improves the tensile strength of the joint compared to the 910/16 specimen and the fractured surfaces are seems as that of the semi-ductile materials (presence of cup and cone at the fractured surface).

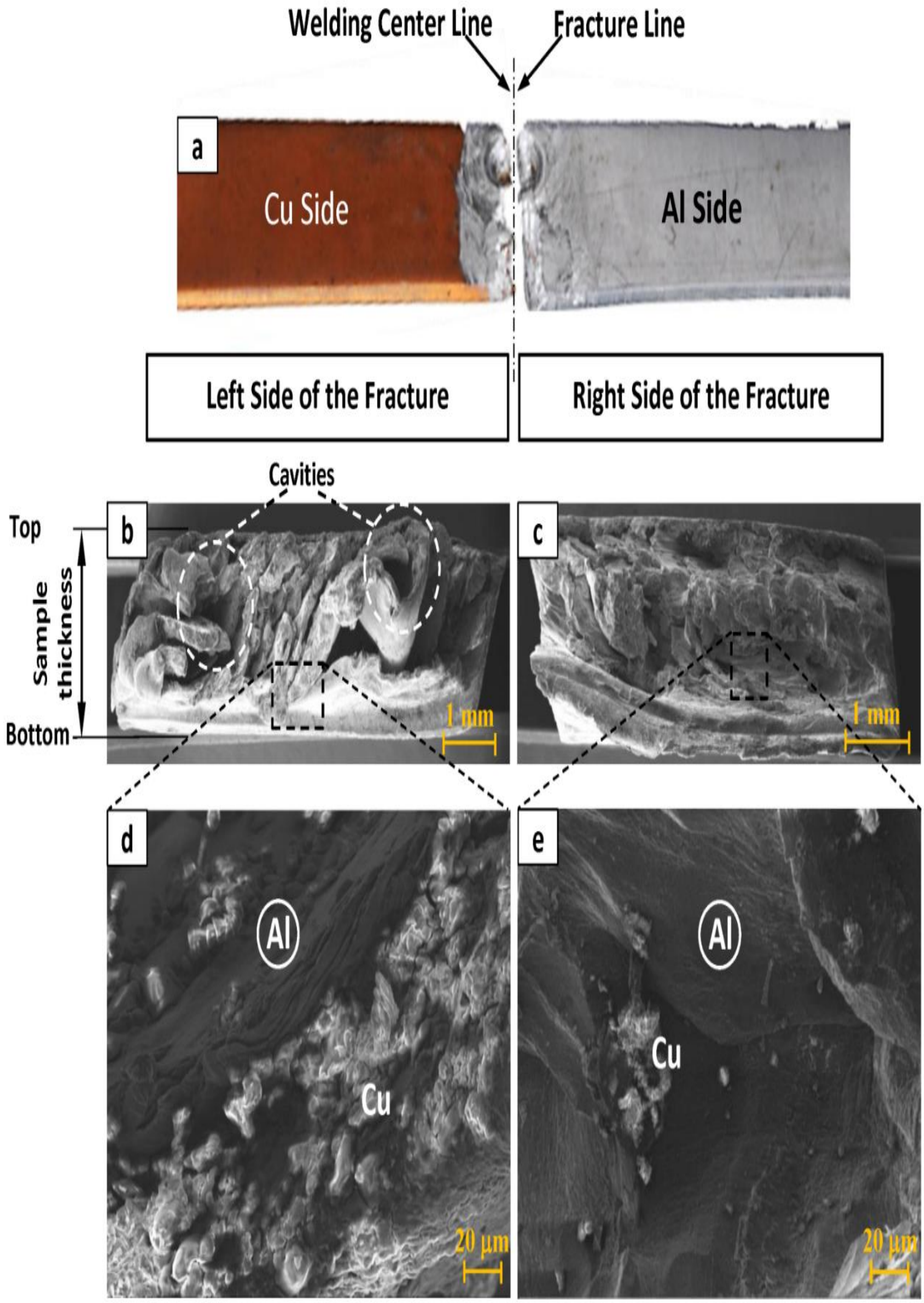


Fig. 5. A photo and SEM images of the fracture of an Al-Cu (not annealed) Butt joint that is welded by FSW at 910 rpm and 16 mm/min. The joint has been fractured due to tensile testing.

