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INVESTIGATIONS OF MICROSTRUCTURE AND MECHANICAL PROPERTIES OF LAP JOINTED DISSIMILAR METALS BY FRICTION STIR SPOT WELDING PROCESS

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ABSTRACT

The joining of different materials is required for industrial application to utilize the hydride structures with attractive advantages such as superior strength to weight ratio, low cost, high tensile strength and less weight of the component. Specifically, Al-Cu composite material is widely used in foil conductors of a transformer, electrical connectors, foil windings in capacitors and tubes in heat exchangers. However, joining or spot welding the Al parts to Cu parts are significant challenge owing to variation in mechanical properties and chemical compositions of joining materials. In this present research work, the friction stir spot welded process (FSSWP) is carried out to join the Al and Cu materials. Further, microstructure and mechanical properties of friction stir spot welded specimens (FSSW) are studied at different tool rotational speeds likely from 1000rpm to 1500rpm. The microstructural study is carried out using scanning electron microscope images at the interface and overall welded region. The tensile strength of both single and double spot-welded specimens is analyzed using a universal tensile test machine. The output of this study states that the optimal tool rotational speed is 1500rpm for both single and double spot-welded specimens. Moreover, the double spot-welded specimen exhibits more tensile with a crack-free spot-welded surface than that of the single spot-welded specimen. The tensile strength double spot-welded specimen has a 6.8% higher strength than that of a single spot-welded specimen. Based on the present study, it is concluded that the double spot-welded specimen can be used for different industrial applications to replace Cu material with this Al-Cu material that gives added advantages to those components.

Keywords: *Aluminum, Copper, Friction stir spot weld, Tensile strength, Dissimilar materials.*

1. Introduction

Dissimilar metal joints such as aluminum (Al) – copper (Cu) joints are commonly used to replace the Cu material with the Al material specifically in foil conductors of a transformer, electrical connectors, foil windings in capacitors and tubes in heat exchangers due to significant advantages of Al over Cu, notably has similar electrical property, lower cost and less mass [1]. In such circumstances, there is a need to join the substitute Al part to Cu parts. Generally, spot welding defects such as solidification cracking, porosity, excessive heating and distortion are reduced in the Friction stir spot welding process (FSSWP) than that of the conventional welding processes of arc welding, high energy density beam welding and gas welding. However, Joining and/ or spot welding the Al parts to Cu parts are significant challenges owing to variation in mechanical properties and chemical compositions of joining materials [2]. In addition to it, the joining of Al and Cu is very difficult due to the formation of intermetallic compounds which had brittle in nature. However, the investigation of the microstructure and mechanical properties of FSSPW specimens is limitedly available in the open literature. In this present research work, microstructure and mechanical properties are studied at different tool rotational speeds likely from 1000rpm to 1500rpm. This study gives the optimal tool rotational speed at which the maximum tensile strength with a crack-free spot-welded surface is achieved.

2. Literature Survey

Wei Zhang et al. [3] evaluated the microstructure of FSSWP of Al to Cu, in which tooth shape configuration was made to join the dissimilar materials. In this configuration, the parent material content in the welded region was tailored to enhance the mixing of the material with an adequate flow rate of material. The strength of the regular butt joint arrangement was compared with that of the new design configuration. The trial-and-error method was used to identify the optimal process parameters of 1500

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rotational speed and 30mm/min welding speed with 0.2mm depth of penetration of the plunger tool. Scanning electron microscopy images were used to analyze the microstructure of the interface region and joint region. The presence of elements and the formation of phases were analyzed by using an energy dispersive spectrum and X-ray diffraction, respectively. The result revealed that the tooth-shaped joint configuration produced the defect-free spot-welded joint. Moreover, the Al matrix was formed with dense particles at the stir zone which led to the creation of the composite structure. In addition to it, the development of the diffusion layer at the interface region was confirmed by using EDS analysis at both the joint configurations. A combination of Cu and Al elements such as Cu_2Al and Cu_9Al_4 were formed at the interface region due to the high chemical affinity between Cu and Al elements. The tensile test was performed to evaluate the bonding Cu2Al and Cu9Al4 strength of the joints and found that a 9.6kN load was withstood by the new design configuration. These results were compared to the butt joint which has a 7.9kN force which was less than a 2kN load. Moreover, a fracture was initiated in the ductility form and separation of material occurred in the brittle form.

