THE EFFECT OF ROTATIONAL SPEEDS ON THE MECHANICAL PROPERTIES OF DISSIMILAR FRICTION STIR WELDING FOR COMMERCIALLY PURE ALUMINIUM AND COPPER

Kasim K. Alshemary (e-mail: k_alshemary@yahoo.com)
School of Chemical Engineering, University of Al-Qadisiya

ABSTRACT:

In this study, dissimilar sheets of commercial pure aluminum and copper, 4 mm thickness were butt joined by Friction Stir Welding (FSW) to experimentally explore the effect of tool rotational speeds on the mechanical properties. Three rotational speeds of 1200, 1700 and 2200 rpm were applied. The transverse speed and the axial force were kept constant at 50 mm/min and 5 KN, respectively. X-ray diffraction (XRD), Vickers microhardness and tensile strength were investigated at these different rotational speeds. The joint welded at 1700 rpm was compared with their counterparts and observed significantly better. The formation of relatively hard brittle intermetallic compounds AlCu and Al_4Cu_9

تأثير السرعة الدورانية على الخواص الميكانيكية للحام الاحتكاكي للألمنيوم والنحاس التجاريين

قاسم الشمري

الخلاصة:

في هذه الدراسة تمت عملية اللحام الاحتكاكي بين شريحتي الالمنيوم التجاري النقي والنحاس وبسمك 3 ملم وذلك للاستكشاف التجريبي حول تأثير السرع الدورانية على الخواص الميكانيكية. تم تطبيق ثلاث سرع دورانية مختلفة (1200,1700,2200 دورة بالدقيقة) مع ثبات سرعة اللحام (50 ملم/الدقيقة) والقوة المسلطة (5 كيلونيوتن). اداة اللحام تتألف من كتف ودبوس اسطوانيتي الشكل. تم اجراء فحوصات حيود الاشعة والصلادة وقوة الشد على العينات الملحومة بسرع مختلفة واظهرت النتائج ان افضل عينة لحمت بسرعة 1700 دورة بالدقيقة عند مقارنتها بباقي العينات. تم ملاحظة تكون مركبات هشة (AlCu , Al_4Cu_9) عند العينة الملحومة بسرعة دورانية 2200 دورة بالدقيقة. اثبتت نتائج الصلادة تفوقها في منطقة الكتلة الصلبة (NZ) مقارنة بمنطقة المتاثرة ميكانيكيا (TMAZ) والمنطقة المتأثرة بالحرارة (HAZ).

