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EFFECT OF TOOL ROTATIONAL SPEED IN FRICTION STIR LAP WELDING OF 7075-T651 Al ALLOY TO AISI 304 STAINLESS STEEL

ABSTRACT

7075-T651 Al alloy was successfully lap-joined to AISI 304 stainless steel by friction stir lap welding (FSLW) employing four different tool rotational speeds (388, 535, 720, and 980 rpm). Cross-sectional areas, tensile shear strength, and microhardness of the joints were investigated. When the rotational speed was increased, the hook size formed on the advancing sides of the joint increased, which caused the tensile shear strength of the joint to decrease. The joint made at 388 rpm had a tensile shear load of 9442 N while at 980 rpm possessed 4176 N. All the joints fractured from the top 7075-T651 base sheet as a tensile mode on the advancing side. Therefore, the joined areas are stronger. At low rotation speed, the joint broke vertically from the HAZ of the 7075-T651 sheet. Otherwise, it broke from the region next to the hook and along the hook direction. Intermetallic compounds caused hardness to increase.

Keywords: Friction Stir Lap Welding, 7075-T651 Al Alloy, AISI 304 Stainless Steel, Tool Rotation Speed, Mechanical Properties

1. INTRODUCTION

Aluminum (Al) alloys are very important structural metals, especially for the automotive and aerospace sectors since they have a high strength-to-weight ratio and good machinability [1]. 7075 aluminum alloy is a high-strength aluminum alloy and is often used in the aerospace industry as structural components, for example, in aircraft body panels and wings [2]. Austenitic stainless steel AISI 304, one of the most popular metals, is commonly used in medical equipment, aircraft, and automobiles. The main characteristics of this metal are excellent toughness, low thermal conductivity, high work hardening, and great corrosion and wear resistance [3]. In many applications, the use of different metals together by joining is desired to obtain better mechanical and metallurgical characteristics. Using aluminum and steel together by combining them in a structure can significantly reduce overall weight. These materials can be utilized in the design of various structures for automobiles, aircraft, and many other applications [4, 5, 6 and 7]. Hybrid structures produced by combining Al alloy and stainless steel can simultaneously provide the advantages of two materials, for example, taking the outstanding mechanical properties of steel and the lightweight feature of Al alloy [8]. But, Al alloy and steel have different mechanical and metallurgical properties, such as a large difference in melting temperatures, significantly different

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thermal expansion and thermal conductivity values, and the low solubility of aluminum in iron. Therefore, these materials are extremely difficult to weld, particularly using fusion welding methods, because brittle Fe-Al intermetallic compounds (IMCs) readily form at the interface owing to the very low solubility between aluminum and steel. Large IMCs formed can severely impair the mechanical characteristics of the weld [9, 10, 11, 12, and 13]. Since solid-state welding processes, for instance, friction stir welding (FSW) [14], due to its low operating temperatures and low heat input have offered advantages like significantly preventing the formation of extremely brittle IMCs and solidification defects usually seen in the traditional fusion welding, it is believed that it has a great capacity for soundly joining the Al alloy to steel and thus have received a great deal of attention in recent years [15].

FSW technique has exhibited excellent results in the joining of different materials such as Al alloy/Mg alloy, Al alloy/Cu alloy, and Al alloy/ Fe alloy [16]. Movahedi et al. studied friction stir lap welding (FSLW) of 3mm thick Al-5083 alloy and St-12 steel plates and it was observed that $Al_{13}Fe_4$ and Al_5Fe_2 IMCs were formed at the interface [17]. A layer of IMC less than 10 microns was reported to be non-harmful to the weld. Chen and Nakata conducted FSLW of 1 mm thick magnesium alloy and steel sheets [18]. It was concluded that a higher tool plunge depth provided higher weld strength. Chen et al. observed the absence of IMCs and a maximum temperature of 450°C in the friction stir spot welding (FSSW) of different AA 6111 and DC04 steel materials [19]. Shen et al. carried out FSLW of 2.2mm thick AA5754 and DP600 steel sheets using a WC carbide welding tool [20]. The weld with the maximum strength was made at a tool plunge depth of 0.389mm. A 170-micron thick Fe_4Al_{13} IMC layer at the interface and the highest hardness of 352 Hv in the weld were found. Kimapong and Watanabe studied combining 3mm thick A5083 Al alloy plates with 3mm thick SS400 mild steel plates by FSLW [21]. A maximum of 77% welding efficiency was acquired according to the base metal of the Al alloy. FeAl and $FeAl_3$ IMCs were detected to form at the interface. Increasing welding speed led to a decrease in the thickness of the IMC increasing the weld strength.

Shamsujjoha et al. investigated FSLW of 6.4mm thick AA 6061 Al alloy plates to 3.2mm 1018 mild steel plates [22]. They obtained a welding efficiency of 58% in regard to the base metal of the Al alloy. A higher weld strength was acquired with a higher tool plunge depth. Also, they stated that the weld strength improved when the top plate was placed on the advancing side. Geng et al. studied the FSLW of 5052 Al alloy to DP590 steel [23]. The formation of (IMC) and its thickness increased in direct proportion with increasing tool rotation speed. The Al-rich IMCs layer over 1.5μm thick and serious internal cavities flaws remarkably reduced the weld strength. A low tool rotation speed of 500 rpm was recommended. Dehghani et al. studied friction stir butt welding (FSBW) of Al 5186 and mild steel [24]. They acquired the results that low welding speeds of 14-40mm/min cause thick IMCs to form, which leads to weak joints, and also tunnel defects are formed at very low welding speeds. Liu et al. investigated combining AA6061-T6 with trip steel through FSBW [25]. They similarly found that high welding speed results in lessening the IMC layer because of the reduction in the high-temperature period. According to Elrefaey et al. a poor joint was produced when the tool pin did not plunge enough to reach the bottom steel sheet surface [26].

