Welding and joining of brass CuZn30-aluminum AA1100 were obtained using micro two-stage refilled friction stir spot welding (mTS-RFSSW), which was carried out to eliminate the holes formed by the micro friction stir spot welding (mFSSW) process. The mTS-RFSSW process begins with the mFSSW welding process using tools with a pin inner diameter of 2.69 mm, pin outer diameter 1.811 mm and shoulder diameter of 4.954 mm, followed by a second stage process called mTS-RFSSW, which is a hole closing process using a tool with a pinless tool with shoulder diameter 4.954 mm. This study aimed to determine the effect of the second stage of dwell time on the mechanical properties produced in the mTS-RFSSW welding technique using brass CuZn30 and aluminum AA1100 with a thickness of 0.42 mm. In this study, the variable parameter is the second stage dwell time which varies from 3 s, 4 s, 5 s, and 6 s, respectively. An optical microscope that aims to observe the macrostructure shows that an upward hook is formed in each joining process. Based on the scanning electron micrograph, the resulting formation of different intermetallic compounds (IMC) with varying thicknesses occurs in every variation of dwell time. The high dwell time indicates discontinued IMC, which affects the tensile force. The IMC formed at the interface of brass CuZn30 and aluminum AA1100 is dominated by more than 30 % Cu. The highest hardness value is found in the stir zone because the formation of intermetallic compounds influences refined grains. The highest maximum shear force and cross tensile force was obtained 371.35 N and 54.88 N, respectively, in the dwell time of 3 s. The result of fracture properties after the lap shear test shows the presence of small dimples with microcracks that indicate brittle failure

Keywords: Friction Stir Spot Welding, mTS-RFSSW, Brass CuZn30, AA1100, dwell time

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IDENTIFICATION OF THE INFLUENCE OF MICRO TWO-STAGE REFILLED FRICTION STIR SPOT WELDING WITH VARIATION DWELL TIME ON DISSIMILAR BRASS CuZn30-ALUMINUM AA1100

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1. Introduction

Welding and joining of dissimilar materials using conventional welding may cause solidification defects, so the process of joining dissimilar materials is still in development. Another problem that arises in joining dissimilar materials is the formation of intermetallic compounds (IMC), which affect the quality of the welding joints [1]. An alternative joining method to overcome the formation of intermetallic compounds is friction welding [2]. In addition, friction stir welding (FSW) and friction stir spot welding (FSSW) is also alternative method to reduce solidification cracking which is common in fusion welding. The FSW method by varying the control pressure affects the tensile strength of aluminum AA6061 [3]. The FSW method is applied to similar and dissimilar materials, such as brass and aluminum, with good thermal conductivity and corrosion resistance. However, the process of joining dissimilar materials has an issue. It is quite difficult to do with conventional joining methods because it produces brittle intermetallic compounds at high temperatures due to differences in physical properties and high affinity between the two materials. To overcome these issue, one of the joining methods can be used to reduce these issues, namely FSSW, which is a solid state joining process of two overlapping materials using a non-consumable rotary tool at a certain speed so that the friction between the tools and the workpiece produces heat that does not cause melting of the workpiece, which causes the workpiece to soften and plastically deform. However, this FSSW process can produce defects, namely the keyhole, while the two-stage refilled friction stir spot welding (TS-RFSSW) joining process is a hole formed due to the pins on the tools being closed by pressing the former hole material with a flat-shaped tool (pinless tool) where the filling holes affect the strength of the weld [4]. Research on keyholes using refilled friction stir welding on the aluminum alloy to high-strength steel materials has been carried out to increase the strength of the joints [5]. The paper [6] investigates mechanical properties and macro-microstructures of micro two-stage refilled friction stir spot welding (mTS-RFSSW) on aluminum AA1100 using dwell time and tool geometry. Although many studies have been conducted on the process of joining mTS-RFSSW on similar materials, there are several studies on dissimilar materials, such as brass CuZn30 and aluminum AA1100, and research on mTS-RFSSW on brass-aluminum is limited. It is because the mTS-RFSSW joining process produces an intermetallic compound (IMC) layer, which affects the strength of the dissimilar joining of the material. Therefore, research devoted to the development of these fields is necessary and important to develop the use of brass and aluminum materials through the influence of mTS-RFSSW joining process parameters on dissimilar materials to analyze macrostructure, microstructure, intermetallic compound, lap shear force, cross tensile force, and fracture properties.

2. Literature review and problem statement

Brass CuZn30 and Aluminum AA1100 have high-strength properties and are used in electronics manufacturing. Weld joints of dissimilar material form an intermetallic compound at the interface and cracks in the IMC, affecting the joint's strength. Welding and joining of aluminum and brass is unsuitable if conventional welding is carried out because it causes porosity and solidification defects. Therefore, brass and aluminum materials can be applied using friction stir welding (FSW) as an alternative to the non-fusion joining method [7]. There are many papers investigating friction stir welding joints of dissimilar materials. For example, the paper [8] investigates mechanical properties and microstructural evolution friction stir spot welding joint process on aluminum AA1060 and copper variation tool geometry. Placing brass sheets at the upper and aluminum at the bottom also influence tensile force and microstructure [9]. An increase in joining time causes the intermetallic compound to thicken, thereby reducing the joining strength of refilled friction stir spot welding aluminum AA5083/AZ231. Intermetallic compound layers are formed to achieve metallurgical bonds between dissimilar materials. However, within a certain intermetallic thickness cause a decrease in tensile strength. Results in a research paper [10] reveal that the process of joining refilled friction stir spot welding on aluminum/zinc-coated steel material forms a non-uniform and discontinuous intermetallic compound layer. However, this study [10] did not measure the thickness of the intermetallic compound layer. This point is deeply discussed in a research paper [11] that describes the intermetallic compound formed between the joints of refilled friction stir spot welding aluminum/steel uniform, where thick IMC results from a higher rotation speed and different mechanical properties. Paper [12] also analyzed the formation of intermetallic compounds on dissimilar materials of low carbon and aluminum 6061, where the IMC formed in the stir zone is thicker compared to other areas.