Liu et al. [4] studied butt welding based on the friction stir welding process in which a new type of barrier was configured. In the Cu-Al joint, the bonding strength between the Al-Cu material was enhanced due to the adaption of Al as a barrier material. Moreover, the pin was located in such a way that more Al material mixed in the interface region than the Cu material. An increase in the Al content in the welded region improved the quality of the interface region. The interface region namely chaotic and smooth was found in this barrier method of the FSW process. The results revealed that the offset of the pin for accommodating more Al material than Cu material was limited up the particulate limits. Similarly, the tool rotational speed of the tool reduced the formation of voids up to a certain value. Further increases in the rotational speed of the tool increase the presence of voids and reduced the quality of the welded region. The optimal offset value of the pin produced the higher bonding region of the Al-Cu material.

3. Test procedure

Material:

Al and Cu material, tools, anvil and power supply units are used during the experimental work. Commercially available Al and Cu materials are selected as a parent material to study the microstructure and mechanical properties of the FSSWP process. The chemical composition of Al and Cu sheets are shown in Table 1 and Table 2, respectively. In addition to it, the properties of the Al and Cu sheet are shown in Table 3 and Table 4, respectively.

Tool:

Tool design plays an important role in the FSSWP as it affects the formation of microstructure and mechanical strength of the friction stir spot welded specimen. The design of the tool depends on the tool material, geometrical characteristics and spot-welding process parameters. The tool used during this operation is specifically made with H13 material. A schematic representation of the tool is shown in Figure 1. The tool geometry mainly consists of the Tool head, shoulder and pin diameters were 25mm, 18 mm and 5.5mm, respectively. The length of the tool head, shoulder and pin is 125mm, 25 mm and 5.5mm, respectively. The tool geometry is designed in such a way that the tool withstands the rotational speed of 1000rpm to 1500rpm. Process parameters are the key factors for the generation of frictional heat, the flow of material to make bonding between Al and Cu, induction of torque, force induced along the axial direction, enhance the weld integrity and reduction of tool degradation. Rotational speed, dwell time, plunge depth and plunge rate are taken as the process parameters, out of which, the rotational speed is varied and maintained while the other parameters remain constant. The heat generation influences the material flow during the joining process as the reduction in heat generation led to reducing the flow of the material. It results in the root cause of defect formation such as pinholes, voids, inadequate joining region, lack of material and reduction in the bonding strength. Moreover, excessive heating of the joining region due to frictional heat leads to an increase in the heat-affected zone and formation of coarse grain structure, reduction of hardness and tensile strength. Hence, carrying out the spot-welding process at different rotational speeds and analysis of microstructure are needed to better understand the properties of the joining region.

Table 1 Chemical composition of Al

Elements	Zn	Ti	Fe	Cu	Mn	Si	Mg	Al
Wt (%)	0.25	0.15	0.70	0.15	0.33	0.53	0.69	Bal.

Table 2 Chemical composition of Cu

Elements	Zn	Ti	Cu
Wt (%)	9.15	0.01	Bal.

Table 3 Properties of Al

Properties of Al		
1	Tensile strength (MPa)	105 – 120
2	Hardness Brinell (HB)	33
3	Melting point (ºC)	645 – 655
4	Electrical resistivity(ohm-cm)	0.00000299
5	Elongation at 50 mm (%)	5 min
6	Thermal conductivity (W/m.K)	223

Table 4 Properties of Cu

Properties of Cu		
1	Tensile strength (MPa)	225-380
2	Hardness Brinell (HV)	125-150
3	Melting point (ºC)	1070-1080
4	Electrical conductivity (%)	100 - 101
5	Elongation (%)	55
6	Thermal conductivity (W/m.K)	390

Selection of Process Parameters for FSSWP

In the study, dwell time, axial load, overlapping length, rotating speed, single spot and double spot are considered as important process parameters.

Dwell Time:

The rotating tool is maintained at the same position for the period of 12 s which was named as dwell time period. This process is performed after the plugging of the tool into workpieces. More quantity of frictional heat is generated as the tool was rotating at the same position. As a result, the materials in the interface region become to plasticize zone that leads to the flow of the material in the required direction.

Axial Load:

The constant load of 7.5kN is applied along the tool axis direction to penetrate it into the workpiece. The axial load is applied to the tool, in such a way that the tool is retained its stability as well as the movement towards the depth direction.

Overlapping Length:

The Al and Cu materials are overlapped for a distance of 30mm in the case of friction stir single spot-welding process (FSSSWP) whereas 50mm for friction stir double spot-welding process (FSDSWP). Throughout this study, these distances are denoted as overlapping lengths. These distances are incorporated in the FSSWP to ensure the life of the joint and the elimination of failure due to edge tearing and low bending strength.

