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The Effect of Rotational Tool Speed on Dissimilar Joint Aluminum-Copper Plate Friction Stir Welded Joint

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Friction stir welding; dissimilar joint; rotational tool speed; stir zone.

Abstract
The study investigates the impact of rotational tool speed on the mechanical properties and microstructure of aluminum-cooper friction stir-welded joints. It found that higher rotational speed leads to increased grain size, possibly due to increased heat production. Higher hardness values in the stir zone result from uniform dispersion of smaller copper particles. The study found that 540 rpm yields the maximum hardness value in the stir zone, measuring 67 VHN. However, higher speed results in defects like voids, cracks, and intermetallic compounds (IMCs), which are linked to the formation of IMCs at elevated temperatures. The optimal welding conditions at 550 rpm balance grain refinement, hardness enhancement, and defect mitigation, contributing to the understanding of welding process parameters.

INTRODUCTION

The development of dissimilar material joints in industrial applications has been driven by their technical and economic advantages, particularly in the context of joining aluminum and copper materials. According to Boucherit *et al*. (2017), the utilization of aluminum and copper in the transportation and energy sectors is prevalent due to its notable electrical conductivity, corrosion resistance, and low-density features. This requires a dependable joining method for fabricating Al/Cu components. The liquid state welding technique can lead to the formation of compaction flaws, such as porosity and hot cracking. Consequently, its effectiveness is diminished when used to welding different materials (Liu *et al*., 2007). In this particular scenario, the utilization of the solid-state welding technique, also known as welding under solid conditions, proves to be more efficacious for joining aluminum and copper materials. This is primarily due to its capability to amalgamate dissimilar materials in a solid state, thereby mitigating the occurrence of metallurgical reactions that typically transpire at elevated temperatures (Muthu & Jayabalan, 2015). Friction stir welding (FSW) is a solid-state welding technique that has been effectively utilized for joining different materials. The Friction Stir Welding (FSW) technique is a solid-state welding process that has been developed by leveraging the fundamental principles of Friction Welding (FW). FW involves the joining of two materials in a solid state by employing heat energy generated through the rotation and tool pressure applied to two plates. This heat causes a localized melting of the base metal, facilitating the welding process.

The outcomes of the joints achieved in the FSW welding process are significantly influenced by the welding settings. The heat input generated during welding is influenced by two main key elements, namely the rotational speed and welding speed. An increase in rotational speed coupled with a decrease in welding speed leads to an escalation in heat input (Jatimurti *et al*., 2019). According to Osman *et al*., (2019), changes in welding speed during the joining process of copper and aluminum have been shown to result in inadequate bonding. This may be attributed to a reduction in heat input, leading to a drop in tensile strength of the final joint. The occurrence of these phenomena may be attributed to significant fluctuations in welding speed, which subsequently lead to the identification of faults in the surface groove, such as insufficient material filling. Additionally, inadequate heat input contributes to weak copper-aluminum bonds. Conversely, when welding speed variations are minimized, connections are achieved without any defects. Similar findings were seen in research carried out by (Khodir *et al*., 2016), which demonstrated a reduction in tensile strength with increasing changes in welding speed. The observed phenomenon can be attributed to a reduction in temperature within the stir zone when the welding speed is increased, leading to the production of metallurgical bonds that exhibit lower strength. The study conducted by Muthu and Jayabalan (2015) had varying outcomes. Specifically, it was observed that an increase in welding speed variation led to a rise in the tensile strength of aluminum and copper joints. However, this trend reversed at greater welding speed variations, causing a decrease in tensile strength. This phenomenon occurs due to the presence of significant variations in welding speed, which leads to an elevated heat input. Consequently, turbulent flow is induced inside the stir zone, leading to the formation of defects such as fractures and tunnel defects. The optimal welding speed is achieved within the range of 70 and 80 mm/min, resulting in tensile strengths of 104 and 113 MPa, respectively. This is attributed to the adequate heat input, which facilitates the distribution of copper particles within the stir zone region. Conversely, higher welding speeds lead to a decrease in tensile strength due to insufficient heat input during the copper-aluminum connection, resulting in a tunnel defect within the stir zone area. Khajeh *et al*. (2021) noted that the ratio of traverse speed (V) to welding speed (W), which stands for heat input, has a considerable impact on joint characteristics. As the main causes of reduced strength and ductility in non-optimized joints, they identified voids and intermetallic compounds (IMCs). The number of IMCs discovered to rise with increasing rotation speed. However, raising the rotation speed slighly reduced the hardness of the stir zone (Khodir *et al*., 2016)