Furthermore, the dwell time affects the thickness of the IMC, where the higher the dwell time, the thicker the IMC formation. The other parameters used in FSSW welding joints are tool geometry, which affects the microstructure, mechanical properties of welded joints, and weld profiles [10]. And regarding in research paper [13] explained that using pinless tools on similar and dissimilar material friction stir spot welding resulted in higher lap shear forces than tools with pins. In addition, welding parameters such as tool plunge depth also affect the lap shear force. However, the drawback of FSSW is that the keyhole is formed from tools with pins, which allows the keyhole to become a place for water to be trapped, which may cause corrosion. Therefore need, a method to close the keyhole, namely using the mTS-RFSSW method, is a derivation of the FSSW now considered an alternative method to obtain high joint strength. In addition, the main advantages of mTS-RFSSW are the solid-state process, low distortion, and no melt-related defects, even in non-weldable alloy materials with conventional techniques, and also it does not generate heat to cause melting of the material, minimizes distortion, does not occur melting, which may cause solidification defects, and has a strong mTS-RFSSW joining. High weldability, even on alloy materials that are difficult to weld (non-weldable) by conventional techniques. mTS-RFSSW technology is an alternative to the relatively simple brass-aluminum joining process even in some respects, and it has advantages compared to conventional methods, for example, the conventional welding process and the riveting joining.

There are parameters for the mTS-RFSSW joining process that are used, namely dwell time, plunge depth, tool geometry, and tool rotational speed. Dwell time is the time it takes for the tool to rotate on the surface of the weld before the tool lifts. The effect of dwell time on the weld results can be seen from the heat generated. The longer the dwell time in an FSSW process, the greater the heat generated. This effect is due to the larger time it takes for the tool to generate heat from the welding process. Several studies have been conducted to investigate microstructure and mechanical properties characterization using process parameters for mTS-RFSSW on dissimilar material joint. For example, the paper [14] shows that increasing joining time causes the intermetallic compound to thicken, reducing the joining strength of refilled friction stir spot welding aluminum AA5083/AZ231. Recently, only a few researches have been done regarding the mTS-RFSSW joining on the dissimilar materials of brass CuZn30 and aluminum AA1100. The dissimilar mTS-RFSSW joining process for CuZn30-aluminum AA1100 brass material is still an alternative and inspiring in the manufacturing and automotive industry because it produces a lightweight material and minimizes the formation of intermetallic compounds. In addition, in the wiring and electrical industry, one of which is the battery, the mTS-RFSSW method is a new development. Therefore, joining dissimilar materials that can produce high-strength materials is necessary. Related literature revealed that a very limited number of studies about micro two stage refilled friction stir spot welding dissimilar joint on brass and aluminum. Therefore, all this allows to assert that it is expedient to conduct a study on identify of the effects of variations in the second stage of dwell time (3, 4, 5, and 6 s) of a micro two-stage refilled friction stir spot welding joint of dissimilar materials brass CuZn30 and aluminum AA1100 with thickness 0.42 mm to address its influence the metallography properties (such as cross sections of macrostructure, microstructure, intermetallic compound, and distribution of microhardness by Vickers) and mechanical properties (such as lap shear force, cross tensile force, and fracture properties after lap shear test) is the main objective of this research study.

3. The aim and objectives of the study

The aim of research study is to identify the influence of variations second stage dwell time micro two-stage refilled friction stir spot welding (mTS-RFSSW) joint of the mechanical and metallography properties on overlap brass CuZn30 and aluminum AA1100. This will make it possible to develop the alternative joining technology process dissimilar material using micro two stage refilled stir spot welding method. Thus bonding metallurgical and increase the joining strength on dissimilar materials.

And to achieve this aim, the following objectives were accomplished:

– to observe macrostructure, microstructure, and intermetallic compound microhardness Vickers distribution on dissimilar mTS-RFSSW dissimilar joints brass CuZn30 and aluminum AA1100;

– to analyze lap shear force, cross tensile force, and fracture properties after the lap shear test.

4. Materials and methods

4. 1. Object and hypothesis of the study

The study was performed with 0.42 mm thick sheets of A1100 and brass CuZn30 used in the mTS-RFSSW. The chemical composition of materials A1100 (composition in wt%. >99 %Al, 0.1–0.2 % Cu, 0.02–0.05 % Mg, 0.03–0.05 % Si, 0.15–0.20 % Zn, 0.25–0.4 % Mn, 0.05–0.1 % Fe) and material properties (ultimate tensile strength 115 MPa, yield strength 105 MPa, elongation 15–28 %, microhardness Vickers 40 HV, thermal conductivity 220 $W \cdot m^{-1} \times K^{-1}$, heat capacity 904 $J \cdot kg^{-1} \times K^{-1}$, melting point 643–657 °C). Brass has the chemical composition (composition in wt%. 64–68 % Cu, max 0.1 % Zn, 0.05 % Fe, max 0.05 % Pb) and mechanical properties (ultimate tensile strength 365 MPa, yield strength 140 MPa, elongation 40–52 %, microhardness Vickers 120 HV, thermal conductivity 123 $W \cdot m^{-1} \times K^{-1}$, heat capacity 377 $J \cdot kg^{-1} \times K^{-1}$, melting point 899-904 °C). The micro fiction stir spot welding operation using CNC-3A Milling T.U EMCO with die grinding Maktec 91A is shown in Fig. 1. The tools are made of high-strength steels (HSS) schematically shown in Fig. 2. During the joining process of micro two stage refilled friction stir spot welding dissimilar brass CuZn30 and aluminum AA1100, it is estimated that hook and intermetallic compound layers will occur which will affect the lap shear force and cross tensile force.

Specifications of Maktec tuner drilling machine – die grinder 6 mm Mt 912, electrical power: 480 W, no-load speed: 33,000 rpm, collet: 6 mm. The assumptions applied to this research as a constant variable namely tilt angle 0°, plunge depth of 0.7 mm, dwell time on the first stage is 6 s, spindle speed of 33,000 rpm, and plunge speed of 4 mm/minute. The independent variable in this study is dwell time in the second stage. The dwell time used is 3 s, 4 s, 5 s, and 6 s, respectively. The parameter process of this research is shown in Table 1. The mTS-RFSSW is used during the keyhole refilling process to determine the effect of variation second dwell time on the macrostructure, microstructure, mechanical properties (such as lap shear force, cross tensile force and microhardness by Vickers), and fracture properties.