INTRODUCTION

As a newly-developed solid-state joining technique, FSW has many advantages including low processing temperature, easy work-piece preparation and microstructure refinement in the welds. FSW is a clean, environment friendly and non-harmful process as it is not accompanied by an arc formation, radiation and toxic gas emission (Shukla and Shah, 2010). Nowadays, FSW welding technique has a wide potential application in aerospace, ship building, automobile and other manufacturing industries. It has been applied widely to join metallic materials such as aluminum, magnesium and copper alloys. (Mishra 2005, Nandan et.al 2008). A high-quality joint of dissimilar aluminum and copper is hard to be produced by fusion welding techniques due to the large differences between melting points and thermal properties (Weigl et.al. 2011, Ouyang et.al. 2006). Therefore, dissimilar welding of aluminum and copper is a challenging technique to be developed, and that welding of these two metals is a key problem to be solved. Several problems have been found using conventional fusion welding technologies. Joints defects such as voids and inclusions can seriously compromise the mechanical performance of the weld joint. Moreover, gas protection shields have to be used which means another complexity to the whole process (Vural et.al 2007).
Investigating the joint properties by FSW of aluminum 6061 alloy and copper was performed and considered difficult to weld due to major differences between their microhardness, melting points, electric and thermal conductivity. However, the generated heat required is much higher than in almost any other materials (Shukla and Shah, 2010). Kwon and his colleagues (Kwon et.al. 2009) have studied the effect of tool rotational speed (500 rpm, 1000 rpm, 2000 rpm and 3000 rpm) on microstructures and mechanical properties of aluminum alloys using FSW technique. They observed that high rotational speeds could raise strain rate and thereby affect the recrystallization process. In general, the size of dynamically recrystallized grains in NZ decreases with the increase of the strain rate. A higher tool rotational speed also results in a higher temperature and slower cooling rate in the NZ. On the other hand, a lower heat input condition due to a lower rotational speed results in lack of stirring action and causes formation of defects (Elangovan and Balasubramanian ,2007). Galvao et al (Galvao et al 2011) studied the effect of process parameters on the formation and distribution of brittle structures by FSW using aluminum and copper. They observed that with increasing heat input, mixed material zones dimension and homogeneity also increase. In FSW of dissimilar metals, one of the concerns is the formation of brittle intermetallic compounds such as Al_2Cu, AlCu and Al_4Cu_9 which are responsible for preferential development of crack in the tensile test (Shukla and Shah, 2010). Besides, many researchers reported that intermetallic compounds existed in the FSW of dissimilar Al-Cu joints (Ouyang et.al. 2006, Xue et.al. 2011, and Xue et.al. 2010). LIU et al (LIU et al 2008) observed that there are no new Al-Cu intermetallic compounds in the Cu-5A06Al joints. Mishra and Ma (Mishra 2005) pointed out that FSW of dissimilar metals of aluminum and copper is still not successful in sound joint production.
Until now, there are many problems to be solved including deep understanding of the processing parameter optimization. The aim of this study is to optimize the effect of tool rotational speed on the XRD, Vickers microhardness and tensile strength of dissimilar commercial pure aluminum and copper joints produced by FSW.

MATERIALS AND METHODS

In this study, FSW of regular butt joint configuration on dissimilar commercial pure aluminum and copper sheets was investigated, with a thickness of 4mm supplied. The workpieces were cut into the size of 150×100mm. The type of FSW joint was butt joint parallel to the rolling direction of the sheets during the welding process. The chemical compositions of the commercial pure aluminium and copper are listed in Tables 1 and Tables 2. In FSW, the advancing side (AS) is the side where the velocity vector of rotation tool and transverse speed are in the same direction; whereas the side where the velocity vector are opposite is referred to

as retreating side (RS). Copper, which is the harder material, was placed in AS; while aluminum sheets clamped at RS due to its low melting point than copper. The workpieces were cleaned using acetone before welding to remove grease and stains that may affect the quality of welding. For the welding tool, a smooth shoulder and unthreaded columnar pin were used. Table 3 shows the chemical composition of the medium carbon steel welding tool. The welding tool used, which has 18mm diameter shoulder and 5mm diameter pin, conventionally was heat-treated to have 50HRC. The tool pin shape and dimension are presented in Figure 1(a). The tilt angle of the tool is 3, and the tool pin has a constant offset about 2 mm toward the Al side.
FSW was conducted using a milling machine, type KAMA (3Hp; TRPER R8; 50 KN). The spindle of milling machine was set at three different rotational speeds of 1200, 1700 and 2200 rpm, and transverse speed of 50 mm/min. The axial force was kept constant at 5 KN during welding processes. The schematic diagram of the welding process is shown in Figure 1(b).
The welding joints were analysed by XRD, using a copper target to identify the phases formed in the welded joints. The instrument used in this work was D8 Advance X-ray diffract meter. The average Vickers microhardness test was carried out on the cross-section perpendicular to the welding direction according to ASTM: E384 standards, using (FV-700E). Tensile tests were also carried out using a Universal Testing Machine operating at a speed of 1 mm/min as per ASTM: E8 standards.