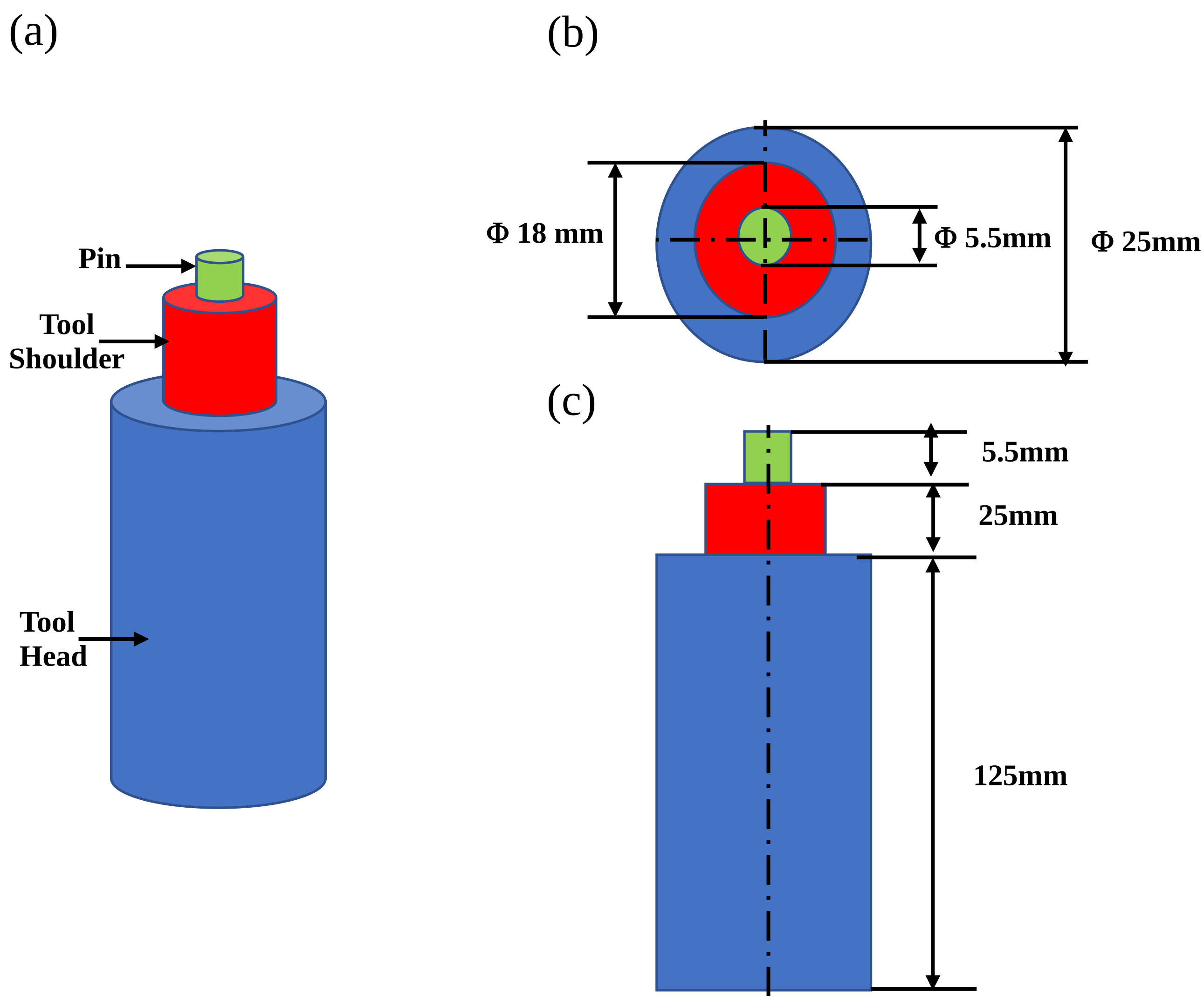


Figure 1 (a) Schematic representation of Overall view of Tool, (b) Top view of Tool, (c) Front view of Tool.

Rotational Speed:

The spindle rotation is varied from 1000rpm to 1500rpm at the interval of 250rpm to analyze the influence of tool rotational speeds on the mechanical properties of the joints. The above mention tool rotational speeds are used to study both processes such as FSSSWP and FSDSWP.