Numerous prior investigations have consistently shown a common issue in the connecting of dissimilar materials, specifically the notable reduction in tensile strength observed in copper-aluminum connections. The occurrence of a crack defect in the joint is attributed to an excessively high heat input, whereas a tunnel defect is formed due to an excessively low heat input. Consequently, the presence of these welding defects leads to a reduction in the tensile strength of the copper-aluminum joint. The objective of this study is to investigate the impact of varying rotational welding speeds with lower welding speed (50 mm/minute) and thickness plate (3mm) in friction stir welding (FSW) on the quality of aluminum-copper joints.

RESEARCH METHODS

The materials employed in this investigation consist of A5005 aluminum plate and C10100 copper plate, both measuring 150 mm x 150 mm x 3 mm, as seen in Figure 1.a. The FSW welding tool employed in this study is fabricated from st90 high carbon steel, including specific parameters including a shoulder diameter of 18 mm and a pin diameter of 4 mm, as seen in Figure 1.b.

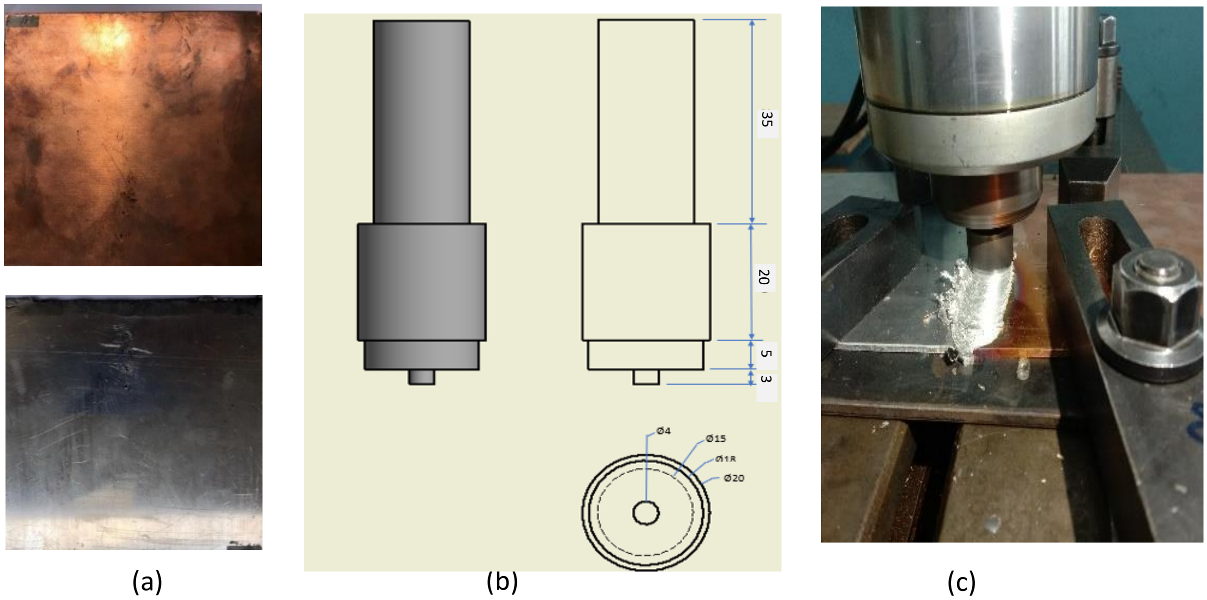


FIGURE 1. (a) Aluminum and cooper plate, (b) tool dimensions, and (c) welding processing