RESULTS AND DISCUSSION

Surface Appearance

Figure 2 shows the schematic diagram for the different welding zones; the NZ in the centre of the weld line where the pin has passed. TMAZ is immediately adjacent to NZ. HAZ is located between TMAZ and the unaffected BM which experiences a thermal cycle. BM is a remote material from the weld, and from the experimental perspective, it has a thermal cycle from the weld which is not affected by the heat in terms of microstructure or mechanical properties (Shukla and Shah, 2010 , Nandan et.al 2008). There is a remarkable difference in the internal structures of the NZ and the TMAZ; whereas the NZ is composed of fine-equiaxed recrystallization grains, the TMAZ is composed of coarse-bent recovered grains where no recrystallization is observed. Evidence from previous studies suggest that recrystallized grains in the NZ are due to mechanical action of the pin tool that generates a continuous dynamic recrystallization process (Weigl et.al. 2011).
Figure 3 shows the surface appearance of dissimilar FSW joints between aluminium and copper, using low rotational speed of 1200 rpm. Semicircular metal traces are observed in the stir zone. Rotational speed of 1200 rpm cannot provide enough heat input to producing sound joints. Most frequently such a process leads to heating and plasticize only one side of the material and does not lead to plasticize the counterpart of the material. This is a typical feature of dissimilar FSW between aluminum and copper. The dissimilar joining of aluminum and copper gives very low strength; most of the samples were fractured during the sample cutting. Aluminum has more plasticizing capacity during FSW than copper when using low rotational speed which leads to deform only aluminum (Shukla and Shah, 2010).
Figure 4 shows the weld profile of dissimilar FSW joints of aluminium and copper, using rotational speed of 1700 rpm. Figure 4 shows no defects at the top side of the joint, one can see only a small amount of welding flash at the copper side. In addition, the weld profile at the top side is completely covered with aluminium metal. This is so because at the same processing tempeature, aluminium has better plastic flowability than copper due to its lower melting point. Rotation speed of 1700 rpm can provide sufficient heat input and pin plunge depth involvs greater engagement.
At high rotational speed of 2200 rpm, the surface morphology of the stir zone became rough as opposed to that conducted at 1700 rpm. Figure 5 shows particles of copper spread with

aluminum which indicates excessive mixing of the material during welding process. The high temperatures associated with strong stirring action of the pin tool result in the formation of intermetallic compounds AlCu and Al_4Cu_9 (Abdollah-Zadeh et.al. 2008).

X-Ray Diffraction (XRD) Analysis

XRD analysis was also examined in order to identify the phases composition in FSW region, using a copper target. The analysis of XRD pattern results is shown in Figure 6. The relevant parameters corresponding to the diffraction peaks in the diagram have been computed using X' Pert High Score Plus software. The figure shows the XRD analysis for dissimilar FSW aluminium and copper in the stir zone at the three different rotational speeds As shown in Figure 6a intermetallic compounds are formed at rotational speed of 2200 rpm. This means that a chemical reaction has occurred between the aluminium and copper during welding process. Hard brittle intermetallic compounds between dissimilar joints of aluminum and copper are formed through liquid state reaction which resulted from the high rotational speed and phase transformation due to excess of heat generation (Meran 2006). Figure 6(b and c), shows only aluminium and copper exist in the dissimilar FSW joints at 1700 and 1200 rpm, repectively and no aluminium-copper intermetallic compounds are formed. This indicates that neither chemical reaction between aluminium and copper and nor phase transformation has occurred during the dissimilar FSW process which is in consistence with the results by Li et al (Li et al 2012).

Mechanical Properties

Microhardness measurements:

Figure 7 demonstrates the microhardness profiles of the dissimilar FSW aluminium and copper from the center line of the welded joints at the three different rotational speeds. The figure shows higher microhardness at the NZ. Microhardness observed is slightly higher than those of the base metals, mainly due to the formation of hard brittle intermetallic compounds AlCu and Al_4Cu_9 during welding process, especially at the rotational speed of 2200 rpm. A higher tool rotational speed results in a higher heat input and a slower cooling rate which leads to the formation of hard brittle intermetallic compounds in the NZ. On the other hand, a lower heat input condition due to a lower rotational speed (i.e. 1200 rpm) results in a lack of stirring action and causes the formation of defects, without forming intermetallic compounds (Elangovan and Balasubramanian ,2007). The microhardness value of the joint was FSW at rotation speed of 1200 and 1700 rpm much higher than that of the base metals. This may be due to the existence of large copper particles and layers. These copper layers have a high microhardness value. This is probably developed during FSW process, and producing a high dislocation density; that is why a high microhardness value can be seen at the rotation speeds of 1200 and 1700 rpm. In addition, the microhardness in the NZ increases slightly with the decrease in the grain size through the following relationship (Hirata et.al. 2007).