Single spot:
In this study, microstructure and tensile strength are analyzed based on the formation of only one spot welding process. Hear, the dwell time, axial load, overlapping length, and rotating speed are taken as 10s, 7.5kN, 30mm and 1000rpm to 1500rpm, respectively.

Double spot:
In this study, microstructure and tensile strength are analyzed based on the formation of two spot welds with a pitch value of 15mm distance. Here, the dwell time, axial load, overlapping length, and rotating speed are taken as 10s, 7.5kN, 50mm and 1000rpm to 1500rpm, respectively.

FSSWP working principal:
In this experimental work, Spot welding based on the principle of friction stir welding process is done as the traverse movement of the tool was restricted. The overall arrangement of the FSSWP is shown in Figure 2. Two sheets namely Al and Cu are overlapped and the rotating tool is plugged into the overlapped region of the

sheet to induce the spot weld between the Al and Cu materials. Here, an anvil is used for holding the two sheets to ensure the alignment of two sheets and maintain the shoulder to contact with the upper sheet. Different stages of the friction stir spot welding process are shown in Figure 3. Four stages are followed to complete the FSSWP operation such as Initiating, plugging, dwelling and retracting stages. In initiating stage, the tool approaches the material to make the joint between the Al and Cu parent material (stage 3a). Then, the tool plug into the Cu material and further moves towards the Al material in stage 3b.

The dwell time of the 12s is used to make the material for plastic deformation in stage 3c. As a result, the material becomes softened as well as deformed with a higher strain rate at the plunge stage as well as dwell stage during the spot-welding operation. It leads to the flow of the material in the direction of the tool rotation and mixes well with the nearer regions. Moreover, the materials flow in the direction of axial as well as the circumferential direction that leads to avoiding the formation oxide layer in between the interface region of the two materials. The rotating tool is withdrawn at the end of the welding process after reaching the dwell time period in stage 3d. The factors such as high forging pressure, heating, plasticize material flow, formation of fine-grain structure and development of metallurgical bonging are induced the defect-free joint at the interface region. Moreover, the interaction time of the tool and material affects the heat transfer resulting in the reduction of heating and cooling rate. In addition to it, the plastic deformation of the material is affected by the thermo-mechanical interaction of the material. Recrystallization is occurred at the interface region due to the involvement of heat transfer as well as plastic deformation. Compared to the friction stir welding process, the FSSWP is completed within less period of time which increased the complexity of the process.

$$\text{Heat input for the FSSWP} = \int_{t_1}^{t_2} \frac{2\,\pi\ X\ Rotational\ speed\ X\ Torque}{60}\,dt \quad (1)$$

The heat produced during the FSSWP operation is calculated by using equation number 1 for the duration of $(t_2 - t_1)$. The parameters t_1 and t_2 are the tool plugging and withdrawal time. Moreover, he temperature of the anvil increased up to a certain value due to the interaction of the tool with the parent materials.