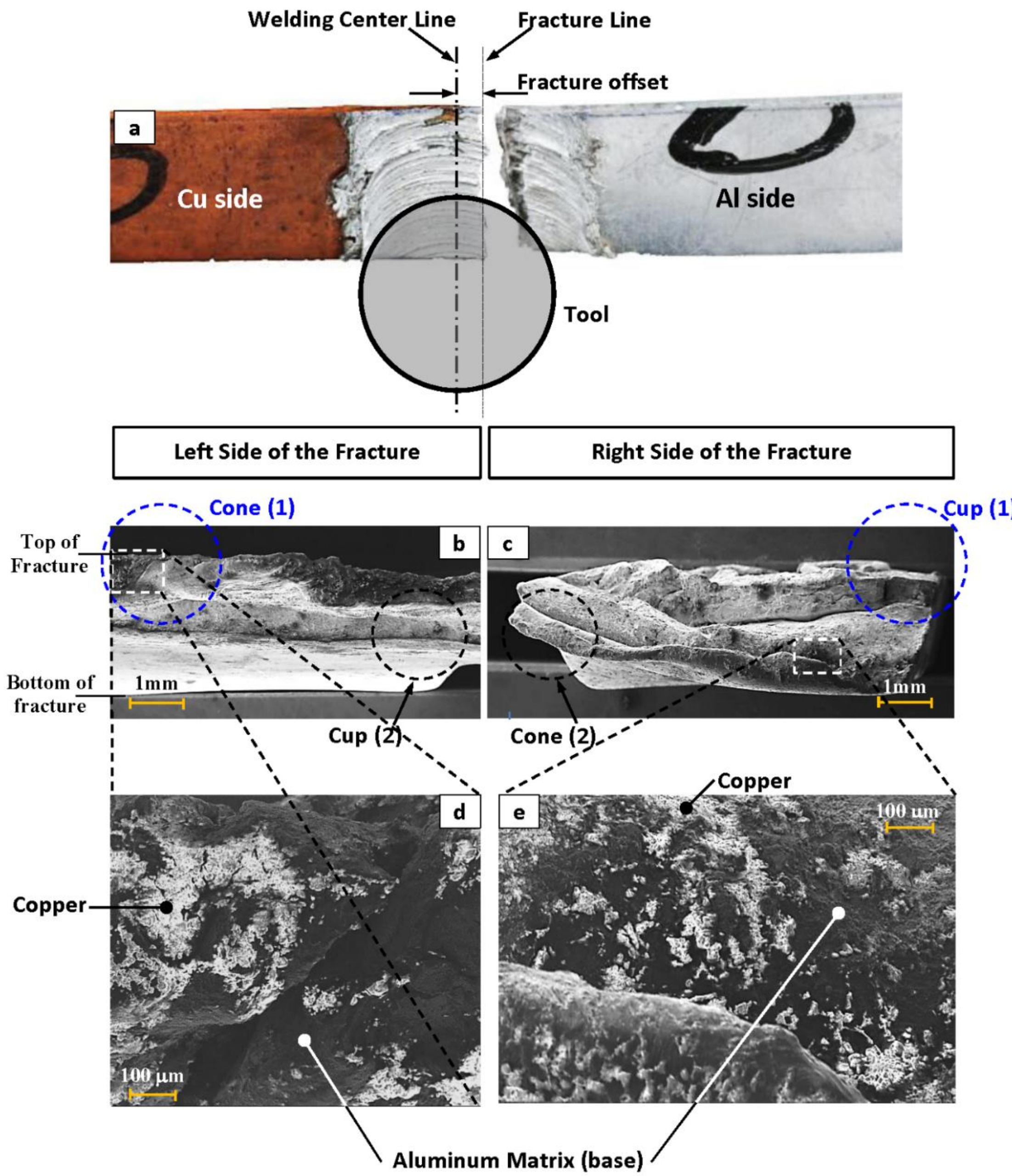


Fig. 6. A photo and SEM images of the fracture of an Al- annealed Cu Butt joint that is welded by FSW at 1700 rpm and 16 mm/min. The joint has been fractured due to tensile testing.