Wan et al. stated that a harmful large layer consisting of IMCs formed in the weld of FSLW 6082-T6 Al alloy and Q235A steel when increasing tool rotation speed [27]. Astarita et al. investigated the joining of 2198 and 7075 Al alloy sheets by the FSLW method and found that the tool rotation speed had a greater influence on the joint mechanical properties than welding speed [28]. Tool rotational speed is one of the most critical FSLW parameters in generating heat and mixing materials and thus obtaining stronger joints. When looking at the literature, it is seen that there is a need for studies on joining 7075 Al alloy to AISI 304 stainless steel. Therefore, the joining of these very different materials by the FSLW technique was investigated by studying the influence of tool rotation speed on the joint strength.

2. RESEARCH SIGNIFICANCE

In this study, 7075-T651 aluminum alloy and AISI 304 stainless steel, which are difficult to combine with traditional welding methods, were joined by friction stir lap welding. As a result of the welding process, the weldability of both materials with each other was investigated. As a result of the data obtained, it is clear that there is no defect in the joining process and the welding process was carried out without any problems in the microstructure and microhardness analyses performed after welding.

Highlights:

- Tool rotation speed played a crucial role in the joining of 7075-T651 Al alloy and AISI 304 stainless steel sheets by friction stir lap welding method in terms of joint geometry and mechanical properties.
- The hook size had a significant effect on the joint strength.
- Intermetallic compounds between Al and Fe formed and resulted in an increase in the hardness at the joining area.

3. EXPERIMENTAL METHOD-PROCESS

2 mm thick, 100 mm long, and wide 7075-T651 Al alloy sheet were put over an area of 50x100 mm^2 on the 1.5mm AISI 304 stainless steel sheet, then they were joined via the FSLW method for various tool rotational speeds (388, 535, 720, and 980 rpm) as shown in schematic illustration in Figure 1. The characteristics of these sheets are provide in Tables 1 and 2. During the joining process, the tool inclination angle of 1.5 degrees clockwise, the feed rate (welding speed) of 37 mm/min, and the plunge depth of 2.8mm from the top sheet were kept constant. The joints were made from the middle of the overlap area of the sheets on the Falco FMH-4 model machine. The tool used in welding operations was produced from tungsten carbide material, and its dimensions are given in Figure 2. After the joining of the sheets, they were cut to obtain specimens for examination of cross-section, tensile shear strength, and microhardness. Photos of tensile shear and cross-sectional area specimens were presented in Figures 3 and 4, respectively. The cross-sectional areas of the joints were sanded, polished, and etched with Keller solution to see the joining area structure, especially for the 7075-T651 Al alloy side. An optical view of the cross-sectional areas of the joints is shown in Figure 5. AOB THV-1D brand Vickers microhardness tester was used for measuring the hardness of the joints with a 0.1kg load and 10 seconds dwell time. Instron 2736-004 tester was used for measuring the tensile shear strength of the joints at room temperature at 0.5mm/min constant cross-head speed. Rigaku Ultima IV X-Ray Diffractometer machine was used for XRD analysis.

Table 1. Chemical composition of the sheets

Sheet	Element (wt.%)								
7075-T651	Fe	Ni	Cu	Si	Mn	Zn	Al	Ca	Mg
	0.005	0.005	0.05	0.1	0.2-1	0.6-1.4	2.3-3.5	0.04	Rest
AISI 304	S	P	C	N	Si	Mn	Ni	Cr	Fe
	0.030	0.045	0.08	0.10	0.75	2	8-10.5	18-20	Rest

Table 2. Mechanical characteristics of the sheets

Sheet	Tensile Strength (N/mm^2)	Yield Strength (N/mm^2)	Elongation (%)	Vickers Hardness (HV)
7075-T651	275	170	11	167
AISI 304	520	200	40	210