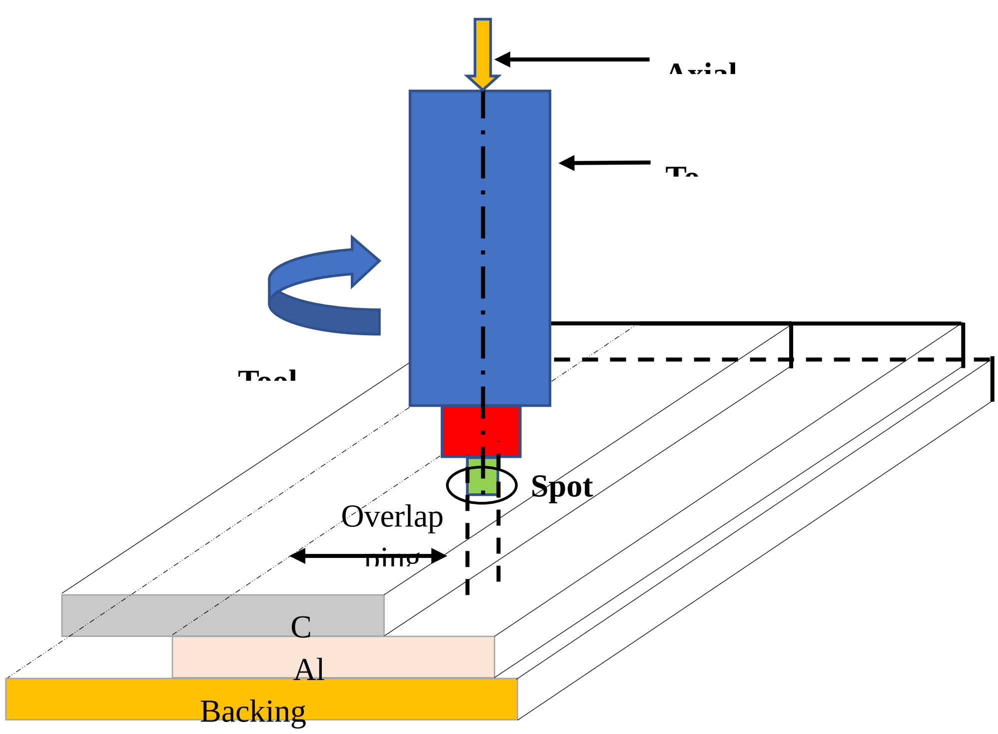


Figure 2 Arrangement of friction stir spot welding process

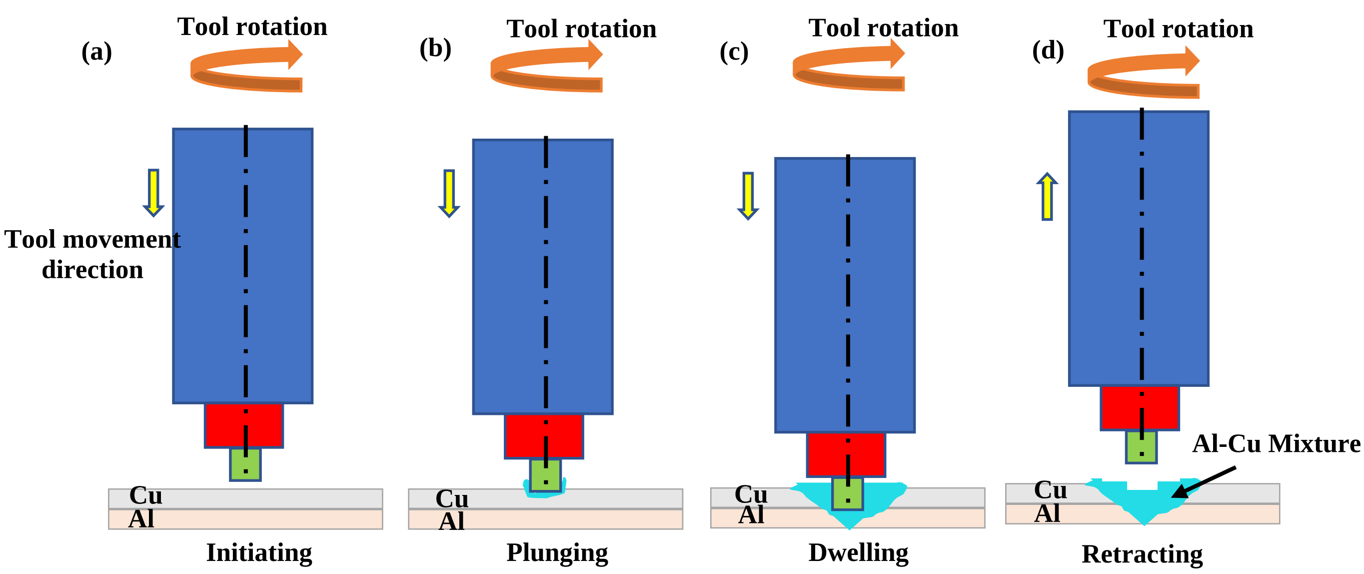
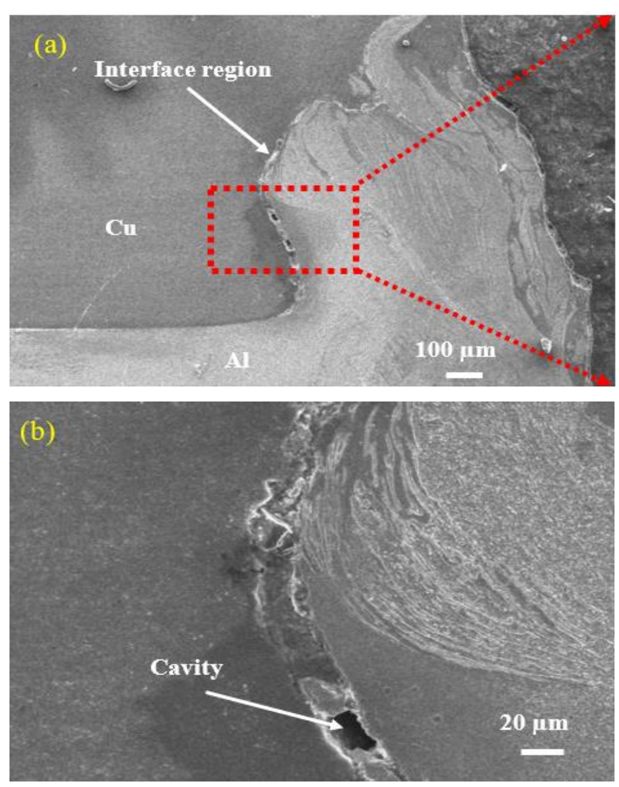