3.3 Formability of Al-Cu Joints Welded by FSW

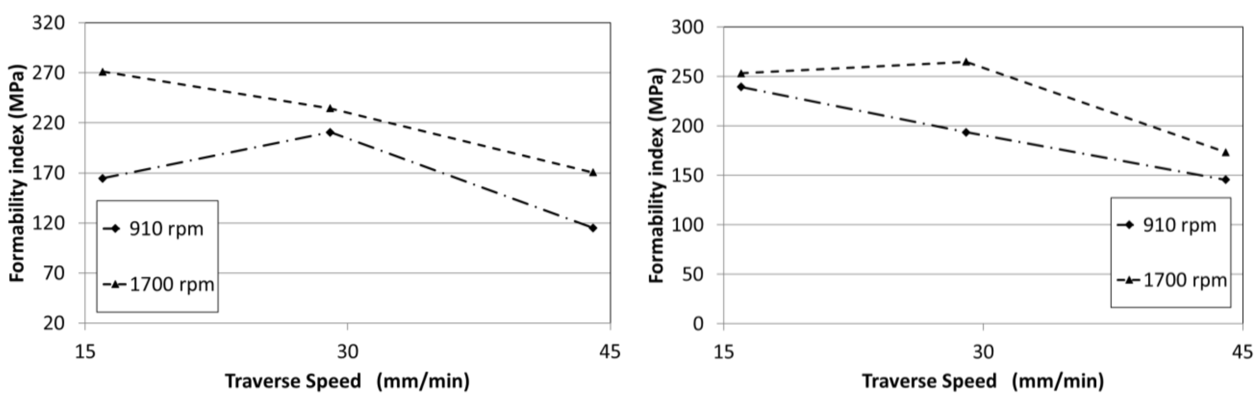
Most of the welding processes are considered primary processes that should be followed by a secondary process. In many applications, the secondary process is one of the forming methods so, the investigation of the formability of Al-Cu joints welded by FSW is so important for the applicability of the welding process. The formability investigation will include the calculation of the forming index based on the tensile test data, determining the bending strength from the free bending U-shape test, and finally obtaining the maximum load and studying the fractures that are produced during the formability cup-shape test.

3.3.1 Formability index of Al-Cu joints welded by FSW

The formability index can be calculated theoretically based on the following equation [26],

$$\text{Formability Index} = \text{Ultimate tensile strength (MPa)} \times \text{Elongation (\%)} \quad (2)$$

The formability index is a measure of the formability forces required for a forming process. The formability index is calculated for the welded joints at different traverse speeds in the case of annealed and non-annealed copper, and the results are presented in Fig. 7. However, only the extreme rotational speeds, i.e. the highest and the lowest rotational speeds are presented to clarify the influence of the rotational speed on the formability index. It can be seen from Fig. 7 that the formability index in the case of a higher rotational speed, i.e. 1700 rpm, is higher than in the case of a lower rotational speed, i.e. 910 rpm, and that is due to the high joint strength in case of 1700 rpm than in case of 910 rpm. Increasing the traverse speed decreases the formability index and that is due to the decrease in the strength of the welded joint with the traverse speed, and such a conclusion is clearly illustrated in Fig. 5. Increasing the rotational speed or decreasing the traverse speed increases the amount of heat energy added to the joint, which improves the adhesion and the tensile strength of the joint, consequently, increases the formability index of the joint, and vice versa. This concludes that FSW joints with large formability index should not be used in forming applications because it requires large forming forces, as well as a lot of energy, will be used, which can destroy the feasibility of the forming process, and this conclusion is illustrated in the bending tests that are presented in the next section.



(a) (b)

Fig. 7. Formability index of the welded Al-Cu joint by FSW as a function of the welding traverse speed, in case of (a) non-annealed copper and (b) annealed copper.