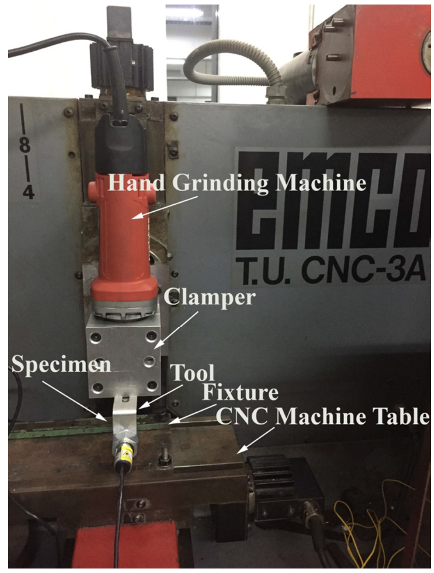
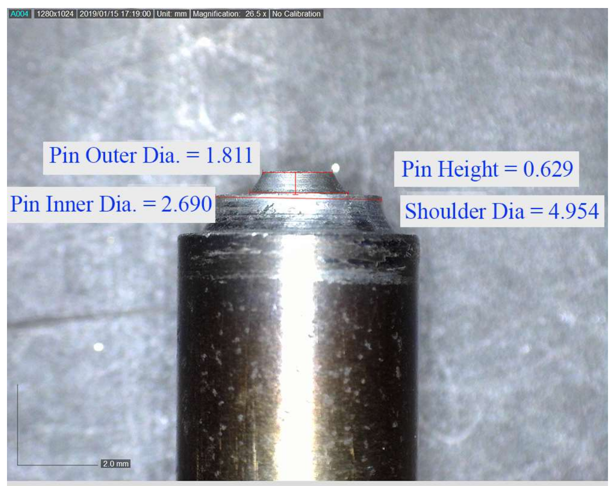


Fig. 1. mTS-RFSSW welding machine



a

b

Fig. 2. Tools of mTS-RFSSW: *a* – first stage (conventional friction stir spot welding) using tool with pin; *b* – second stage (two-stage refilled friction stir spot welding)

Table 1

Parameter process

No.	Tool rotational speed, rpm	Plunge rate, mm/min	Plunge depth, mm	Dwell time, s
1	33,000	4	0.7	3
2	33,000	4	0.7	4
3	33,000	4	0.7	5
4	33,000	4	0.7	6

4. 2. Mechanical properties

The specimen used in the mTS-RFSSW welding process is an AA1100 thin plate with a thickness of 0.42 mm with a CuZn30 plate with a thickness of 0.4 mm were cut using wire cut electrical discharge machining. The lap shear test was cut to 130 mm×25 cm and placed to maintain an overlap area of 25×25 mm shown in Fig. 3, *a*. For the cross tensile test, specimens were cut to size 150×25 mm and placed to maintain an overlap area of 25×25 mm, as shown in Fig. 3, *b*.

For macrostructure tests, specimens were cut to size 30×30 mm according to ASTM C273 standard and ISO 14273. Tensilon A&D RTF2350 with load capacity 50 kN and constant displacement rate of 2 mm/min. All tests were performed in two replications. All specimens were cleaned using alcohol. Tests on specimens using the Tensilon A&D machine are divided into two types. In the lap shear test, the speed is 0.5 mm/minute; in the cross-tension test, the speed is 1 mm/minute. The specimen placement is attempted to evenly distribute the tensile force where the weld point is right in the middle. In the cross-tension test specimen, before testing, the front and back ends of each specimen are bent to facilitate the clamping of the specimen. The total specimens measured were 8 specimens for the cross-tension test and 8 for the lap shear test, with a variation of 4 dwell times for refilling and two replications for each variation. Microhardness distribution was measured at sheet brass CuZn30 and aluminum AA1100 using loads of 100 g for 10 s with the adjacent indention distance of 0.5 mm.

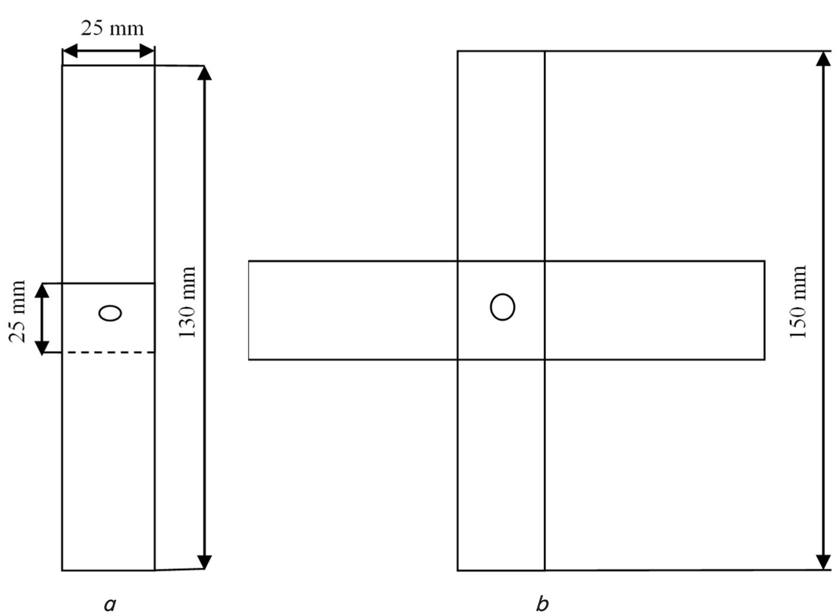


Fig. 3. Schematic diagram and dimension of: *a* — lap shear specimen; *b* — cross tensile specimen

4. 3. Macrostructure and microstructure characterization

All cross-section specimens were ground with 300, 500, 700, 900, 1000, 1200, 1500, and 2000, then polished with 0.05 mm silica suspension and etched with Keller's reagent. For observation of macrostructure and microstructure using an optical measuring microscope, Inverted Metallurgical Microscope Olympus BX41M-LED. Microstructural observations were conducted on a Zeiss-MERLIN Compact Scanning Electron Microscope (SEM) to characterize the phase formed at the interface, Energy Dispersive Spectroscopy (EDS). This test was also carried out to analyze fractography using a 3D optical profiler and Scanning Electron Microscopy (SEM) to study the failure mode of the welded joint.

5. Results of the experiment of macrostructure-microstructure analysis, and mechanical and fracture properties

5. 1. Macrostructure and microstructure analysis

Fig. 4 shows cross-sectional macrostructure and microstructure of mTS-RFSSW brass CuZn30- aluminum AA1100 using variation dwell time 3 s, 4 s, 5 s, and 6 s.