Figure 3 Different stages of friction stir spot welding process

3.Results and discussion

3.1 Microstructure examination

Three different rotational speeds of tool namely 1000, 1250 and 1500rpm are used to spot weld the Al-Cu dissimilar materials at two different configurations such as single and double spot location. The resultant interface regions are analyzed by using SEM images. The interface region of a single and double spot at 1000rpm rotational speed is shown in Figure 4a-c, respectively. The presence of cavities in Figure 4a reveals that the bonding between the Al-Cu interface regions of the FSSSW specimen is broken that leading to form discontinuity at the interface of the single spot-welding region. The defect size of 20µm width and 50µm length is observed in Figure 4b. However, friction stir double spot-welded joint of Al-Cu materials are well formed at the interface regions due to a reduction in the formation of the crack, cavity and induced high metallurgical bonding between the two regions (Figure 4c) [5]. The tensile strength of single and double spots at 1000rpm rotational speed is tested by a universal tensile test machine and corresponding tensile strength values are found as 26.3 and 40.7 MPa, respectively (Figure 7). It revealed that the FSDSW joint possess significantly higher tensile strength than that of the FSSSW joint at 1000rpm rotational speed. Moreover, the tensile force is sheared by two joints in the FSDSW joint which is equal to half of a load of the FSSSW joint. As a result, the strength of the FSDSW joint increased more than that of the FSSSW joint.



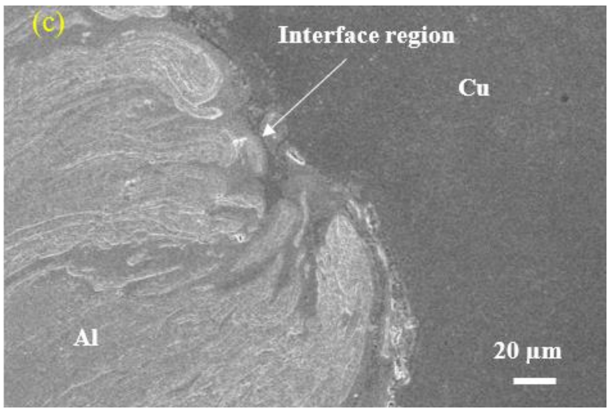


Figure 4 SEM images of Microstructure of Al-Cu friction stir spot welded specimen at 1000rpm (a) Single sport, (b) Magnified view of single spot specimen, (c) Double spot

Further, the influence of the rotational speed is studied at 1250rpm. The rotational speed for single and double spot joint are increased by 250rpm and analyze is take place to evaluate the tensile strength of the joints. The SEM images at the interface region of FSSSW and FSDSW joints at stir friction welding parameters of 1250rpm rotational speed are shown in Figure 5 a-b, respectively. The interface images of FSSSW (Figure 5a) at 1250rpm rotational speed are found as some crack-free surfaces with some broken bonding regions due to improper bonding occurring between the Al-Cu material. Moreover, metallurgical bonding is formed well in some regions due to an increase in the diffusion rate of material during the welding process than that of the FSSSW at 1000rpm rotational speed (Figure 4a). Still, some of the regions possess weakly bonded regions owing to the uneven distribution of material. A superior bonded region is observed in the FSDSW (Figure 5b) at 1250rpm rotational speed when compared to FSDSW (Figure 4c) at 1000rpm rotational speed [6]. In addition to it, the crack-free metallurgical boning is observed in the FSDSW (Figure 5b) at 1250rpm rotational speed when compared to FSSSW (Figure 5a) at 1250rpm rotational speed. The tensile test report states that the FSDSW and FSSSW joints at 1250rpm welding parameters possess 46.1 MPa and 65.4 MPa, respectively (Figure 7). It reveals that the FSDSW specimen has high metallurgical bonding strength due to the least number of crack and weld defects present in the interface regions. Hence, it has been confirmed that tensile strength and bonding efficiency increase with increasing the number of spot welds.