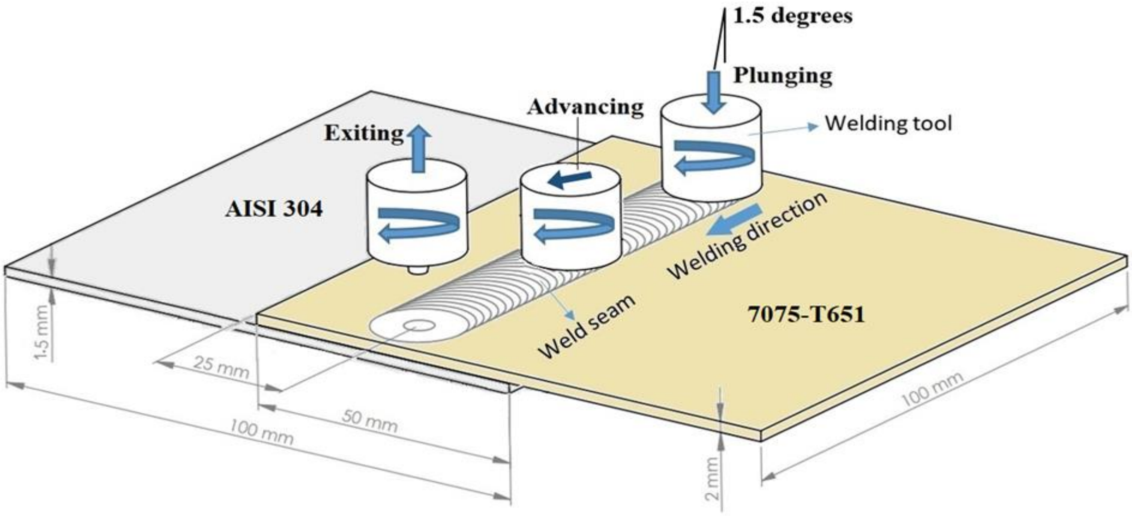

Figure 1. Schematic illustration of FSLW of the sheets

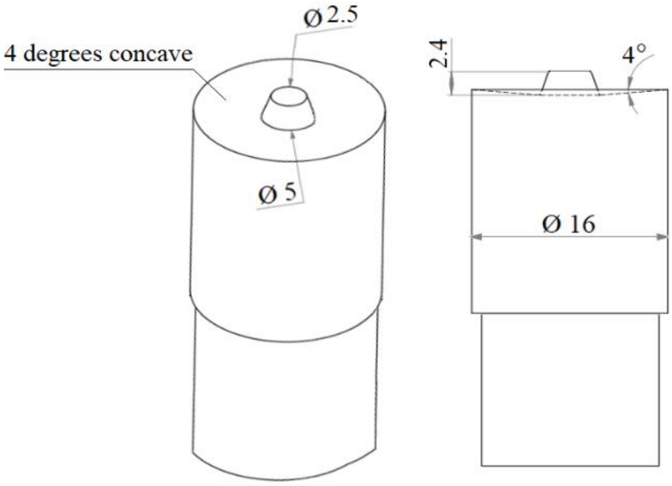

Figure 2. FSLW tool geometry

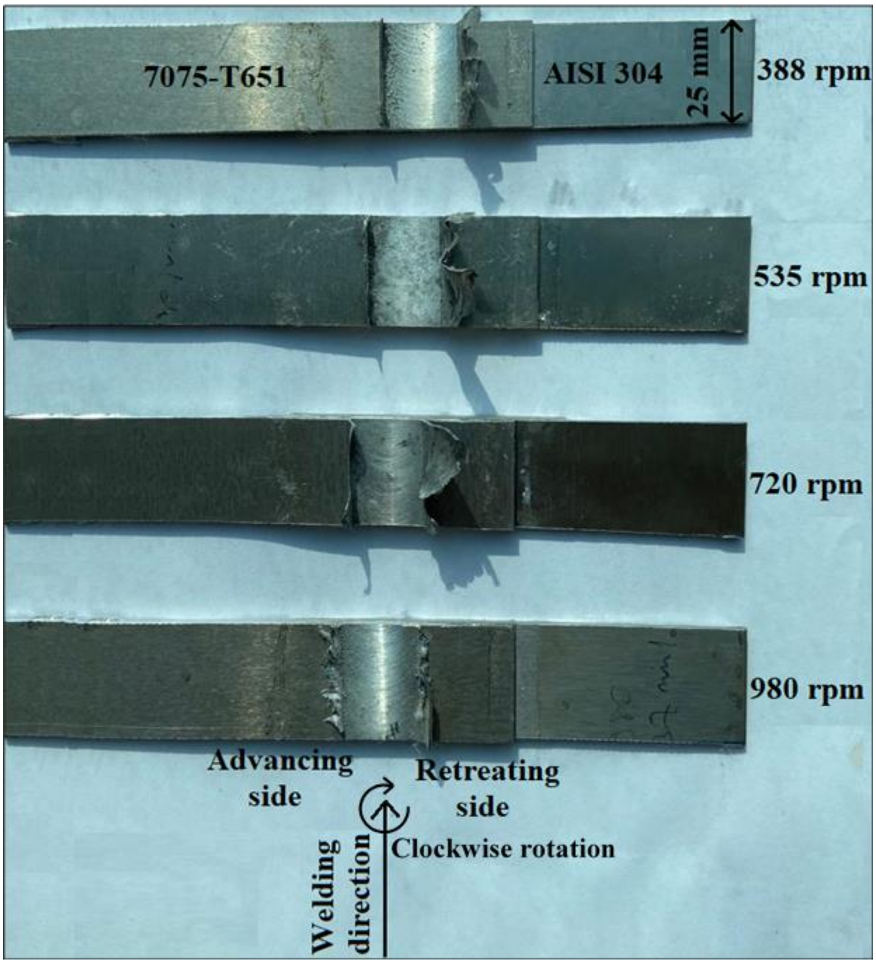

Figure 3. Tensile shear test samples manufactured from the cutting welded sheets

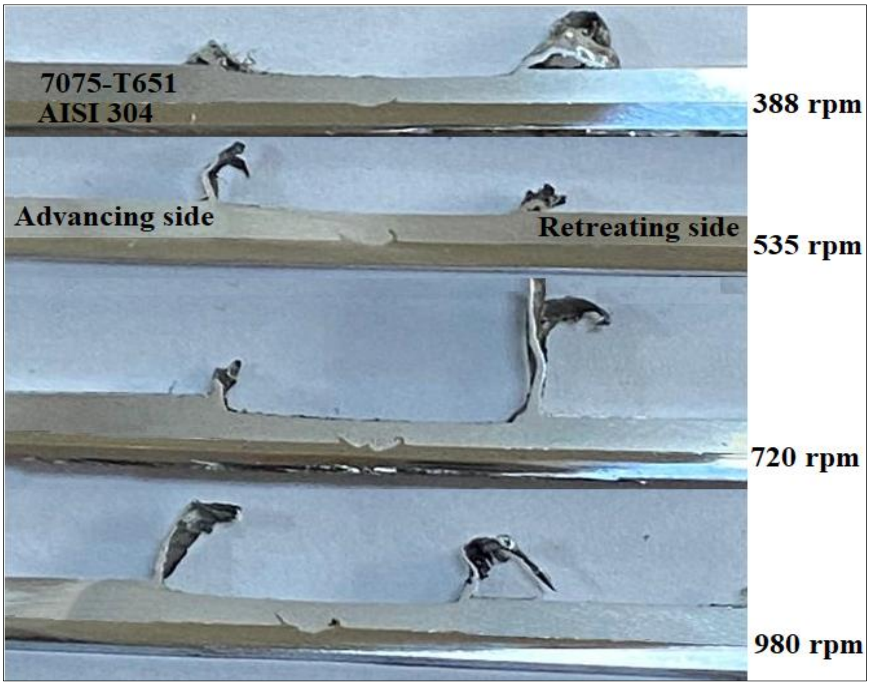

Figure 4. Cross-section photo of the produced lap joints

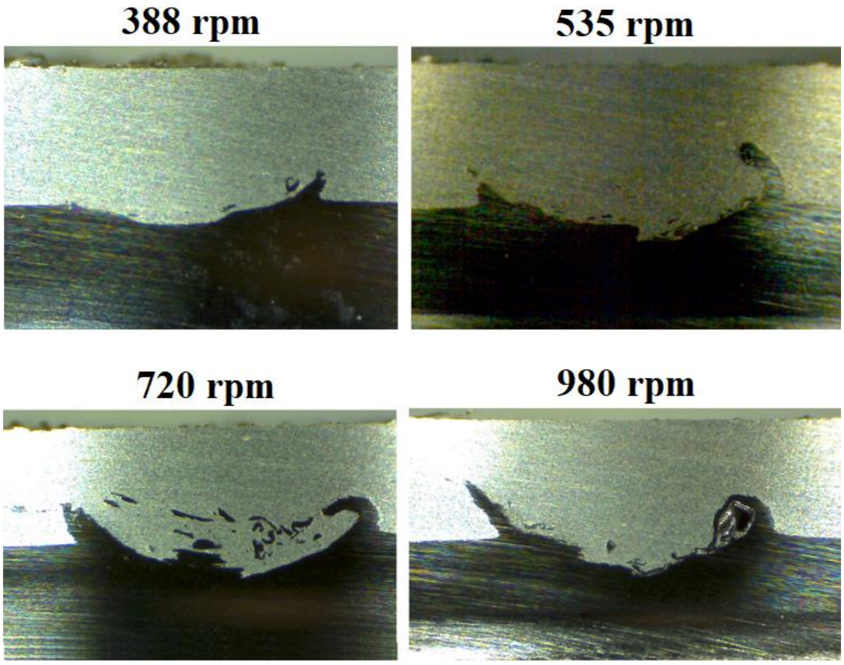

Figure 5. Macro views of the cross-sectional areas of lap joints

4. FINDINGS AND DISCUSSIONS

Optical images of the advancing side, middle, and retreating side attained from the cross-sections of the lap joints are shown in Figure 6. It can be seen that the hook formed on the advancing side of the joint fabricated at the tool rotation speed of 388 rpm is much smaller in terms of size when compared with those of the other joints fabricated at higher rotation speeds. Moreover, on the advancing side, the joint hook length, and its height relative to the interface of sheets increased with increasing rotation. Similarly, the joint hook formed on the retreating side generally extended more and headed toward the stir zone as the rotation speed increased. In addition, in general, the number of fragments broken off from AISI 304 stainless steel bottom sheet material and dispersed on the top 7075-T651 Al alloy sheet material in the stir zone increased with the increased rotation speed, as seen on the middle side of the joints. Furthermore, the occurrence of some micro cavities was detected in the joint interface on the middle side as well as a large cavity next to the hook on the retreating side at the high rotation speed.