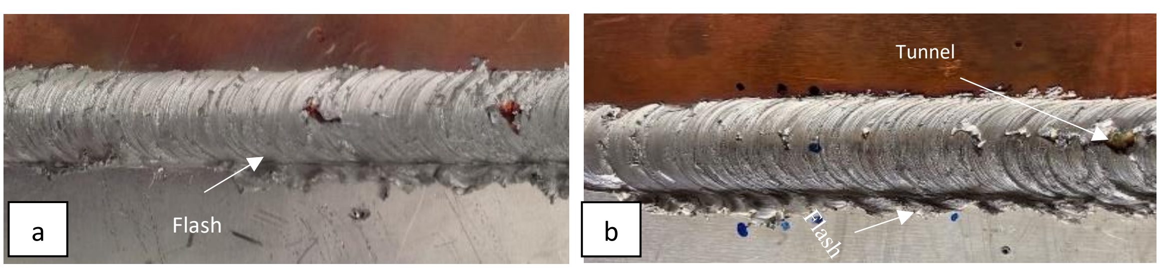
Tabel 1. The welding settings for Friction Stir Welding (FSW)

Spindle rotational speed (RPM)	***Welding speed (mm/minute)***	***Plunge Depth (mm)***
540, 910, 1500, and 2280	*50*	*3*

The present study involved conducting tests on welded specimens in order to assess their mechanical and physical qualities. These tests encompassed tensile testing in accordance with ASTM E8 standards, microVickers hardness testing, as well as macrostructural and microstructural analysis.

RESULT AND DISCUSSION

We've completed the FSW welding procedures. The pure copper and aluminum plate A5005 have been joined to the butt joint location throughout all rotation speed variations. Figure 3 illustrates the outcome of the welding procedure.



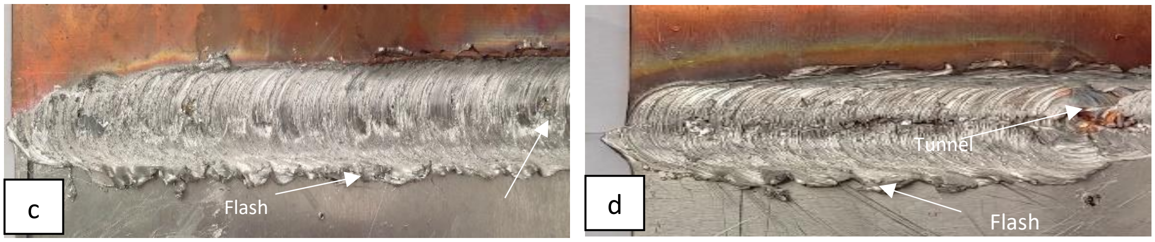


Figure 2. The results of the dissimilar aluminum- copper friction stir welded joint with a variation in rotational speed (a) 540 rpm, (b) 910 rpm, (c) 1500 rpm, and (d) 2280 rpm.

The results of welding all variations occur surface defects such as flash and tunnel defects. Flash defects can arise because of excessive temperatures, causing the displacement of the soft metal during the FSW process (Albanai, 2020). The flash occurs greater at higher rotational speed and in the aluminum plate area. The formation of tunnel defects in higher rotational speed (910 and 2280 rpm) some of the aluminum in stirred area is thrown from the surface and has not yet had time to diffuse into the copper.