3.3.2 Bending test results

Bending tests were done for the Al-Cu joints welded at the different rotational speeds examined in this work, i.e. 1700 rpm, 1280 rpm, and 910 rpm, while the traverse speed was kept constant at 16 mm/min. The bending load-displacement curves of the performed tests are presented in **Fig. 8.** It has to be mentioned that the joint welded at a rotational speed of 910 rpm and a traverse speed of 16 mm/min fractured and cracked during the bending test, such that it was not possible to continue the test and present the results. The punch load increases as the punch travel downwards into the welded blank to form the U-shape until reaching a maximum value, then the load gradually decreases until it reaches a minimum value and stabilizes, and at that point, the forming process has been completed. The maximum bending force in the case of the joint welded at a rotational speed of 1700 rpm is 260 kgf while in the case of the 1280 rpm joint is 150 kgf. The maximum bending force in the case of a 1700 rpm joint is about 1.7 times more than the 1280 rpm joint, and that is due to the difference in the joint strength. Images of Al-Cu joints after the bending test are presented in Fig. 9. The joint welded at a rotational speed of 1700 rpm endured the bending test, while the joint welded at a rotational speed of 910 rpm failed the test and was broken. An important conclusion that can be drawn from the results presented in Fig. 6 is that the energy required for forming the 1700 rpm joint is higher than that of the 1280 rpm joint. The forming energy is calculated based on the following,

$$\text{Forming Energy} = \int_0^x F\,dx \qquad (3)$$

Where F is the forming force, i.e. the punch load, and x is the punch displacement. Carrying the above integral over the force-displacement curve presented in Fig. 8 will result in the area under the curve. The forming energy in the case of the 1700 rpm joint is 41.07 kJ, while in the case of the 1280 rpm joint is 12.56 kJ. The forming energy in the case of the 1700 rpm joint is about 3.3 times larger than in the case of the 1280 rpm joint, which indicates that the energy bill will be at least 3.3 times larger. It can be concluded that using large rotational speeds together with low traverse speeds in FSW will result in an extraordinarily strong joint that can affect the feasibility of the joint if it is used further in a forming process. On the other hand, using low rotational speeds and high traverse speeds in FSW can result in a weak joint that can be easily broken during the forming process.

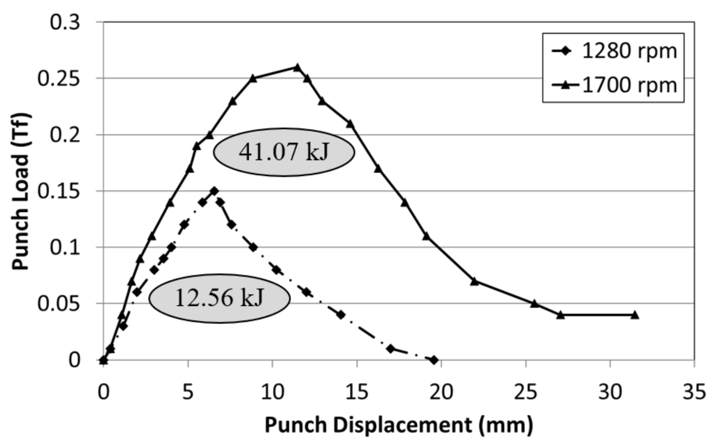
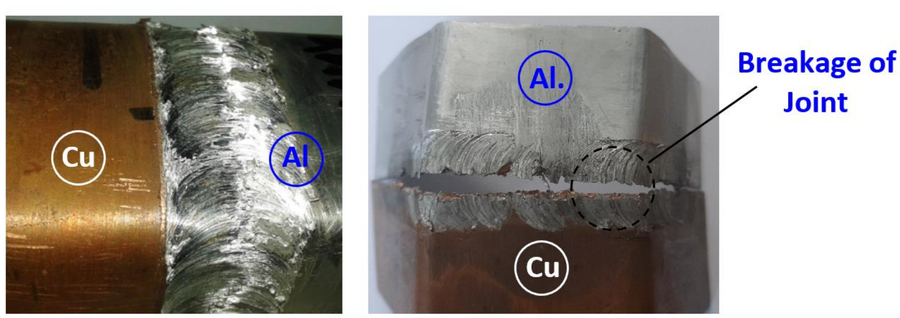


Fig. 8. Bending load-displacement curve for the Al-Cu joint welded at rotational speeds of 1700 rpm and 1280 rpm, while the traverse speed was constant at 16 mm/min. The copper has been annealed.



(a) 1700 rpm (b) 910 rpm

Fig. 9. Images of the Al-Cu joint welded at rotational speeds of (a) 1700 rpm and (b) 910 rpm after the bending test. The traverse speed is equal to 16 mm/min. The copper has been annealed.