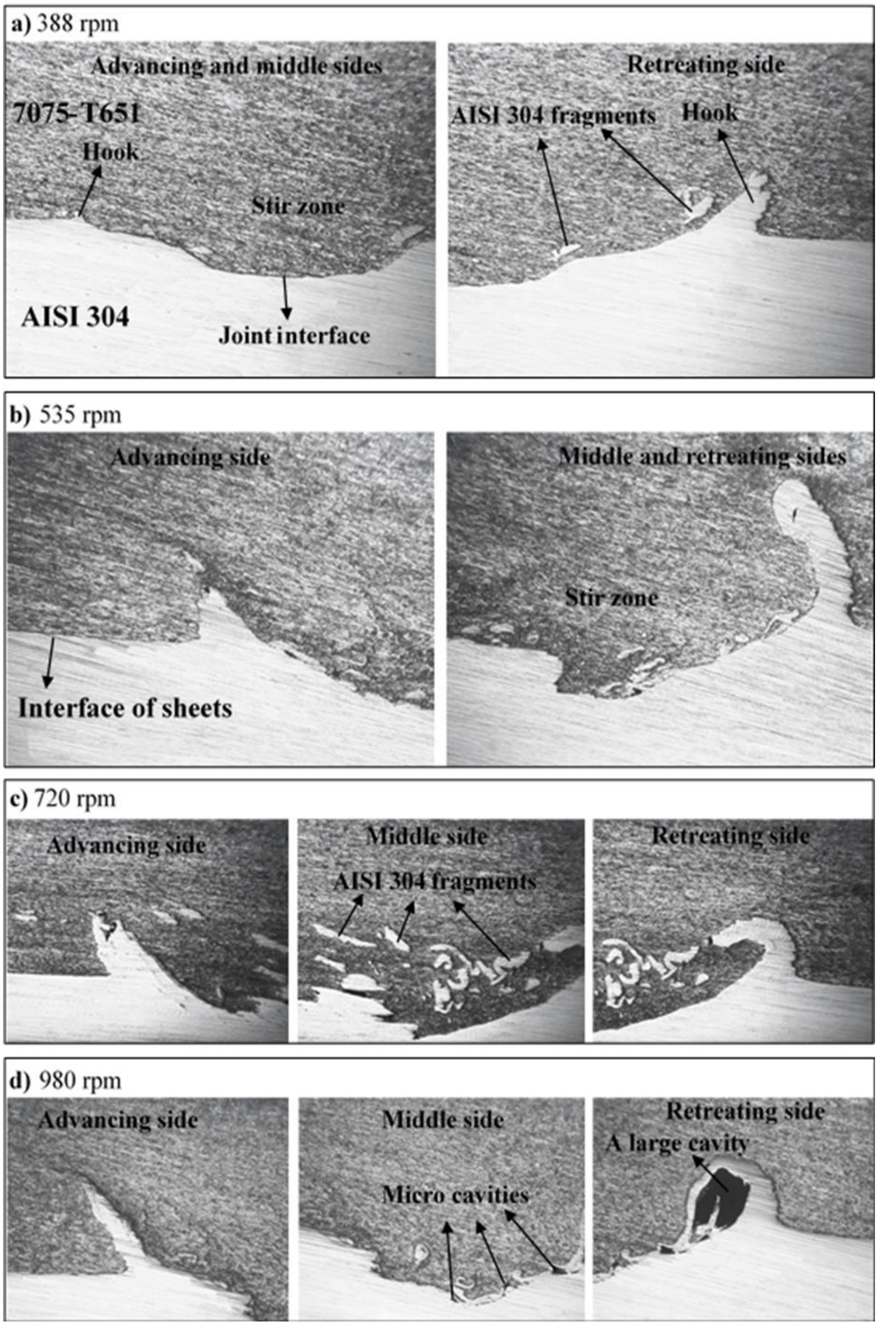

Figure 6. Optical photographs of the advancing side, middle, and retreating sides obtained from the cross-sections of the lap joints

Figure 7 shows XRD analysis results taken from the cross-sectional areas of the joints made at the lowest 388 and highest 980 rpm tool rotation speeds. Intermetallic compounds of Al13Fe4, Al3Fe2, and Al3Fe were found in both joints. Similar intermetallic compounds in the FSBW of 7075 Al alloy and AISI 304 stainless steel were determined by [29]. It can be seen from Figure 7 that the XRD analysis results of the joints are slightly different.

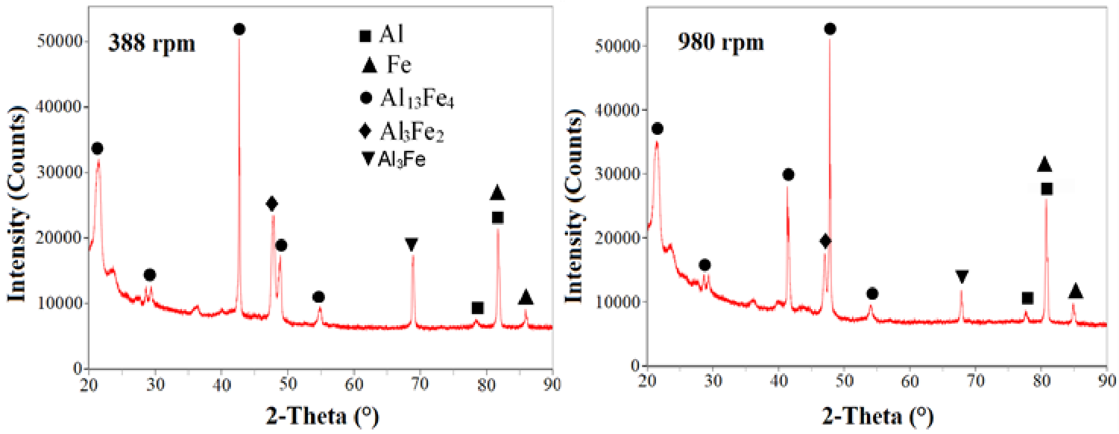

Figure 7. XRD analysis results obtained from the cross-sectional areas of the joints made at 388 and 980 rpm tool rotation speeds

The Vicker microhardness distributions along the shown horizontal line in Figure 8a on the 7075-T651 sheet just above the interface of the sheets on the cross-sectional areas of the lap joints were acquired and the results are demonstrated in Figure 8b. Microhardness measurements started from the 7075-T651 base metal (BM) and continued until the end of the stir zone (SZ). The hardness of the BM was found to be around 167 HV, and this value decreased when approaching the heat-affected zone (HAZ), and then the thermo-mechanically affected zone (TMAZ) for all the joints. This may be because HAZ and TMAZ were exposed to heat and thus the formation of larger grains in their microstructure, resulting in a decrease in hardness. Also, increasing the tool rotation speed caused the HAZ and TMAZ of the joint to soften. This is probably because of exposure to higher heat. On the other hand, the hardness value considerably increased with entering the stir zones(SZs) of the joints due to the presence of small AISI 304 fragments in these regions. In general, the hardness of the SZ of the joint slightly increased because the SZ contained a higher amount of AISI 304 fragments with increasing tool rotation speed.

Aval and Loureiro [30] researched friction stir welding (FSW) of 7075 Al alloy and AISI 304 stainless steel and attributed the high hardness of the SZ to the formation of steel particles, some reprecipitation of strengthening precipitates and intermetallic compounds in the SZ. The Hardness along the transverse of the cross-sectional area of the joint produced at the tool rotation speed of 720 rpm was measured as well, along the line from the top of the upper 7075-T651 to the bottom of the lower AISI 304 at the joint interface center, as shown in Figure 9. It was observed that the hardness gradually increased from the top of the upper 7075-T651 sheet to the joint interface. This is probably due to the increase in the amount of AISI 304 particles in the stir zone as approaching the joint interface. Then, at the joint interface, the hardness suddenly rose significantly and reached the maximum values. This sudden increase is probably caused by the formation of hard intermetallic compounds at the interface as seen in XRD results of Figure 7. Later, as seen in Figure 9b, the hardness first decreased and then increased slightly when moving from the joint interface to the bottom of the lower AISI 304. This is probably because of exposure more heat of the upper side of AISI 304. Mahto et al. [31] studied the FSLW of 6061-T6 Al alloy and AISI 304 stainless steel. They also determined maximum hardness values at the joint interface and attributed this to the formation of intermetallic compounds (AlFe, Al13Fe4 and AlCrFe2) at the joint interface.