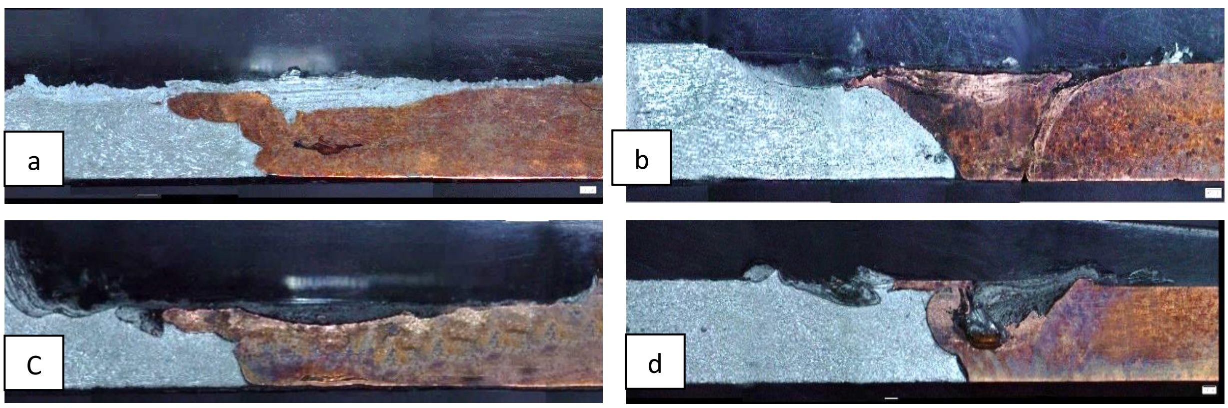


Figure 2. The macrograph cross section of the dissimilar aluminum-copper friction stir welded joint with a variations in rotational speed (A) 540 rpm, (B) 910 rpm, (C) 1500 rpm, and (D) 2280 rpm.

The occurrence of void defects at rotational speeds of 540 rpm and 910 rpm is attributed to insufficient heat input required for the complete melting of both materials, resulting in inadequate metallurgical bonding in a specific region inside the stir zone. This is consistent with the research conducted by Elmetwally *et al*., (2020), which explains that insufficient heat input will cause partial melting of the material, with the molten material binding to the copper and leaving voids in the non-melted material. The formation of voids and tunnels occurs due to insufficient temperature during welding, which hinders the proper intermixing of materials. The formation of voids and tunnels occurs within the steering zone. According to a study conducted by Xue *et al*., (2011), increasing the rotational speed results in the formation of a thick intermetallic layer due to the high temperature, which deteriorates the surface of the welded joint. At a velocity of 2280, a significant cavity defect, commonly referred to as a large-sized cavity defect, occurs in the stir zone on the copper side due to excessive heat input. In a study conducted by Ajri *et al*. (2020), Cavities are formed in the stir zone at high rotational speeds. The occurrence of fracture defects in joints is attributed to the presence of a hard and brittle intermetallic layer (Elmetwally *et al*., 2020). At a speed of 1500 rpm, tunnel defects occur in the Al part and no cracks occur in the welded joint. In all variations, a defect-free connection between aluminum and copper is not obtained.

The objective of microstructure examination is to observe the grain morphology in the base metal, heat-affected zone, and stir zone for each variation of rotational speed in friction stir welding. The observation was conducted using an optical microscope with a magnification of 100x, as seen in Figure 3.