The results of the macrostructure at dwell times of 3 s and 4 s do not appear to form a flash represented in Fig. 4, *a*, *b*. At dwell time 3 s, intermixing and bonding metallurgy occur, as shown in Fig. 4, *b*, because, during the plunging process, the pin and dwell time could stir during the joining process so that an AA1100 sheet was seen entering the CuZn30 sheet. The bottom sheet of material AA1100 flows onto the top sheet of CuZn30 material, resulting in plastic deformation due to friction between the tools and the workpiece, which causes recrystallization so that the microstructure, which is close to heat, has a finer grain structure. At a relatively short dwell time of 3 s, shown in Fig. 4, *a*–*c* with dwell time 3 s, the dissimilar brass CuZn30-aluminum AA1100 exhibited upward hook and no flashes, with the composition of the intermetallic compound formed being Al, Cu, and Zn. In addition, oxygen was detected with a lower percentage than other dwell time variations, as shown in Fig. 5, *a*. At a dwell time of 4 s, as shown in Fig. 4, *d*–*f*, the macro and microstructure are shown in Fig. 4, *d* and do not show flash formation. However, it can be seen that there are microcracks in the intermetallic compound and crack propagation that spreads up to the AA1100 aluminum sheet. The intermixing and bonding metallurgy at the dwell time of 4 s represented in Fig. 4, *e* shows the AA1100 sheet going into the brass sheet. The intermetallic compound layer that formed was relatively evenly distributed, which was dominated by 26.45 % Al-43.27 % Cu-21.32 % Zn, as shown in Fig. 5, *b*. At dwell times of 5 s and 6 s, as shown in Fig. 5, *c*, *d*, the intermetallic compound is 6.67 % Al-48.41 % Cu-22.26 % Zn and contains relatively higher oxygen than at dwell times 3 s and 4 s. The presence of oxygen in the intermetallic compound observed the formation of oxides in the intermetallic area. Fig. 5, *c* also shows that the intermetallic formation at 5 s dwell time is thinner than other dwell times.

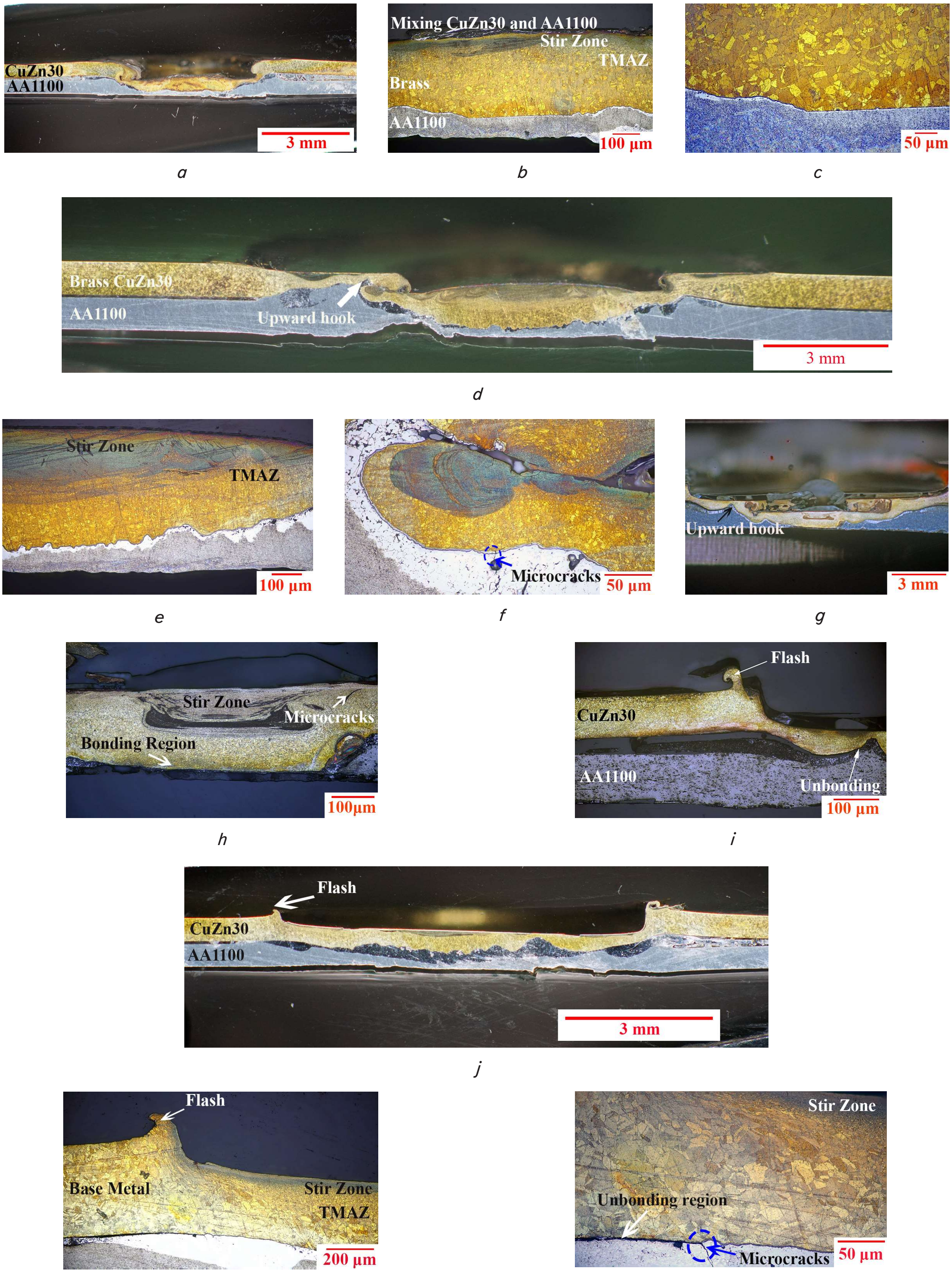


Fig. 4. Cross-sectional macrostructure and microstructure of micro two-stage refilled friction stir spot welding (mTS-RFSSW) brass CuZn30-aluminum AA1100: *a* –macrostructure at dwell time 3 s; *b* – microstructure at dwell time 3 s; *c* – magnified of microstructure at dwell time 3 s; *d* – macrostructure at dwell time 4 s; *e* – microstructure at dwell time 4 s; *f* – magnified of microstructure at dwell time 4 s; *g* – macrostructure at dwell time 5 s; *h* – microstructure at dwell time 5 s; *i* – magnified of microstructure at dwell time 5 s; *j* – macrostructure at dwell time 6 s; *k* – microstructure at dwell time 6 s; *l* – magnified of microstructure at dwell time 6 s