3.3.3 Cup test results

The results of the punch force-displacement curves during the deep drawing of Al-Cu welded joints are plotted in Fig. 10. The Al-Cu joint is welded at rotational speeds of 1700 rpm and 1280 rpm, while the traverse speed was constant at 16 mm/min. During the cup-forming test, the load increases as the punch start to form the cup until the blank passes throw the die then the load decreases, as can be seen in **Fig. 8**. It has to be mentioned that the joint welded at a rotational speed of 910 rpm and a traverse speed of 16 mm/min fractured during the cup test. It can be concluded by comparing the loads in the cup test to the bending test, that the loads in the cup test are higher than the loads in the bending test. In the bending test the stresses are uniaxial, i.e. in the direction parallel to the welding line as indicated in **Fig. 11**, while in the cup test, the stresses are biaxial, i.e. in the welding direction and normal to the welding direction, which resists the punch motion and increases the punch load. The welding direction is called the x-direction in **Fig. 11,** while the direction perpendicular to the welding direction will be called the y-direction. The work done to withdraw the Al-Cu joint welded at a speed of 1700 rpm is 36 kJ, while in the case of the 1280 rpm joint is 23.6 kJ, as indicated in Fig. 8. The forming energy in case of withdrawing the Al-Cu joint into a cup is calculated based on Eq. (3), which is the area under the load-displacement curve. The forming energy in the case of the 1700 rpm joint is about 1.52 times larger than in the case of the 1280 rpm joint, which is in line with the previous conclusion of the bending test, i.e. more forming energy is required for the joints that are welded at large rotational speeds together with low traverse speeds due to the strain hardening that occurs during the welding process.

Images of the welded Al-Cu joint after the cup test are shown in **Fig. 12,** and that is in the case of welding at rotational speeds of (a) 1700 rpm and (b) 910 rpm, while the traverse speed is equal to 16 mm/min, and the copper has been annealed. It can be seen that the breakage of the Al-Cu joint welded at a rotational speed of 910 rpm occurred at the welding line, which is the weakest point in the joint, and a detailed image of the fracture is shown in Fig. 13. Welding at low rotational speeds lowers the heat energy added to the joint, consequently, decreases the amount of aluminum melts that has been transferred from the aluminum side to the copper side. The amount of aluminum melts determines the strength of the welded joint. Increasing the welding rotational speed increases the amount of aluminum melts, and consequently improves the strength of the welded joint. It can be concluded from **Fig. 13** that the failure of the joint occurred in the aluminum covering the joint and the fracture is mainly a cup and cone failure, i.e. a ductile failure under tensile stresses. The lower surface of the joint is subjected to compression stresses due to the applied punch load, while the upper surface of the joint is aluminum and subjected to tensile stresses during the cup test, and due to these tensile stresses' failure occurs in the aluminum in the shape of a cup and cone.

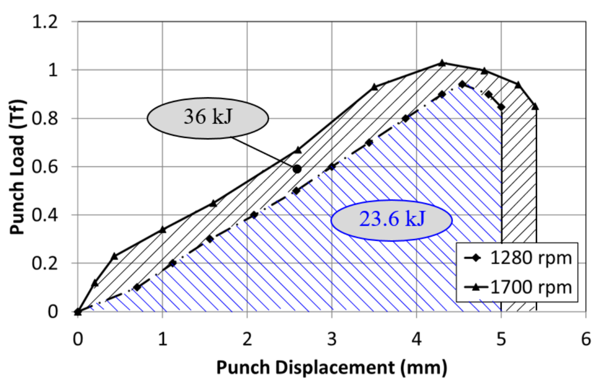


Fig. 10. Cup load-displacement curve for the Al-Cu joint welded at rotational speeds of 1700 rpm and 1280 rpm, while the traverse speed was constant at 16 mm/min. The copper has been annealed.