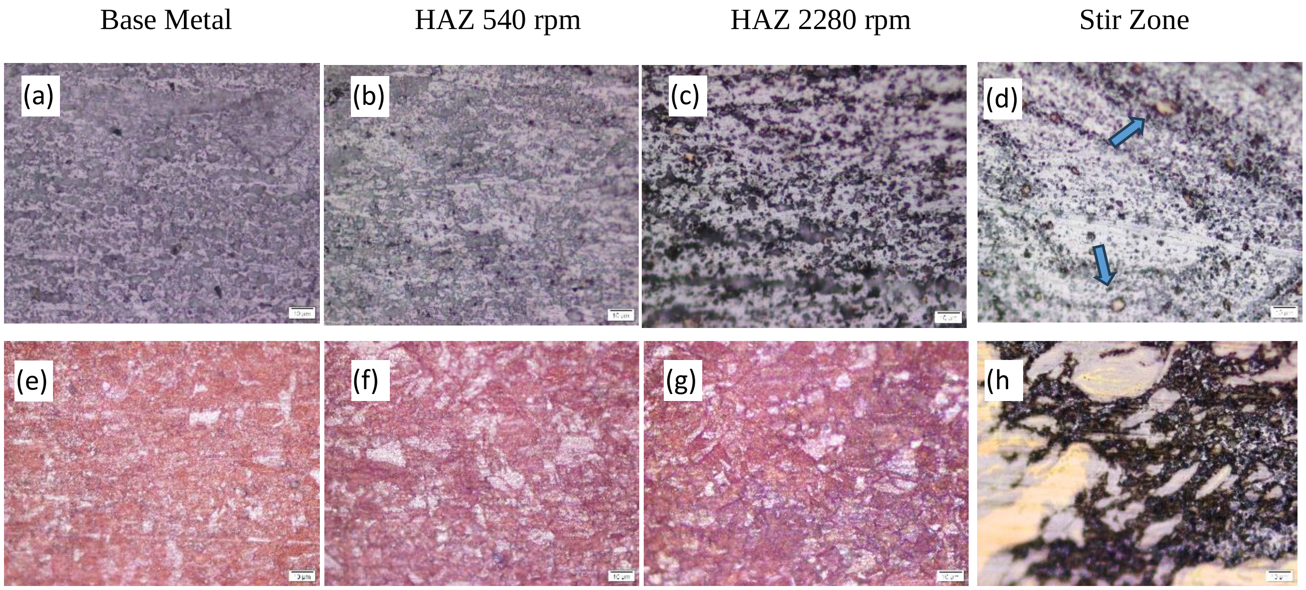


Figure 3. The micrograph of some regions of the dissimilar aluminum-copper friction stir welded joint at rotational speed of 540 rpm, and 2280 rpm, (a) base metal aluminum, HAZ of aluminum at (b)540 rpm (c) 2280 rpm, (d) stir zone at 540 rpm (e) base metal of cooper. HAZ of cooper at (f) 540 rpm, (g) 2280 rpm cooper, (h) stir zone at 2280 rpm.

Figure 3.a & e shows the microstructure of aluminum and copper base metals, while Figure 3.b & c shows the HAZ of aluminum with variations in rotational speed of 540 rpm, 2280 rpm. The microstructure in haz experiences larger grain growth due to the heat generated during the welding process. The grain size in the HAZ has a larger grain size compared to the base metal. As the rotational speed variation increases, the observed grain size becomes larger. This is because the heat produced when the rotational speed variation is increased will produce higher heat. This is in line with Rajakumar's (2011) statement that grain enlargement occurs in the HAZ due to heat and the larger the grain size, the lower the hardness value in the HAZ. Figure 3.f & g also shows the results of observations of the copper microstructure in the HAZ area at varying rotational speeds of 540 rpm, and 2280 rpm. The microstructure observed in the HAZ area has an enlarged grain size compared to the base metal, although it is not significant, but there is enlargement. This is due to the heat produced when the FSW welding process is carried out. According to Tan (2013), in the HAZ area, grain enlargement occurs which results in softening compared to the base metal.

Microstructures of the stir zone area of aluminum-copper joint at rotational speeds of 540 rpm and 2280 rpm are presented by Figure 3 d & h. At low speed there are fewer copper particles compared to 2280 rpm. As the rotational speed used increases, the distribution of copper in the steering area also increases. This is because the higher the speed will affect the rotation of the tool and the heat input produced. However, higher rotation can result in the formation of defects such as cavitation and cracks.

The microvickers hardness test was carried out at 5 points in the base metal areas, HAZ and steering zone, the load used was 300 grams and the duration of the step was 10 seconds. The hardness values for variations in rotational speed are shown in table 4.2. The resulting graph is shown in Figure 4.

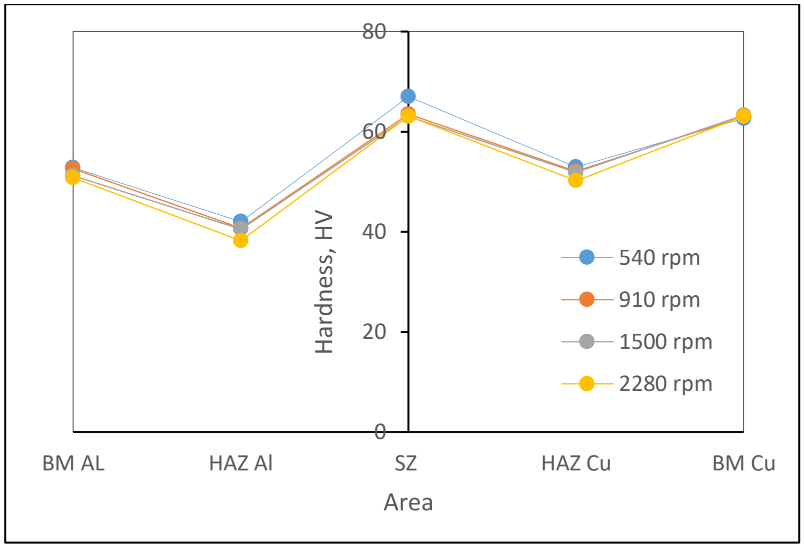


Figure 4. Microhardness of dissimilar aluminum-copper friction stir welded joint at the various rotational speed