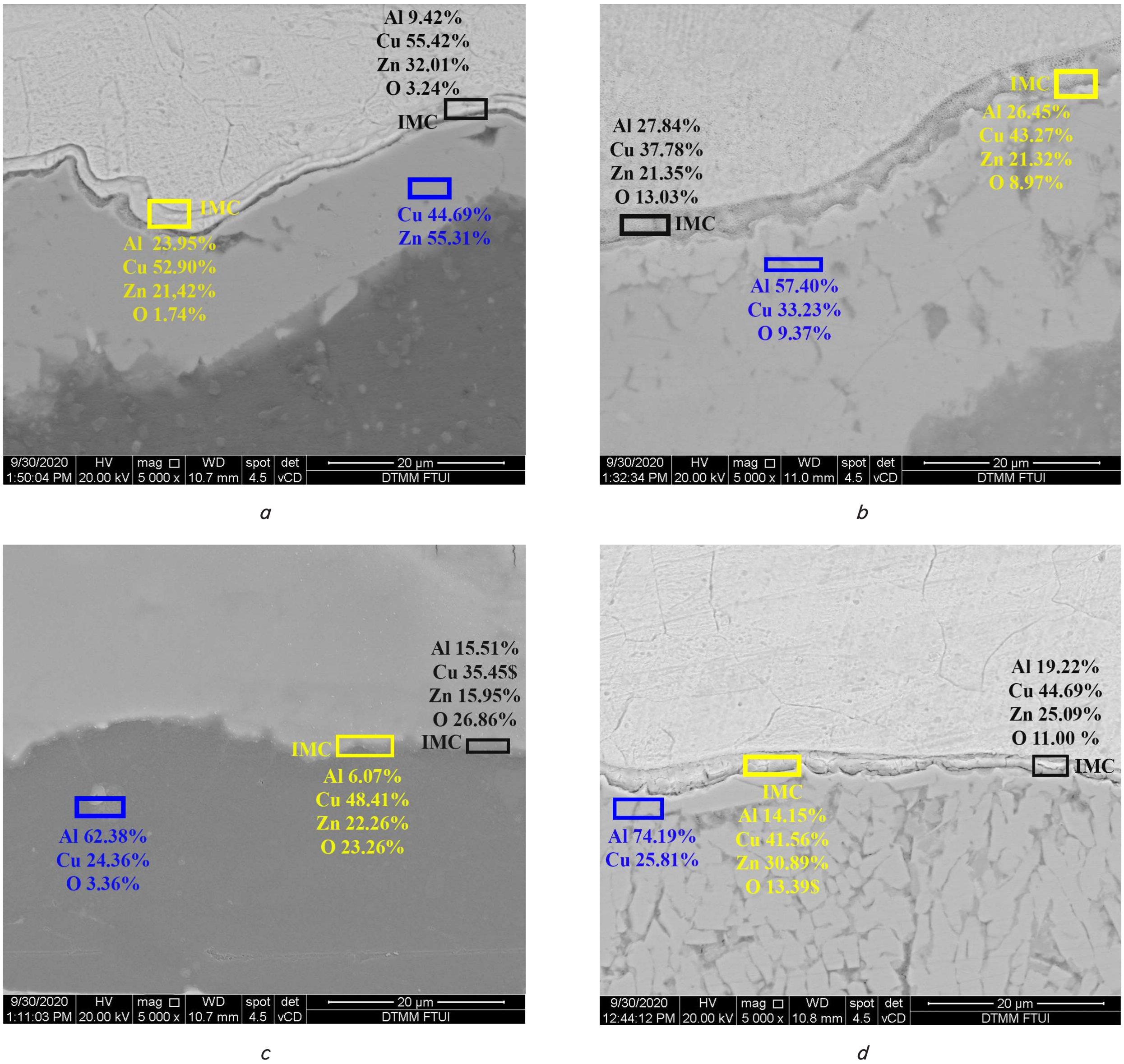


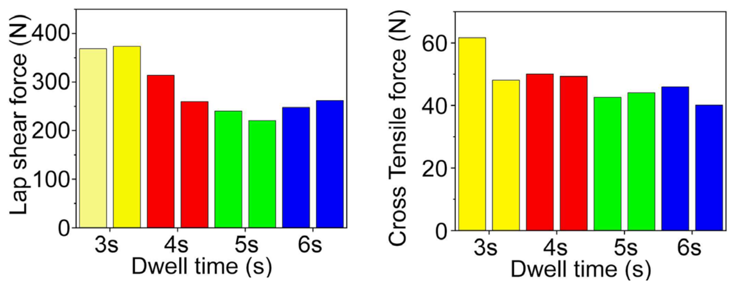
Fig. 5. Scanning electron micrograph of mTS-RFSSW of brass CuZn30-aluminum AA1100: *a* — dwell time of 3 s; *b* — dwell time of 4 s; *c* — dwell time of 5 s; *d* — dwell time of 6 s

Meanwhile, the metallurgical bonding formed is unbonding and partially bonding, as shown in Fig. 4, *i*, likewise with the dwell time of 6 s, which indicates the occurrence of flash and visible microcracks that propagate up to the aluminum sheet. At a dwell time of 5 s, the macro and microstructure formed in Fig. 4, *g–i* form an upward hook and flash. Flash is a material that is pushed out due to the plunging process. When the material starts to soften when there is friction between the tool and the workpiece when plunging, observations show that the longer the dwell time, the temperature may increase, which means that the deformation is severe enough to damage the metallurgical bonding joints. Microcracks occur at the dissimilar material FSSW joints at dwell times 4 s, 5 s, and 6 s in Fig. 4, *f*, *i*, *l*, respectively. This could be due to intermetallic compound (IMC) formation and unbonding or partial bonding in the stir zone. The thick and brittle intermetallic compound (IMC) in the stir zone tends to cause microcracks and microcracks growth. The microstructure of the mTS-RFSSW brass CuZn30-aluminum AA1100 joining shows three different regions: the stir zone, the thermo-mechnically affected zone (TMAZ), and the base metal. The stir zone area produces a finer grain structure because it undergoes dynamic recrystallization involving the thermal cycle. In the HAZ region, because it is only affected by heat due to friction, the grain structure in the HAZ tends to be coarser than that of the TMAZ and stir zone. Observations on the interface between brass CuZn30 and aluminum AA1100 show metallurgical bonds observed through SEM-EDS.