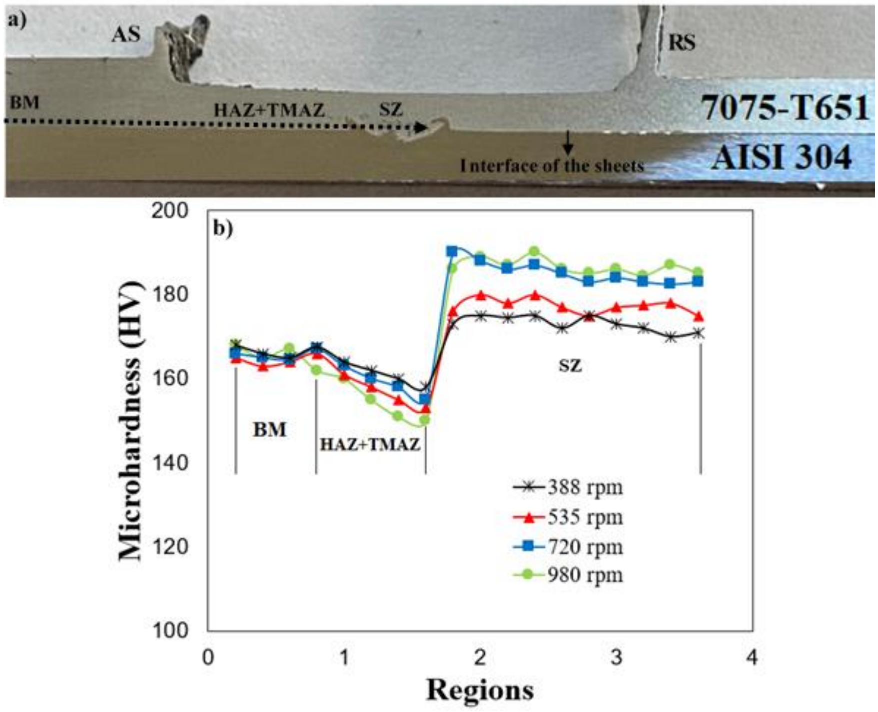

Figure 8. Microhardness distribution along the horizontal line on the 7075-T651 sheet just above the interface of the sheets.
a) Demonstration of hardness measurement way,
b) Hardness measurement results for the lap joints

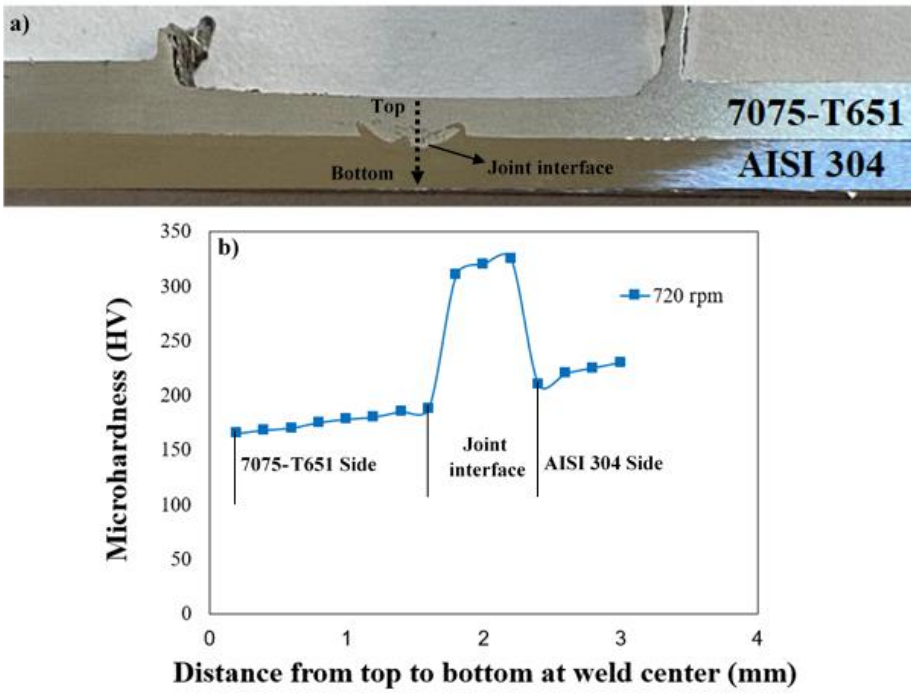

Figure 9. Microhardness measurement at the center of the lap joint from the top of the upper 7075-T651 to the bottom of the lower AISI 304. a) Illustration of the hardness measurement way,
b) Hardness measurement results for the lap joint made at 720 rpm

Tensile shear test of the lap joints and obtained results were presented in Figure 10. It is clear that joint strength got worse with increasing tool rotational speed. The joint created via the lowest tool rotation speed of 388 rpm performed a load-carrying capacity of 9442 N while the joint made with the highest speed of 980 rpm carried a load of 4176 N. The joint of 388 rpm is slightly more than twice as strong as that of 980 rpm. In addition, the joint of 980 rpm showed the lowest elongation compared to other joints. The joint made with the lowest speed of 388 rpm exhibited the highest strength as it had the smallest hook on its advancing side. On the other hand, the joint made with the highest speed of 980 rpm became the weakest one because this joint had the highest and longest hook at its advancing side, as illustrated in Figure 6. Geng et al. studied the FSLW of 5052 Al alloy to DP590 steel using tool rotation speeds from 250 to 1500 rpm [23]. According to their results, the joint tensile shear strength decreased when increasing the tool rotation speed above 500 rpm because of the formation of a larger hook, micro-voids, gaps, and cavities, a decrease in the effective bonding area, and an increase in the thickness of intermetallic compounds. 500 rpm tool rotation speed was suggested to be the best speed for obtaining the strongest joint as it provided suitable heat input resulting in better material deformation. The hook lessens the effective thickness of the top sheet and, as a result, its tensile shear strength. The hook size creates a profound impact through stress concentration under load [32]. Astarita et al. studied FSLW of 2198 and 7075 Al alloy sheets and they stated that the effect of hook defect on the joint strength dominates over other imperfections, and tensile shear strength of the joint is mostly determined by the hook [28].