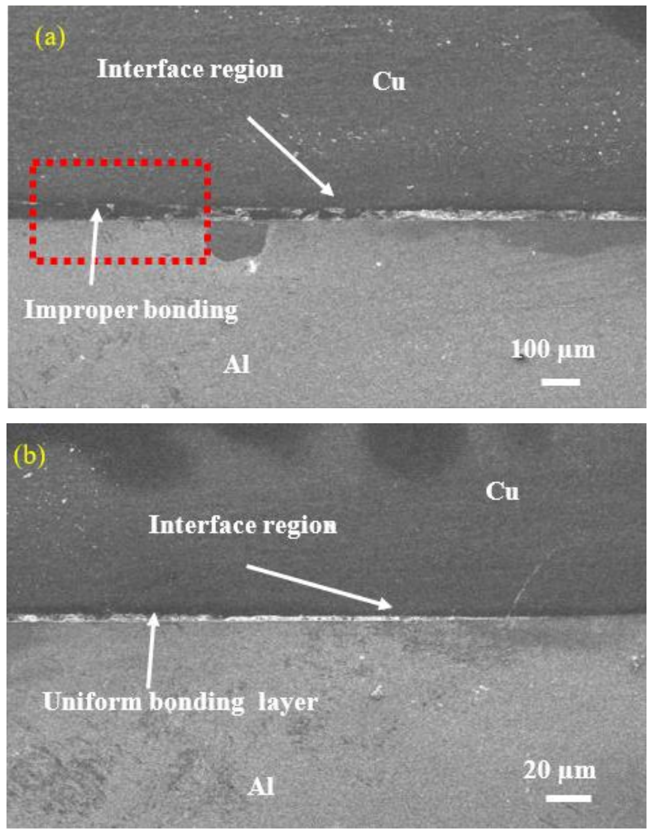


Figure 5 SEM images of Microstructure of Al-Cu friction stir spot welded specimen at 1250rpm (a) Single spot (b) Double spot specimen

Finally, the microstructure of the interface region of the FSSSW and FSDSW joint at the welding parameter of 1500rpm rotational speed is analyzed by using SEM images as shown in Figure 6a-b. Compared to the FSSSW joint (Figure 6a), the FSDSW joint (Figure 6b) had crack-free surfaces. Moreover, better diffusions have occurred at the interface region during the joining of two parent materials leading to an increase in the mechanical interlocking and producing the well-bonded interface structure (Figure 6c). In addition to it, an increase in rotational speed from 1250 rpm to 1500rpm leads to rapid mixing of the parent material that increases the homogeneous distribution of the material in the interface region [7]. The tensile test report states that the FSDSW and FSSSW joints at 1500rpm welding parameters possessed 82.9 MPa and 88.6MPa, respectively (Figure 7) [8]. The universal tensile test results reveal that the FSDSW joint at 1500rpm rotational parameter possessed the highest tensile strength among the single and double spot-welded specimens at different rotational speeds.