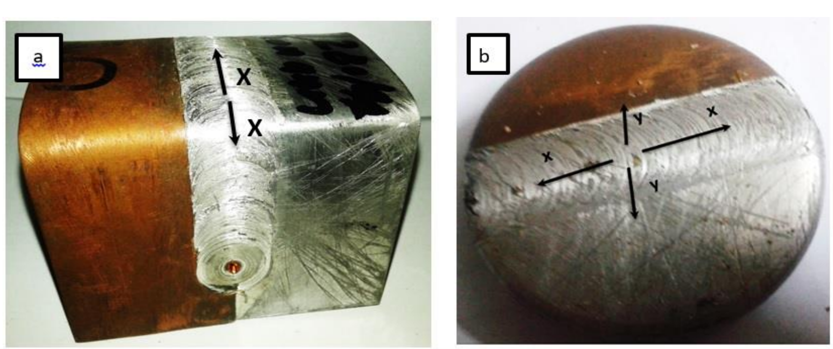
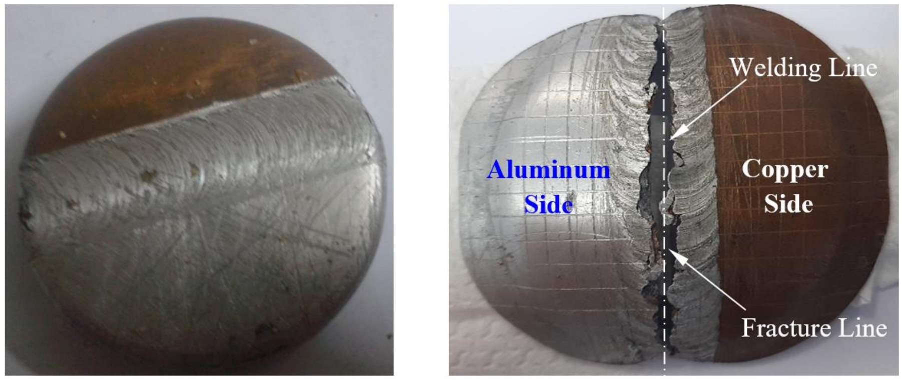


Fig. 11. forming force direction in: (a) bending test, and (b) cup-forming test. x-direction is the direction parallel to the welding line, while the y-direction is the direction perpendicular the welding line.



(a) 1700 rpm (b) 910 rpm

Fig. 12. Images of the Al-Cu joint after the cup test, and that in case of welding at rotational speeds of (a) 1700 rpm and (b) 910 rpm. The traverse speed is equal to 16 mm/min. The copper has been annealed.