$$HV = H_O + k_H d^{-1/2} \tag{1}$$

Where HV is the hardness, H_O and k_H are the appropriate constants associated with the hardness measurements. It was concluded that the microhardness of the NZ increases with the decrease in friction heat flow; whereas the grain size in the NZ decreases when the friction heat flow decreases (Hirata et.al. 2007).

Tensile test profiles

Figure 8 and Figure 9 shows the comparisons of tensile strength of the welded joints at the three different rotational speeds. At rotational speed of 1700 rpm, the tensile strength is higher than that of 1200 and 2200 rpm. The tensile strength of the joint FSW at the rotational speed of

2200 rpm shows a lower value because the joint is only created mainly by the bonds of adhesion between aluminium and copper which results in a low tensile strength. The low tensile strength is mainly due to the formation of intermetallic compounds AlCu and Al_4Cu_9. Moreover, most of the samples are fractured from aluminum base metal side because during FSW the materials in the NZ are exposed to severe plastic deformation which causes a very fine grain structure in the weld joint in comparison to that of aluminum base metal, and consequently it leading to a higher microhardness value and strength. Besides, the tensile strength of aluminum base metal is less than that of copper base metal; therefore, most of specimens are fractured from aluminum base metal (Shukla and Shah, 2010). The welded joints FSW at rotation speeds of 1200 and 2200 rpm was fractured from HAZ in aluminum side; while the weld joint FSW at rotation speed of 1700 rpm was fractured from NZ.

CONCLUSIONS

Commercial pure aluminium and copper have been joined successfully by FSW conditions. There is a range of rotation speed or heat input in which specimen can be joined together successfully, especially at 1700 rpm. Several forms of brittle intermetallic compounds are found in the joint FSW at rotational speed of 2200 rpm. These compounds mainly consist of AlCu and Al_4Cu_9. The microhardness of the NZ showed superior values than that of base metals indicating multiple contradiction effects of work hardening, brittle intermetallic compounds and grain refinement. Regarding tensile strength results, generally the weakest part of welded joints is aluminum base metal and NZ.

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Table 1. Chemical compositions of commercial pure Aluminium

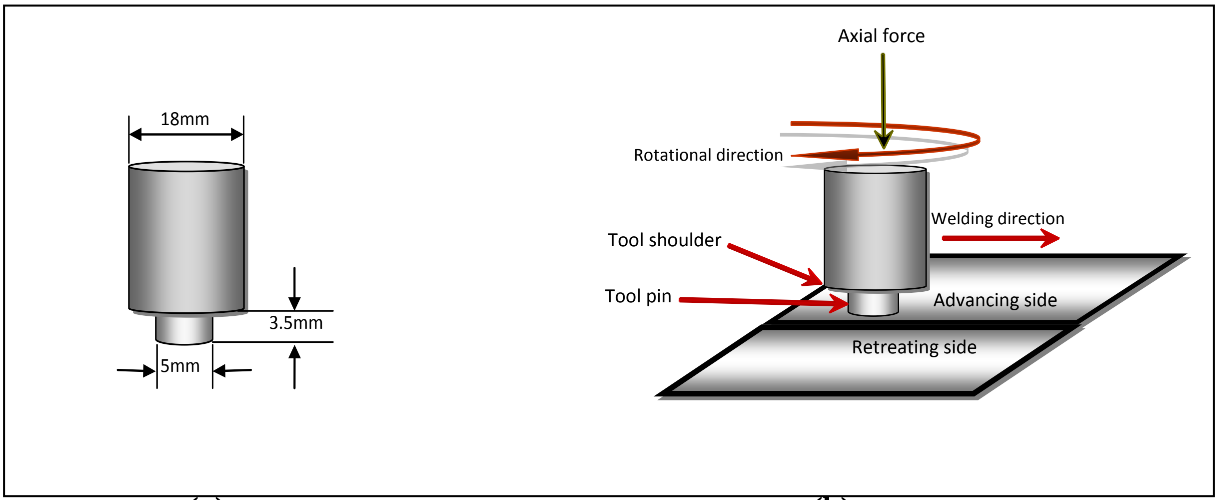
Element	Al	Si	Fe	Mg	Cu	Mn
wt %	Balance	0.21	0.30	0.13	0.05	0.03