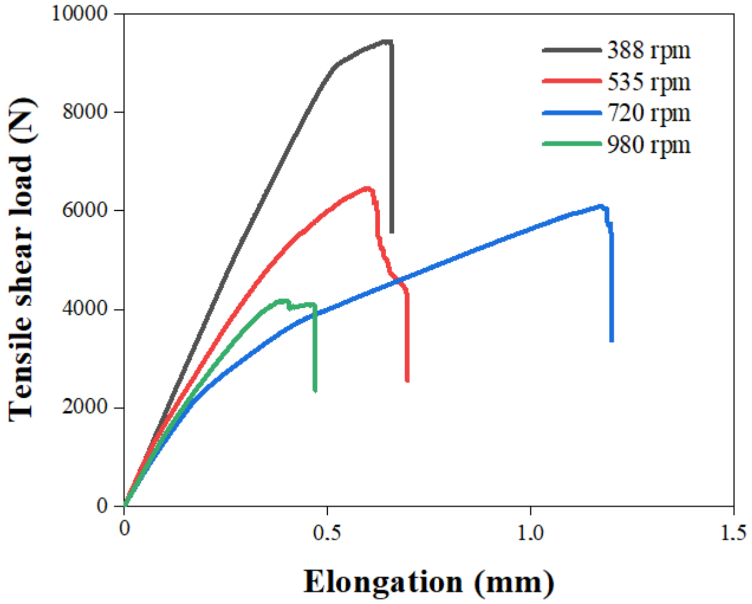

Figure 10. Tensile shear load and elongation for the lap joints

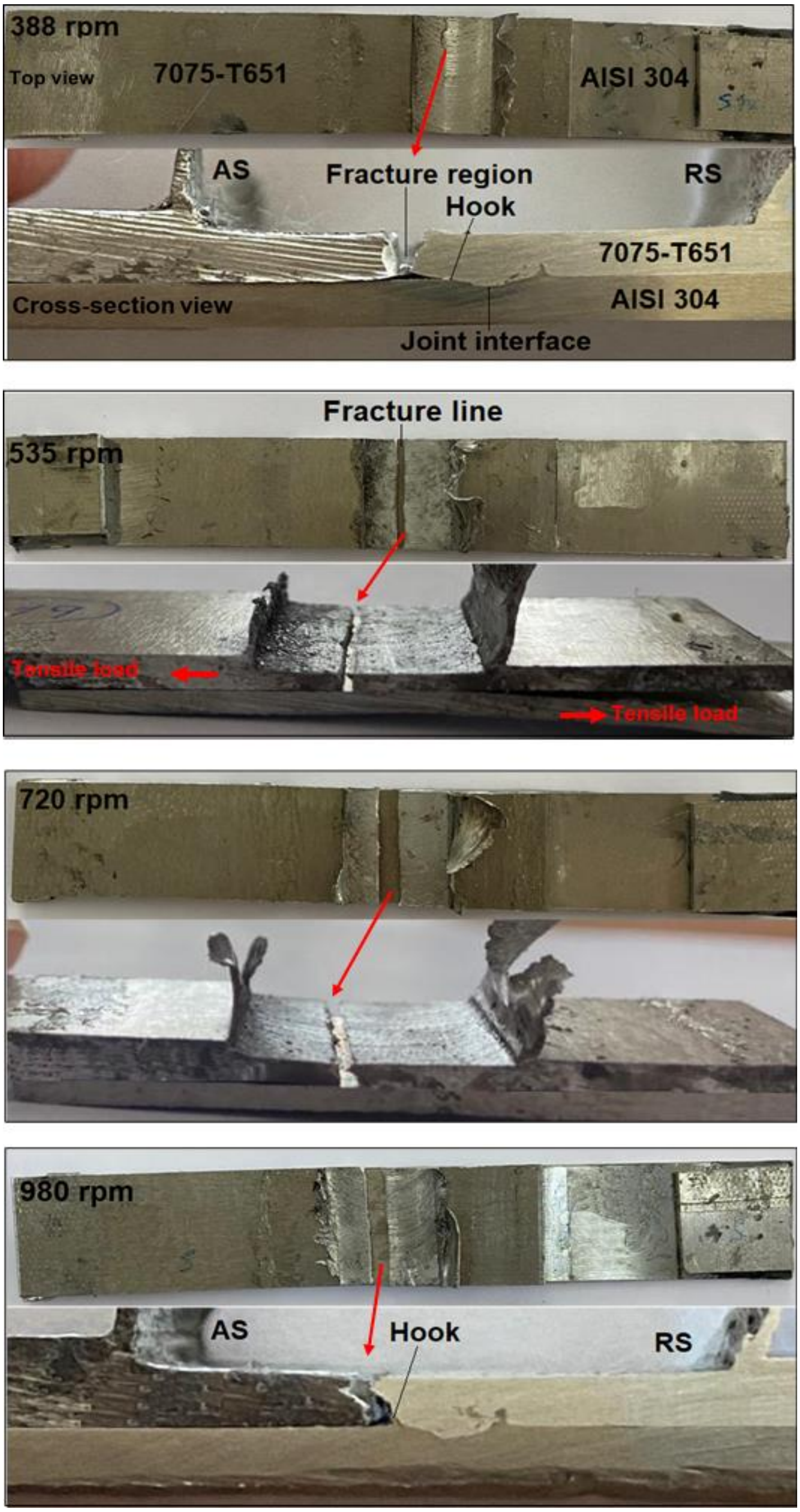

Figure 11. The lap joint samples broken after the tensile shear test and their cross-sectional view