5. 2. Mechanical and fracture properties

Fig. 6, *a*, *b* show lap shear force and cross tensile force of mTS-RFSSW joint of dissimilar material using a variation of the second dwell time, which was carried out using 2 times of replication, respectively.

The maximum lap shear force with the highest average is at a dwell time of 3 s, which is 371 N. The highest cross tensile force result shown in Fig. 6, *b*, is produced at a second dwell time of 4 s, while a dwell time of 5 s has the lowest cross tensile. Overall, it was observed that the dwell time of 3 s and 4 s for both lap shear force and cross tensile force tended to be higher than the dwell time of 5 s and 6 s. The lap shear force decrease from dwell time 3 s to dwell time 6 s, as shown in Fig. 6, *a*. The formation of metallurgical bonds may cause a decrease in lap shear force from 3 s to 5 s to dwell time, and intermetallic compounds (IMC) are formed at the interface. The lap shear force and cross tensile force of micro two-stage friction stir spot welding (mTS-FRSSW) are related to the formation of the hook and the continuous IMC thickness. The discontinuous IMC and the thicker IMC layer tend to crack, affecting the tensile force of the dissimilar material joints. At a dwell time of 3 s, mixing sufficiently softens the two materials, and plastic deformation occurs, resulting in metallurgical bonding in the two materials. Then, when the dwell time is increased, the stir zone appears wider. In addition, the hook that occurs in the stir zone at each dwell time variation produces a different hook. The hook is the weakest part of the stir zone, which often cracks and fails. At a dwell time of 5 s, the stir zone formed has an unbonding region on the hook, causing a decrease in the lap shear force and cross tensile force to 255.5N and 47.08N.



a *b*

Fig. 6. Variation of: *a* – lap shear force; *b* – cross tensile force for CuZn30 and AA1100 micro two-stage refilled friction stir spot welded joints with two replications

Fig. 7 shows the microhardness distribution of the micro two-stage refilled friction stir spots welded joints using a variation of the second dwell time of dissimilar material brass CuZn30-aluminum AA1100, where brass CuZn30 is placed on the top sheet, and aluminum AA1100 is placed on the bottom sheet. It can be seen that the microhardness value in the stir zone, which is the interfacial area, is inhomogeneous. The microhardness value in the stir zone is relatively higher compared to other areas, such as the thermos-mechanically affected zone and the base metal of brass sheet and aluminum sheet, because the grain refinement stir zone occurs due to plastic deformation and dynamic recrystallization during joining and forming intermetallic compound (IMC). The existence of IMC at this interface affects the high excitability of the stir zone [15–18]. Some researchers also mention that the stir zone of dissimilar material results from FSSW joining is an area that has higher hardness, which is caused by high welding temperatures and dynamic recrystallization, which causes high heat input resulting in a finer grain structure accompanied by lots of Cu particle fragments [19, 20]. In dissimilar FSSW Al/Cu welding, the hardness value decreases when it is far from the keyhole [21]. Therefore, it tends to be challenging to determine the relationship between dwell time and microhardness. It was observed that the lowest microhardness value in the stir zone was found at the dwell time of 3 s, while the highest microhardness value was at the dwell time of 4 s. However, it was observed that at dwell times of 3 s, 5 s, and 6 s, there was a decrease in microhardness value due to the high rotation duration, causing an increase in heat input resulting in higher softening. The influence of dwell time was also observed by [22].

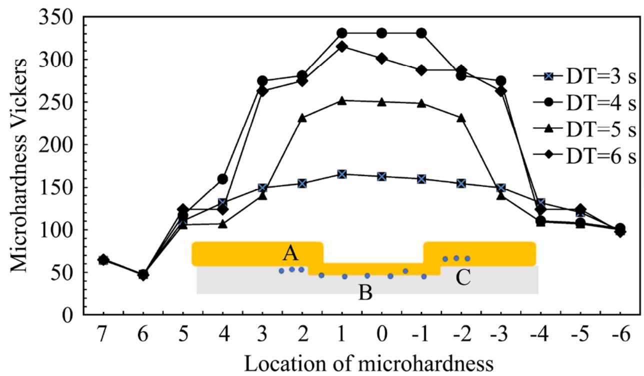
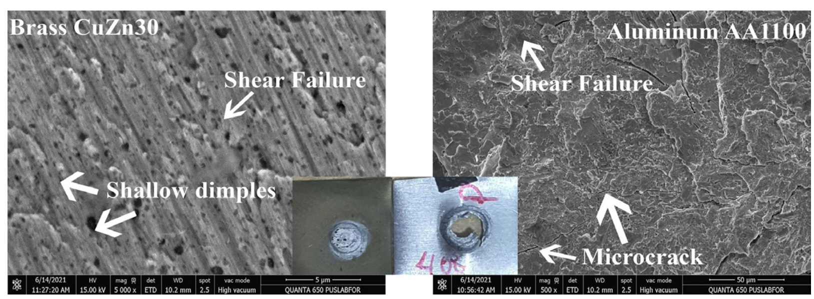
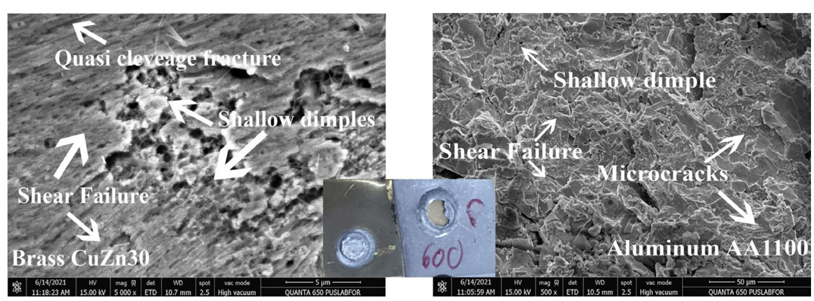


Fig. 7. Distribution microhardness Vickers of mTS-RFSSW with variation dwell time



a



b

Fig. 8. Scanning electron micrograph of fracture areas of mTS-RFSSW brass CuZn30- aluminum AA1100 using: *a* – dwell time of 4 s; *b* – dwell time of 6 s

The mTS-RFSSW fracture surface of dissimilar joint brass CuZn30-aluminum AA1100 was observed after the lap shear test. The fracture surfaces of the lap shear test were taken from the upper (brass CuZn30 sheet) in Fig. 8, *a*, *c* and lower (aluminum AA1100 sheets) in Fig. 8, *b*, c for dwell time 4 s and 6 s.