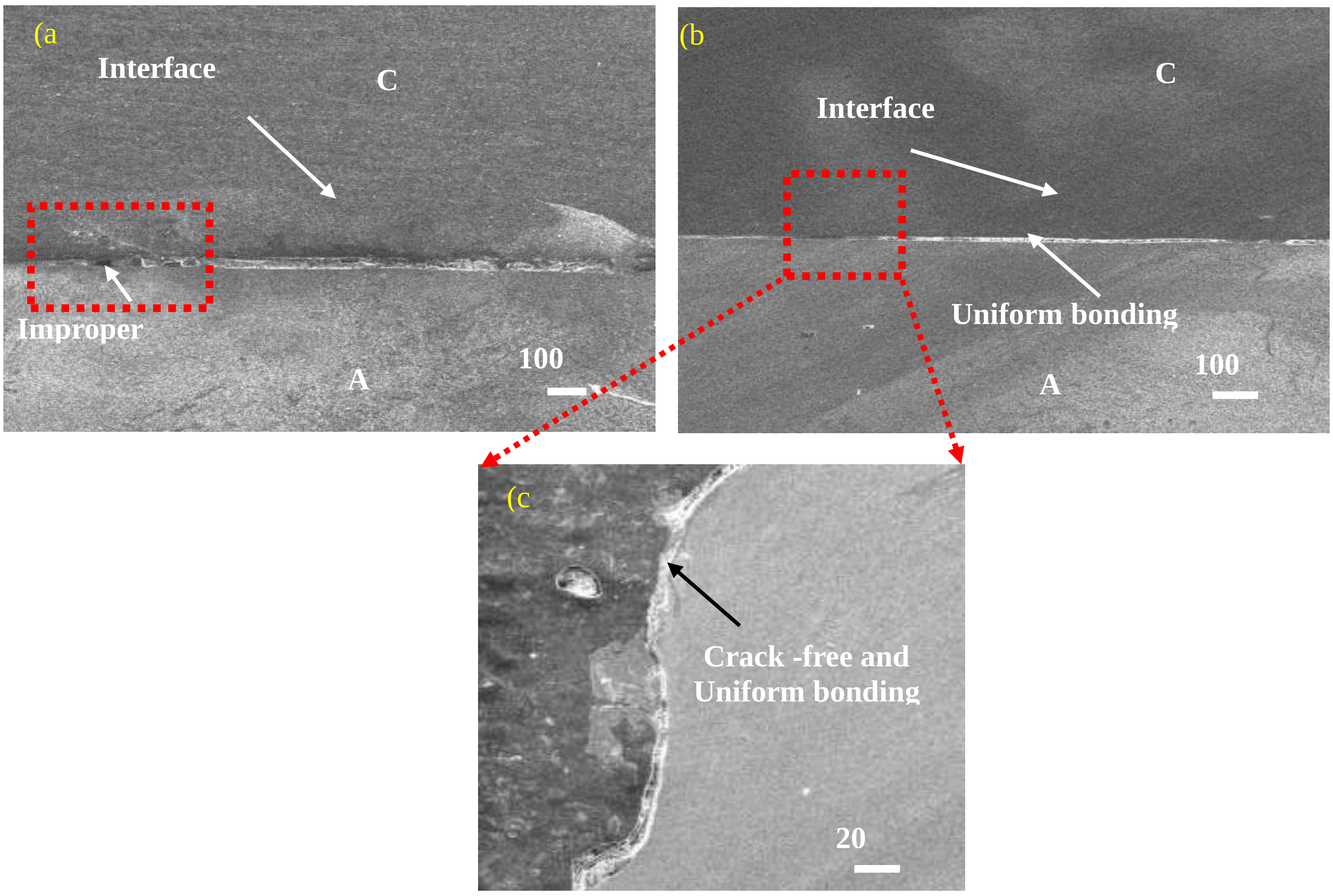


Figure 6 SEM images of Microstructure of Al-Cu friction stir spot welded specimen at 1500rpm (a) Single spot (b) Double spot (c) Magnified view of double spot specimen

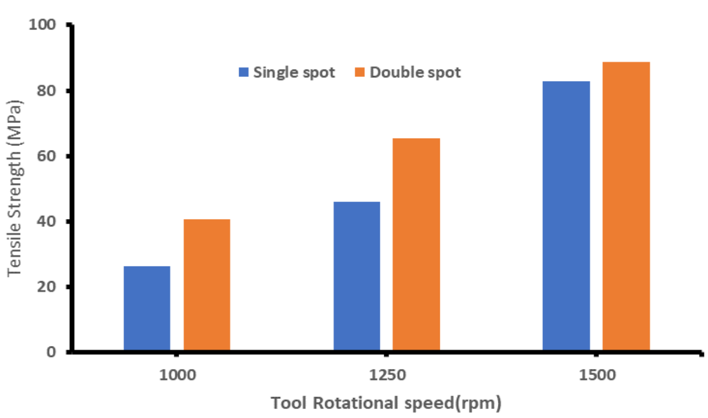


Figure 7 Tensile strength of Friction stir single and double spot-welded specimens

4. Conclusion

In this research work, friction stir spot welding is performed on Al-Cu dissimilar material at two different configurations such as single spot and double spot. The microstructure of the resultant joint region is analyzed using SEM images. Further, the tensile strength of the joint is measured using a universal tensile testing machine and the following conclusions are derived.

i. The defect-free Al-Cu dissimilar material can be joined by using the friction stir spot welding process.

ii. Friction stir double spot welded specimen has higher durability than that of the single spot-welding region as it has negligible crack and voids.

iii. Better diffusions have occurred at the interface region during the joining of two parent materials at a higher tool rotational speed of 1500rpm which leads to an increase in the mechanical interlocking and produces a well-bonded interface structure.

iv. The tensile force is sheared by two joints in the FSDSW joint which is equal to half of a load of the FSSSW joint. As a result, the strength of the FSDSW joint increased more than that of the FSSSW joint.

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