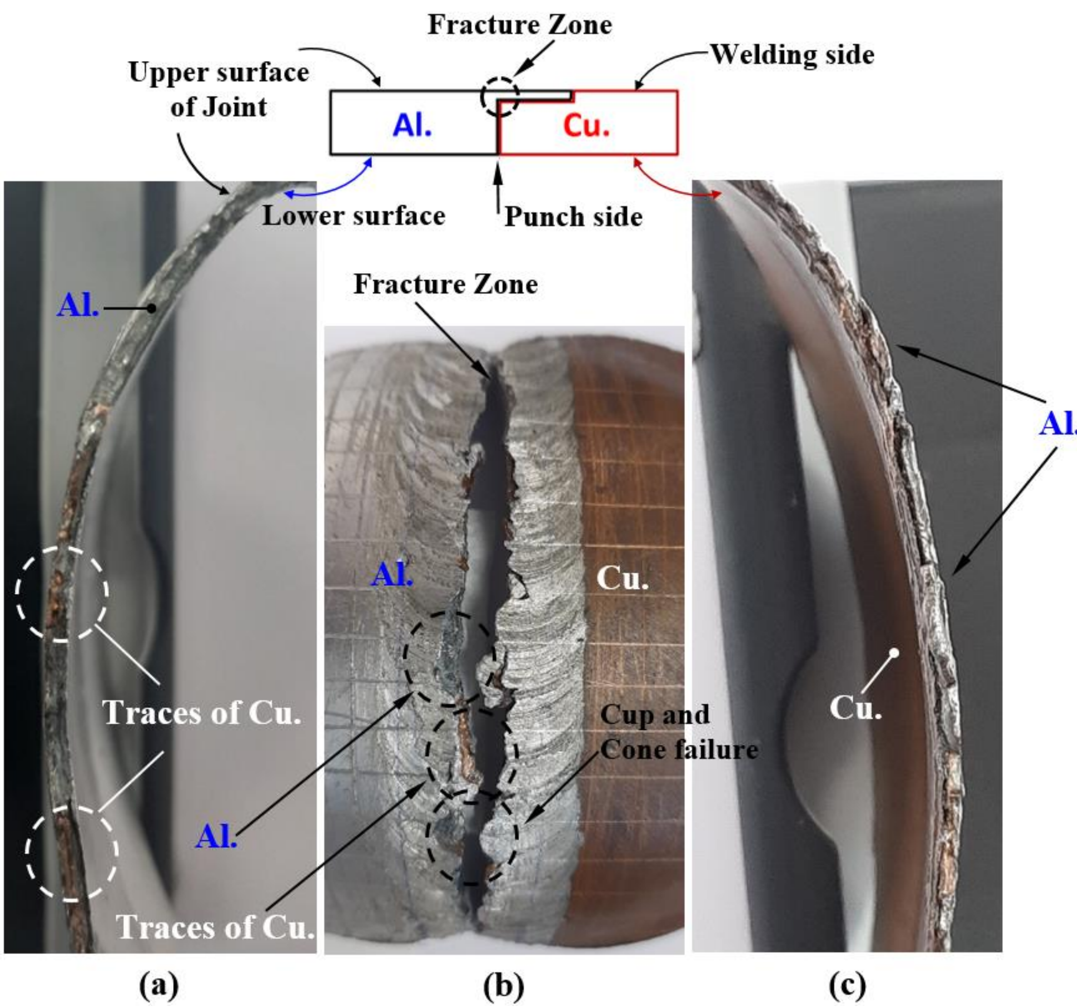


Fig. 13. Image of the fractured Al-Cu joint after the cup test, where (a) is a cross section of the fracture zone at the Aluminum side, (b) is Al-Cu joint after fracture and (c) is a cross section of the fracture zone at the copper side. The Al-Cu joint is welded at a rotational speed of 910 rpm and traverse speed of 16 mm/min. The copper has been annealed.

3.4 Micro Hardness Results

In the present study the micro-hardness of the top and bottom surfaces of the welded joints are mesaured as a function of the distance from the welding line, and perpendicular to the welding line. The micro-hardness distribution at (a) the top and (b) the bottom surface of the Al-Cu joint are presented in **Fig. 14**. The Al-Cu joint is welded at rotational speeds of 1700 rpm and 1280 rpm, while the traverse speed was constant at 16 mm/min, and the copper has been annealed. The base hardness of the Aluminum strip is 27 kg/cm^2, while of the annealed copper strip is 45 kg/cm^2 based on Vickers micro-hardness test.