Fig. 8 shows that there is high deformation of the aluminum sheet where there are tears of aluminum adhering to the brass sheet. The morphology of the fracture at dwell time 4 s in Fig. 8, *a*, *b* shows that based on the lap shear test, it was found that the type of fracture that occurred was a shear fracture. Likewise, this can be seen in the fracture at the dwell time of 6 s, namely the shear fracture mode. The failure starts from the outer periphery to the center region, and it can be seen that the AA1100 aluminum sheet is attached to the brass sheet above it. Several small and fine dimples were formed from the fracture results after lap shear force on the mTS-RFSSW with a dwell time of 4 s and 6 s. The presence of small amounts of dimples and initial cracks is a brittle failure [20]. Fig. 8 also shows the microcracks that propagate on the surface of the aluminum sheet. Thus, the brass-aluminum AA1100 welded joint failure mode is a shear failure, indicating brittle failure. Brittle failure can be caused by crack initiation along the hook and unbonded/partially bonding region and the formation of intermetallic compound layers and oxide layers at the interface of brass CuZn30 and aluminum AA1100 interface.

6. Discussion of the experimental results of mTS-RFSSW brass CuZn30 and Aluminum AA1100

Cross sectional macrostructure and microstructure mTS-RFSSW on dissimilar joints with variations of dwell time, shows that each dwell time produces an upward hook, where the AA1100 aluminum sheet under the Brass CuZn30 plate is extruded onto the CuZn30 brass material accompanied by the formation of intermetallic compounds (IMC) at the interface (Fig. 4). This hook begins the initial failure and propagates through the intermetallic compound, where the thickness of the thick intermetallic compound layer formed from the long duration of dwell time facilitates the initial crack [13]. In addition, Fig. 4, *i*, shows unbonding between CuZn30 brass material and AA1100 aluminum material. This unbonding can weaken the strength of the joint, where the lap shear force and cross tensile force decrease at dwell times of 5 s and 6 s. Dwell time in the stir zone allows the CuZn30 and aluminum AA1100 materials to diffuse to form an intermetallic compound layer at the material interface. The intermetallic compound layer was analyzed using scanning electron micrograph-assisted Energy Dispersive X-Ray shown in Fig. 5 to produce elements Al, Cu, and Zn. In addition, the element oxygen is also visible in the intermetallic compound layer. This affects mechanical properties, such as lap shear force and cross-tensile force. The results of the Vickers hardness distribution shown in Fig. 7 show that the highest hardness is found in the stir zone, which is due to the stir zone grain refinement occurs because, in the stir zone, dynamic recrystallization occurs coupled with the formation of an intermetallic compound layer at the interface. The hardness decreases as we move away from the stir zone. The hardness distribution at the second stage dwell time of 3 s is the lowest hardness. Fracture properties of the lap shear test results are shown in Fig. 8, observed using a scanning electron microscope on the bottom side of CuZn30 brass material and the top side of AA1100 aluminum. The resulting fracture properties are different for each variation of dwell time because they produce different interfacial bonding. Overall, the fracture mode on the mTS-RFSSW at a dwell time of 4 s and 6 s is a brittle fracture.

One of the limitations of this research is that data collection on the distribution of temperature and axial force during the mTS-RFSSW has yet to be carried out, which allows for the addition of these two data, numerical simulations and its correlations with mechanical properties and macrostructure and microstructure. For future development of this research, use other mTS-RFSSW process parameters such as variations in tool geometry, plunge depth, fatigue testing, numerical simulations, and optimizing process parameters to produce optimal response variables.

7. Conclusions

1. Cross-section macrostructure using optical microscope micro two stage-refilled friction stir spot welding (mTS-RFSSW) dissimilar brass CuZn30-aluminum AA1100 joint revealed that upward hooks were formed at every dwell time, and flash was formed at dwell times of 5 s and 6 s, but at dwell times of 3 s and 4 s, no flash was seen. The longer the dwell time, the more flash formed. Microstructure and EDS results in the intermetallic compound formed at the interface of brass CuZn30 and aluminum AA1100 sheets vary at each dwell time. At the dwell time of 5 s and 6 s, intermetallic compound formations are seen accompanied by microcracks. Increasing dwell time causes a decrease in metallurgical bonding at the interface of brass CuZn30 and aluminum AA1100, indicated by the unbonded region and partially bonding in the stir zone, reducing its tensile properties. The stir zone in each dwell time variation has the finest grain structure that affects the microhardness distribution, where the stir zone has the highest hardness value. The lowest microhardness distribution was observed at a dwell time of 3 s.

2. The maximum lap shear force and maximum cross tensile force mTS-RFSSW dissimilar brass CuZn30-aluminium AA1100 joint achieved with a dwell time of 3 s, namely 371.35 N and 54.88 N, respectively. The lap shear force and cross tensile force tend to decrease with increasing dwell time, where the longer dwell time produces welding heat which affects the microstructure and intermetallic compound formation. Fractography after examination of lap shear observed that shear failure plug-out mode occurs in the stir zone, and the presence of dimples and microcracks on the fracture surface after the lap shear test at dwell time 4 s and 6 s tend to cause brittle failure caused by the formation of intermetallic compound and oxidation at the interface of brass CuZn30 and aluminum.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Manuscript has no associated data.