The lowest hardness values were obtained in the HAZ area for aluminum and copper materials, namely 38.2 VHN, and 50.2 VHN, at a speed variation of 2280 rpm. This is because the temperature produced when the rotational speed is high, namely 2280 rpm, produces high heat and grain enlargement occurs in the HAZ area which leads to formation of new strain free grain resulting hardness decreases. Thus, the hardness value of the areas are lower than that the coressponding base materials. The peak hardness value was obtained at 67 VHN at the lowest rotational speed, namely 540 rpm in the stir zone area. The highest hardness value is definitely obtained in the stir zone area due to the mixing process between aluminum and copper and the diffusion of copper particles towards aluminum resulting in the highest hardness value compared to other areas (Bisadi *et al*., 2013). In addition, Rajakumar and Balasubramania (2011) noted that the highest hardness value was obtained in the stir zone area regardless of the rotation speed and welding speed used.

Figure 5.a shows the graphical results of stress and strain in tensile test specimens with variations in rotational speed of 540 rpm, 910 rpm, 1500 rpm, 2280 rpm. Of all the specimens that have been tensile tested, no necking process occurred when broken as seen from the graph. So that there is no plastic increase in length or plastic deformation. This shows that the FSW joint is broken brittlely and there is no increase in length. The average calculated values for the ultimate tensile strength and strain are shown in Figures 5.b.

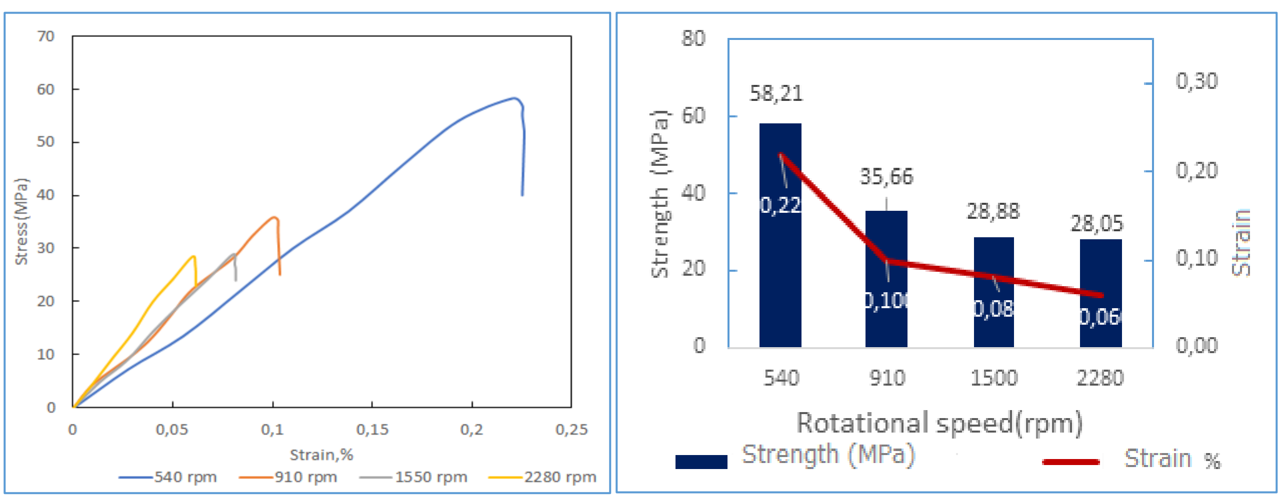


Figure 5. (a) Stress-strain diagram of the tensile test of the dissimilar welded joint at various rotaional speed, (b) Strength and strain of the dissimilar welded joints