Table 2. Chemical compositions of commercial pure Copper

Element	Cu	Fe	Pb	Si
wt %	Balance	0.03	0.07	0.01

Table 3. Chemical compositions of medium carbon steel welding tool

Element	Fe	C	Mn	P
wt %	Balance	0.51	0.59	0.03



(a) **(b)**

Figure 1: Schematic diagram and photo of FSW process

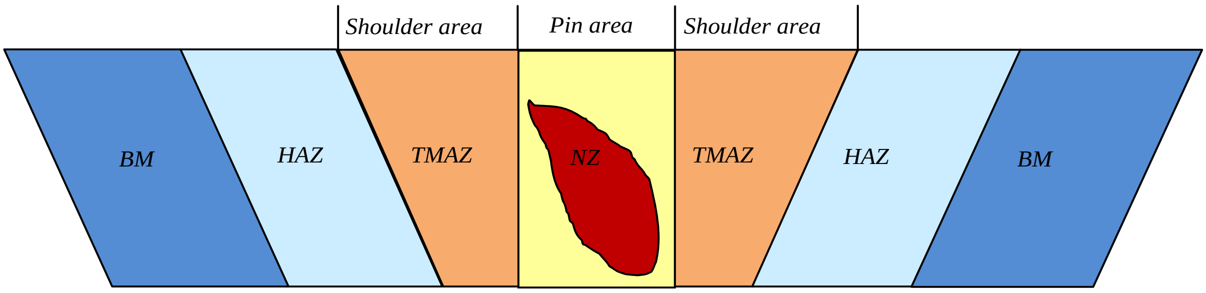


Figure 2: Welding zones after FSW process.

Figure 3: Optical macrograph of dissimilar aluminum and copper joint, FSW at rotational speed of 1200.

Figure 4: Optical macrograph of dissimilar aluminum and copper joint, FSW at rotational speed of 1700.

Figure 5: Optical macrograph of dissimilar aluminum and copper joint, FSW at rotational speed of 2200.