The top view of fractured lap joint samples and their cross-sectional area view as a result of the application of the tensile shear test are seen in Figure 11. It can be seen that no joints were broken from the joint zone interface. All the joints failed from the top 7075-T651 Al alloy sheet on the advancing side (AS). Astarita et al. investigated FSLW of 2198 and 7075 Al alloy sheets and found that all the joints failed from the advancing side mostly because of the hook defect formation [28]. The joint made at 388 rpm ruptured vertically along the thickness 7075-T651 top sheet from the heat-affected zone (HAZ) of the 7075-T651 sheet, away from the joint zone interface, as seen from the cross-section of this joint. The joint produced at 535 rpm failed similarly to the joint formed at 388 rpm but from a region slightly closer to the joint zone. By increasing the tool rotation speed, the breakage approached the joint area, and as seen in the cross-section of the joint produced at 980 rpm, the fracture started from where the hook was and then continued in the direction of the hook and occurred. Since at high tool rotation speeds, for example, 720 and 980 rpm, the height and length of the hook formed on the advancing side were higher, it was the hook responsible for the initiation and region of the fracture. At low tool rotation speeds (388 and 535 rpm), the fracture occurred away from the joint zone, because the hooks formed at the advancing side (AS) were very small as seen in Figure 6 and it became ineffective on the fracture. Since no joints broke from the interfaces of the joints, it can be mentioned that the joint interface is stronger than the tensile shear loads that caused the fracture. XRD analysis outcome for the tensile shear test fracture surface area on the 7075-T651 Al side for the joint manufactured at 388 rpm tool rotation speed is given in Figure 12. AlMg4Zn11, Al0.983Cr0.17, (Fe, Cr), Al0.403Zn0.597, Al4Ni3, and CuMg2 phases were detected. No intermetallic compounds between aluminum (Al) and iron (Fe) were determined in this fracture area, which is most likely because the fracture did not occur from the joint interface.

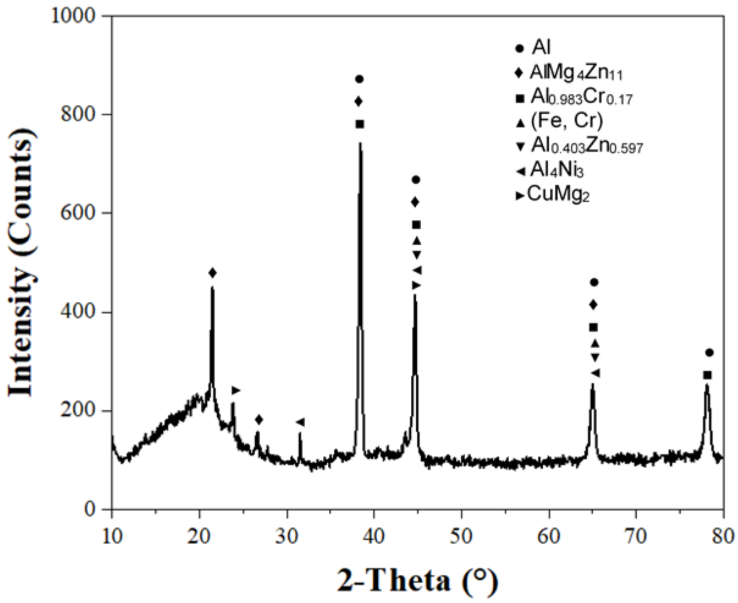

Figure 12. XRD analysis for the fracture surface on the 7075-T651 Al alloy side of the lap joint formed at 388 tool rotation speed

5. CONCLUSION AND RECOMMENDATIONS

Lap joining of 7075-T651 Al sheets with 2mm thickness to AISI 304 stainless steel sheets with 1.5 mm thickness was achieved via the friction stir lap welding (FSLW) method. Lap joints were made by utilizing various welding tool rotational speeds (388, 535, 720, and 980 rpm) and keeping other welding parameters constant. The following outcomes were attained.

- Increasing tool rotation speed increased the size of the hook on the advancing sides of the joint.
- Tool rotation speed played a crucial role in the joint mechanical properties, for instance, tensile shear strength. The joint made at 388 rpm performed a tensile shear load of 9442 N, while the joint manufactured at 980 rpm exhibited a tensile shear load of 4176 N. When the rotation speed was increased from 388 rpm to 980 rpm, the joint strength decreased by more than half. This is because the hook formed on the advancing side became bigger and caused the fracture.
- All the joints fractured from the top 7075-T651 Al sheet and in the tensile mode from the advancing side. At low rotation speeds of 388 and 535 rpm, the rupture occurred nearly vertically from the HAZ of the joints away from the joining interface. However, at high rotation speeds of 720 and 980 rpm, the rupture took place next to the hook on the advancing side with an angle lower than 90 degrees because of the larger size of the hook. There were no failures from the interfaces of joints, in other words, from the joint zones during the tensile shear test, which means that the interfaces of joints are highly strong.
- When the fracture region of the joint produced at 388 rpm was examined, no intermetallic compounds were detected between aluminum and iron. However, higher hardness values were found at the joining interface compared to the 7075-T651 and AISI 304 base metals, this could be because of the formation of intermetallic compounds at the joint interface.
- The higher hardness values were determined at the stir zone of the joint made at a higher rotation speed due to the higher concentration of AISI 304 fragments formed. The highest hardness values were determined at the interfaces of joints because of the formation of intermetallic compounds (Al13Fe4, Al3Fe2, and Al3Fe).

CONFLICT OF INTEREST

The authors have no conflicts of interest to be disclosed.

FINANCIAL DISCLOSURE

The authors declare that this study has received no financial support.

DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in this study do not require an ethical committee.

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