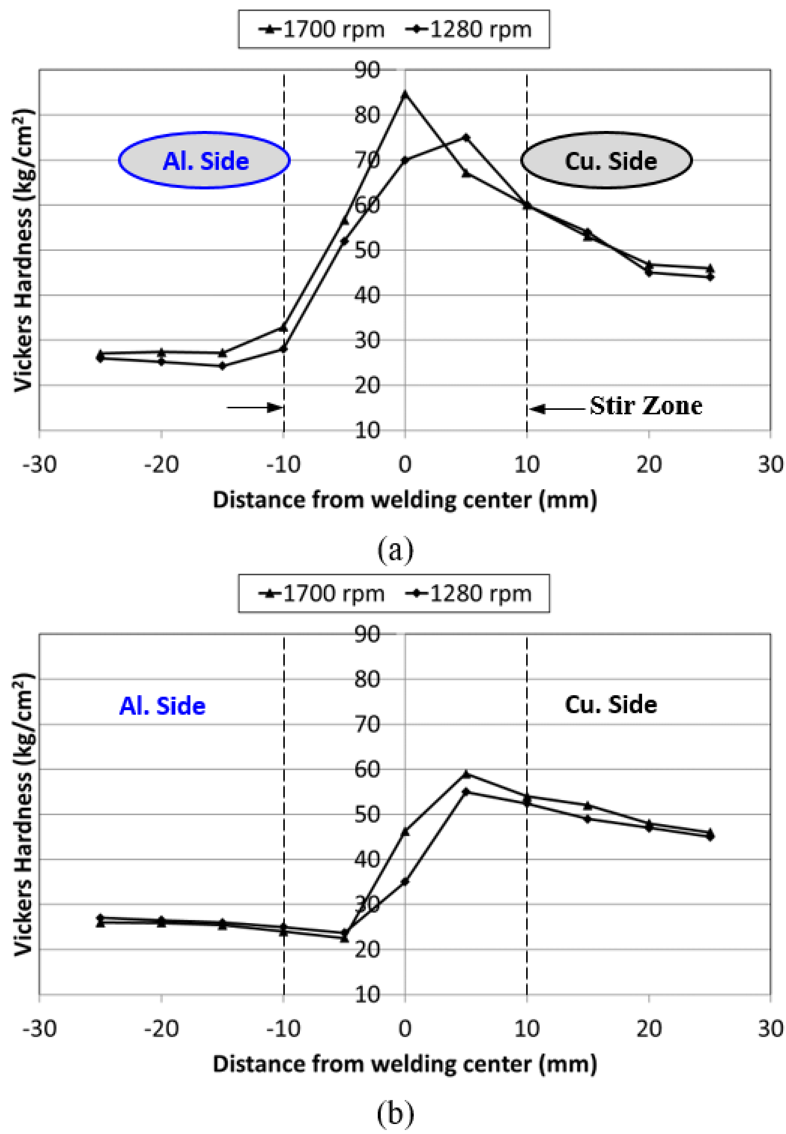


Fig. 14. Micro-Hardness distribution at (a) the top and (b) the bottom surface of the Al-Cu welded joint. The Al-Cu joint is welded at rotational speeds of 1700 rpm and 1280 rpm, while the traverse speed was constant at 16 mm/min. The copper has been annealed.

The maximum Vickers hardness in the stir zone (SZ) and at the top surface of the welded joint is 85 kg/cm^2, while at the bottom surface of the joint is 59 kg/cm^2, and that is in the case of welding at a rotational speed of 1700 rpm. The stir zone is 10 mm left and right to the welding line as indicted in Fig. 14, and it is dependent on the FSW tool diameter, which is in this case is equal to 18 mm. It can be concluded from Fig. 14 that the micro-hardness in the SZ and at the top surface of the welded joint, i.e. the surface facing the FSW tool, is greater than that at the bottom surface, and that is due to the more strain hardening that occurred in the top surface than at the bottom surface. The top surface of the welded joint is subjected to more friction and heating than the bottom surface due to the stirring effect of the welding tool, consequently, more strain hardening at the top than the bottom.

The maximum Vickers hardness at the top surface of the welded joint at a rotational speed of 1700 rpm is 85 kg/cm^2, while at a rotational speed of 1280 rpm is 75 kg/cm^2, which indicates that as the rotational speed increases the hardness increases. Increasing the rotational speed of the welding tool increases the heating of the welded joint, consequently, more strain hardening.

4. CONCLUSIONS

Pure aluminum is welded to pure copper by friction stir welding (FSW), in case of the copper being annealed or not annealed. The welding process is performed under different rotational and welding speeds. The objective of this research is to determine the optimum rotational and traverse speeds of Al-Cu Welded by FSW based on the formability of the joint, and the following conclusions are drawn:

1. Overheating of the welding joint improves the welding strength but on the other hand causes strain hardening, which affects the ductility of the joint.
2. Increasing the rotational speed of the FSW tool increases the hardness of the welded joint.
3. More forming energy is required for the joints that are welded at large rotational speeds together with low traverse speeds due to the strain hardening that occurs during the welding process.
4. The influence of increasing the traverse speed on the ductility of the joint is opposite to its effect on the tensile strength.
5. The elongation% of the welded joint is dependent on the ultimate tensile strength such that if the ultimate tensile strength remains constant, irrespective of the welding conditions, the elongation percentage remains also constant.
6. Increasing the rotational speed or decreasing the traverse speed increases the amount of heat energy added to the joint, which improves the adhesion and the tensile strength of the joint, consequently increases the formability index of the joint, and vice versa.
7. If the function of the joint is stress resistance then the rotational speed should be maximum and the traverse speed should be minimum to enhance the joint strength, but if the welded joint will be used further in a forming process, then high rotational speeds with low traverse speeds should be avoided.

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Conflicts of Interest
The authors declare no conflict of interest.
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