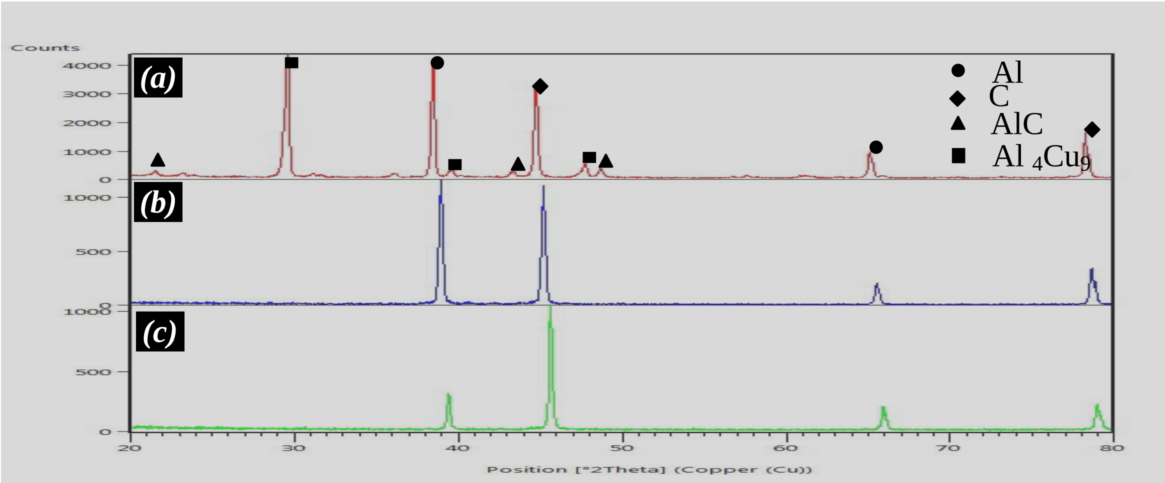


Figure 6: X-ray diffraction analysis of the welded joints FSW at: (a) rotational speed of 2200, (b) rotational speed of 1700 and (c) rotational speed of 1200 rpm.

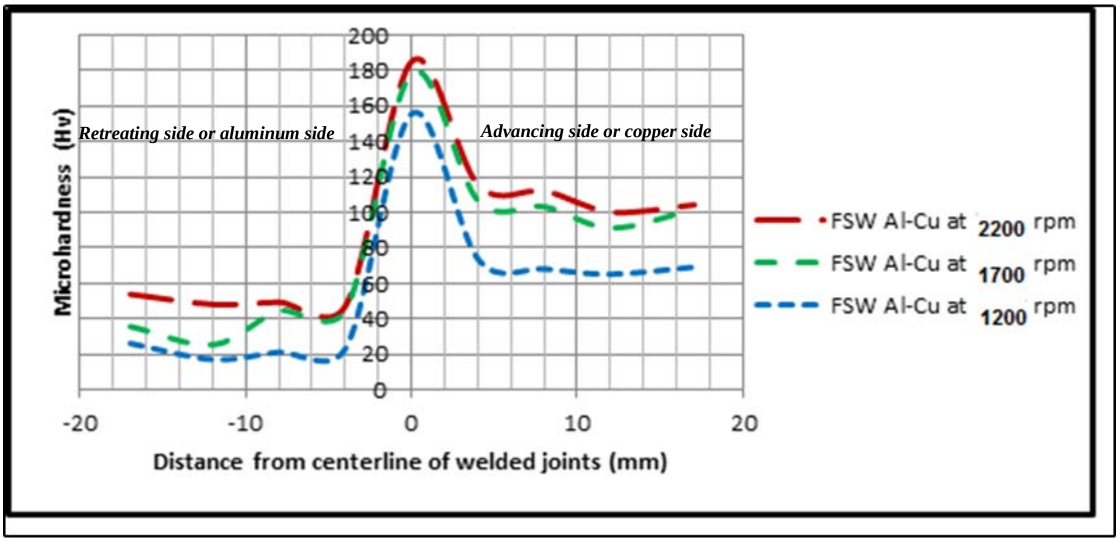


Figure 7: The average microhardness profile across the welded joints at three different rotational speeds.