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References

1. Garg, A., Bhattacharya, A. (2017). Similar and dissimilar joining of AA6061-T6 and copper by single and multi-spot friction stirring. Journal of Materials Processing Technology, 250, 330–344. doi: https://doi.org/10.1016/j.jmatprotec.2017.07.029
2. Irawan, Y. S., Choiron, M. A., Suprapto, W. (2021). Tensile strength and thermal cycle analysis of AA6061 friction weld joints with different diameters and various friction times. Eastern-European Journal of Enterprise Technologies, 2 (12 (110)), 15–21. doi: https://doi.org/10.15587/1729-4061.2021.227224
3. Darmadi, D. B., Abdillah, F. N., Raharjo, R. (2019). Controlling the pressure force to obtain a better quality of aluminum 6061 friction stir welded joint. Eastern-European Journal of Enterprise Technologies, 3 (1 (99)), 6–10. doi: https://doi.org/10.15587/1729-4061.2019.159286
4. Sajed, M. (2016). Parametric study of two-stage refilled friction stir spot welding. Journal of Manufacturing Processes, 24, 307–317. doi: https://doi.org/10.1016/j.jmapro.2016.09.011
5. Chen, K., Liu, X., Ni, J. (2017). Keyhole refilled friction stir spot welding of aluminum alloy to advanced high strength steel. Journal of Materials Processing Technology, 249, 452–462. doi: https://doi.org/10.1016/j.jmatprotec.2017.06.039
6. Sunar Baskoro, A., Azwar Amat, M., Andre Widiyanto, M. (2019). Effect of Tools Geometry and Dwell Time on Mechanical Properties and Macrograph of Two-Stage Refilled Friction Stir Spot Micro Weld. MATEC Web of Conferences, 269, 02002. doi: https://doi.org/10.1051/matecconf/201926902002
7. Esmaeili, A., Sbarufatti, C., Hamouda, A. M. S. (2019). Characteristics of Intermetallic Compounds in Dissimilar Friction Stir Welding: A Review. Metallography, Microstructure, and Analysis, 8 (4), 445–461. doi: https://doi.org/10.1007/s13632-019-00557-w
8. Zhou, L., Zhang, R. X., Li, G. H., Zhou, W. L., Huang, Y. X., Song, X. G. (2018). Effect of pin profile on microstructure and mechanical properties of friction stir spot welded Al-Cu dissimilar metals. Journal of Manufacturing Processes, 36, 1–9. doi: https://doi.org/10.1016/j.jmapro.2018.09.017
9. Rupajati, P., Clarissa, K. G., Baskoro, A. S., Kiswanto, G., Winarto, W. (2021). Characteristics of Mechanical Properties and Microstructure of Micro Friction Stir Spot Welding of AA1100 and Brass. International Journal of Technology, 12 (6), 1302. doi: https://doi.org/10.14716/ijtech.v12i6.5214
10. Shen, Z., Ding, Y., Chen, J., Amirkhiz, B. S., Wen, J. Z., Fu, L., Gerlich, A. P. (2019). Interfacial bonding mechanism in Al/coated steel dissimilar refill friction stir spot welds. Journal of Materials Science & Technology, 35 (6), 1027–1038. doi: https://doi.org/10.1016/j.jmst.2019.01.001
11. Li, P., Chen, S., Dong, H., Ji, H., Li, Y., Guo, X. et al. (2020). Interfacial microstructure and mechanical properties of dissimilar aluminum/steel joint fabricated via refilled friction stir spot welding. Journal of Manufacturing Processes, 49, 385–396. doi: https://doi.org/10.1016/j.jmapro.2019.09.047
12. Hsieh, M.-J., Lee, R.-T., Chiou, Y.-C. (2017). Friction stir spot fusion welding of low-carbon steel to aluminum alloy. Journal of Materials Processing Technology, 240, 118–125. doi: https://doi.org/10.1016/j.jmatprotec.2016.08.034
13. Garg, A., Bhattacharya, A. (2017). Strength and failure analysis of similar and dissimilar friction stir spot welds: Influence of different tools and pin geometries. Materials & Design, 127, 272–286. doi: https://doi.org/10.1016/j.matdes.2017.04.084
14. Dong, Z., Song, Q., Ai, X., Lv, Z. (2019). Effect of joining time on intermetallic compound thickness and mechanical properties of refill friction stir spot welded dissimilar Al/Mg alloys. Journal of Manufacturing Processes, 42, 106–112. doi: https://doi.org/10.1016/j.jmapro.2019.04.013
15. Shen, Z., Ding, Y., Guo, W., Hou, W., Liu, X., Chen, H. et al. (2021). Refill Friction Stir Spot Welding Al Alloy to Copper via Pure Metallurgical Joining Mechanism. Chinese Journal of Mechanical Engineering, 34 (1). doi: https://doi.org/10.1186/s10033-021-00593-0
16. Xue, P., Xiao, B. L., Ma, Z. Y. (2015). Effect of Interfacial Microstructure Evolution on Mechanical Properties and Fracture Behavior of Friction Stir-Welded Al-Cu Joints. Metallurgical and Materials Transactions A, 46 (7), 3091–3103. doi: https://doi.org/10.1007/s11661-015-2909-1
17. Zhou, L., Li, G. H., Zhang, R. X., Zhou, W. L., He, W. X., Huang, Y. X., Song, X. G. (2019). Microstructure evolution and mechanical properties of friction stir spot welded dissimilar aluminum-copper joint. Journal of Alloys and Compounds, 775, 372–382. doi: https://doi.org/10.1016/j.jallcom.2018.10.045
18. Mubiayi, M. P., Akinlabi, E. T. (2016). Evolving properties of friction stir spot welds between AA1060 and commercially pure copper C11000. Transactions of Nonferrous Metals Society of China, 26 (7), 1852–1862. doi: https://doi.org/10.1016/s1003-6326(16)64296-6
19. Zareie Rajani, H. R., Esmaeili, A., Mohammadi, M., Sharbati, M., Givi, M. K. B. (2012). The role of Metal-Matrix Composite development During Friction Stir Welding of Aluminum to Brass in Weld Characteristics. Journal of Materials Engineering and Performance, 21 (11), 2429–2437. doi: https://doi.org/10.1007/s11665-012-0178-3
20. Bisadi, H., Tavakoli, A., Tour Sangsaraki, M., Tour Sangsaraki, K. (2013). The influences of rotational and welding speeds on microstructures and mechanical properties of friction stir welded Al5083 and commercially pure copper sheets lap joints. Materials & Design, 43, 80–88. doi: https://doi.org/10.1016/j.matdes.2012.06.029
21. Shiraly, M., Shamanian, M., Toroghinejad, M. R., Ahmadi Jazani, M. (2013). Effect of Tool Rotation Rate on Microstructure and Mechanical Behavior of Friction Stir Spot-Welded Al/Cu Composite. Journal of Materials Engineering and Performance, 23 (2), 413–420. doi: https://doi.org/10.1007/s11665-013-0768-8
22. Li, G., Zhou, L., Zhou, W., Song, X., Huang, Y. (2019). Influence of dwell time on microstructure evolution and mechanical properties of dissimilar friction stir spot welded aluminum–copper metals. Journal of Materials Research and Technology, 8 (3), 2613–2624. doi: https://doi.org/10.1016/j.jmrt.2019.02.015