Figure 5.b shows the tensile test results in the form of maximum stress and strain for each variation of FSW welding rotational speed. Seen from Figure 5.b there is a decrease in the maximum stress value as the rotational speed increases. The highest maximum stress value was obtained at a rotational speed variation of 540 rpm with a maximum stress value of 58.21 MPa, while the lowest maximum stress value was obtained at a rotational speed of 2280 rpm with a value of 28.50 MPa. The tensile strength value decreases as the rotational speed increases because the resulting heat input increases, resulting in cracks and cavity defects. Research conducted by Guan, (2020) gave almost the same results, namely a decrease in tensile strength as the rotational speed increases. The more defects produced, the more the cross-sectional area of the joint will decrease, and the tensile test value will decrease. In the case of the speed variation of 2280 rpm, the tensile strength value has a very large difference due to the large cavity in the steering zone area which results in a decrease in the tensile strength value. Ajri, (2020) reported that cavity defects are formed at high rotational speeds. The decrease in tensile strength along with increasing rotational speed variations due to higher heat input causes defects in the form of cracks and large cavity defects at variations of 2280 rpm. The defects formed cause the strength of the aluminum and copper welded joint to decrease. A produced Cu hook during the welding process allowed the base materials to joint, and this led to the joint's reported strength. For the welds generated by FSW, the fracture to elongation is as low as 0.06-0.22%. Numerous hard, brittle IMCs and void defects may the main causes of low elongation.

Macrographs of fractures after tensile testing of FSW welding specimens at rotational speed of 550 rpm and 2280 rpm are shown in Figure 6. Of all the rotational speed variations, the results show brittle fracture, the fracture occurs in the stir zone area. Brittle fracture can be indicated by the absence of plastic deformation in the tensile test specimen results and granuular-shaped fault surface (Derniawan *et al*., 2021). The occurrence of brittle fracture can be caused by the result of dissimilar welding joints having a thick growth of intermetallic compounds (Fuse *et al*. 2022). Whilst Figure 6.a depicts that fracture of the welded joint occurs across copper and aluminum, Figure 6.b shows that fracture predominanly occure along the inferface of aluminum and cooper. It may be associated with the IMCs existance. This layer arises due to high temperatures during the welding process of dissimilar or dissimilar materials (Chen *et al*., 2006).

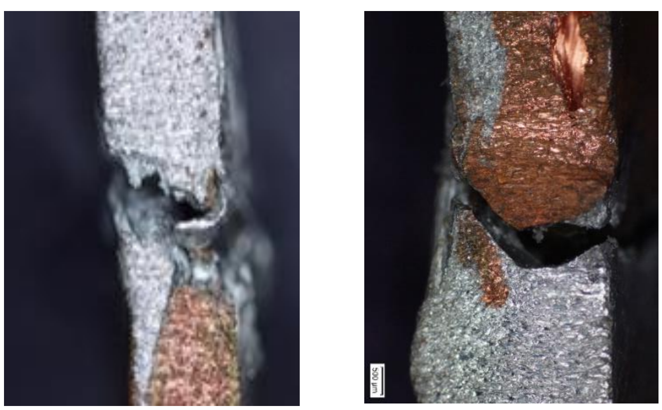


Figure 6. Fracture features of tensile specimens' friction stir welded at (a) 550 rpm, (b) 2280 rpm

CONCLUSSION

Based on the findings derived from the conducted experiments pertaining to the friction stir welding (FSW) of aluminum-copper, wherein several rotational welding speeds were employed (namely, 540 RPM, 910 RPM, 1500 RPM, and 2210 RPM), it can be concluded that the increase in rotatioal speed is accompanied by an increase in the size of the grain created, which can be attributed to the elevated heat generated during the increase in rotational friction stir welding speed. At the lower rotational welding speed smaller cooper particles disperse uniformly in aluminum matrix resulting higher hardness value in stir zone. The rotational welding speed of 550 rpm exhibits the maximum hardness value in the stir zone, measuring 67 VHN. The rotational welding speed of 2280 rpm results in the formation of welding joints that exhibit various defects, including cracks and IMCs. It is possible for defects to arise in the form of fractures at the interface. These cracks are attributed to the formation of IMCs at elevated temperatures. Joints that were devoid of defects were achieved when the welding process was conducted at a speed of 550 rpm. It was observed that an increase in rotational welding speed led to a corresponding lower in joint strength, with a maximum value of 43.66 MPa achieved at a welding speed of 550 rpm.

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