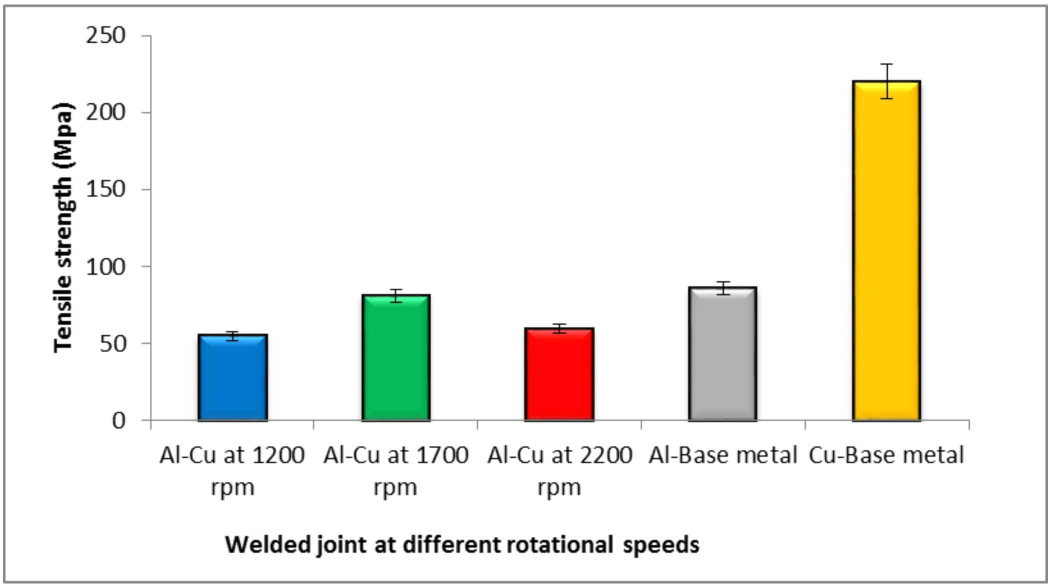


Figure 8: Tensile test profiles of the dissimilar Al-Cu welded joints at three different rotational speeds.

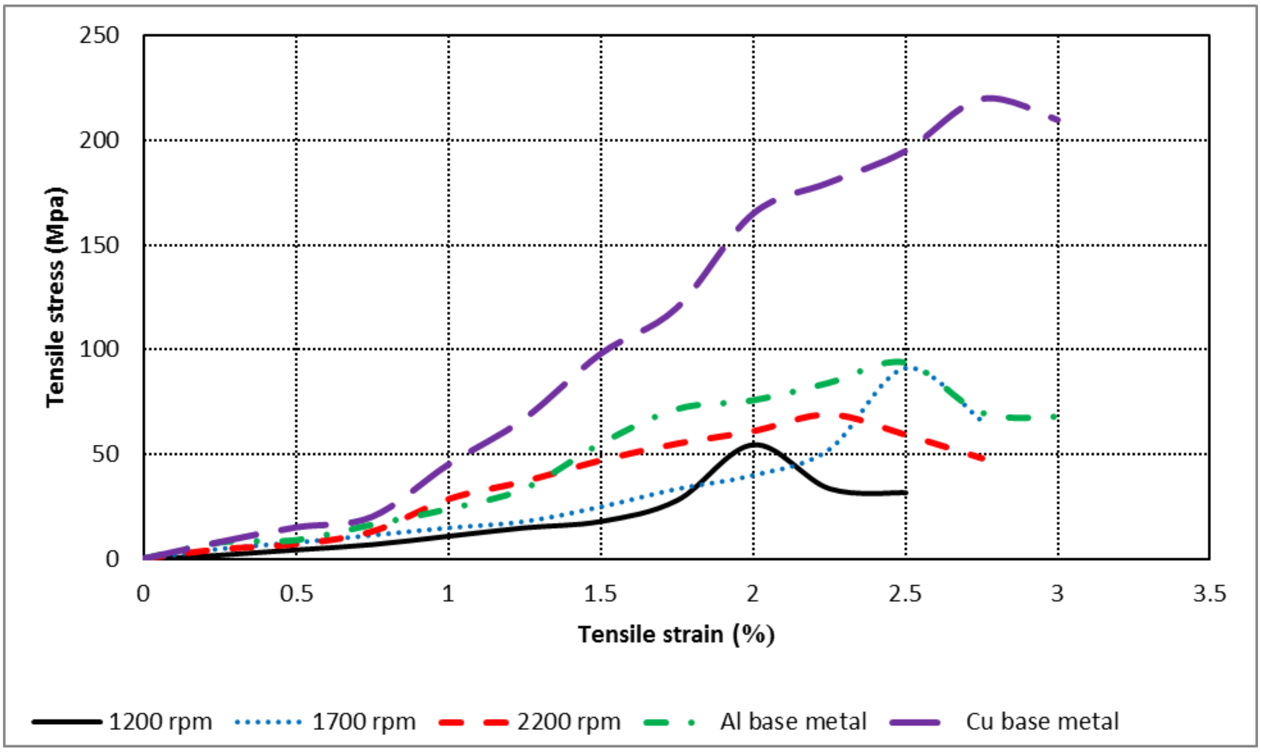


Figure 9 Tensile test of the dissimilar Al-Cu welded joints at three different rotational speeds.

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