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Investigation of the Impact of Tool Pin Geometry and Feed Rate Speed in Friction Stir Lap Welding of 7075 and 5182 Aluminum Alloys

Ömer EKİNCİ[1*]

[1] Sivas University of Science and Technology, Faculty of Aviation and Space Sciences, Department of Astronautical Engineering, Sivas, Türkiye
Ömer Ekinci ORCID No: 0000-0002-0179-6456

Corresponding author: omerekinci@sivas.edu.tr

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Keywords
Friction stir lap welding, Aluminum alloys, Tool pin geometry, Macro and microstructure, Tensile load capacity, Fracture

Abstract: 7075 and 5182 aluminum alloys are critical for aerospace and automotive applications receptively. Joining these alloys can enable more economical and efficient structures. Therefore, the weldability of these materials by friction stir lap welding (FSLW) is of great importance. In this study, the effect of tool tip geometry (conical and cylindrical screw) and welding speed (22, 37 and 51 mm min^{-1}) on the weld microstructure and mechanical properties were studied in joining 7075 and 5182 aluminum alloys with FSLW. Strong welds were acquired with both tools. However, stronger ones were made employing the conical pin tool thanks to having deeper weld penetration and denser microstructure (microstructure with smaller grains). While the resistance of the weld to the tensile load was increased with increasing feed rate for the conical pin tool because the weld area width and vertical downward penetration increased, the opposite occurred for the cylindrical screw pin tool. By the conical pin, the greatest tensile load of 13033 N in the weld made at 51mm min^{-1}, whereas by the cylindrical screw pin, the biggest 12162.5 N was achieved in the weld made at 22 mm min^{-1}. It was an indication of a stronger weld formation for both tools when the lines formed through tool shoulder on top surface of upper sheet were broken into small particles and disappeared. Proper tool feed rate value can show considerable variability depending on tool pin geometry.

7075 ve 5182 Alüminyum Alaşımlarının Sürtünme Karıştırma Bindirme Kaynağında Takım Pimi Geometrisi ve İlerleme Hızının Etkisinin Araştırılması

Anahtar Kelimeler
Sürtünme karıştırma bindirme kaynağı, Alüminyum alaşımları, Takım pimi geometrisi, Makro ve mikroyapı, Çekme yükü kapasitesi, Kırılma

Öz: 7075 ve 5182 alüminyum alaşımları sırasıyla havacılık ve otomotiv uygulamaları için çok önemlidir. Bu alaşımların birleştirilmesi daha ekonomik ve verimli yapılara olanak sağlayabilir. Bu nedenle, bu malzemelerin sürtünme karıştırma bindirme kaynağı (SKBK) ile kaynak edilebilirliği büyük önem arz etmektedir. Bu çalışmada, 7075 ve 5182 alüminyum alaşımların SKBK ile birleştirilmesinde takım uç geometrisinin (konik ve silindirik vidalı) ve kaynak hızının (22, 37 ve 51 mm dak^{-1}) kaynak mikroyapısı ve mekanik özellikleri üzerindeki etkisinin araştırılması temelinde çalışılmıştır. Her iki takımla da güçlü kaynaklar elde edildi. Ancak konik uçlu takım kullanılarak yapılan kaynaklar daha derin nüfuziyete ve daha yoğun bir mikro (daha küçük tanelere sahip mikro yapı) yapıya sahip olması nedeniyle daha güçlü çıkmıştır. Konik uçlu takım ile ilerleme hızının artmasıyla, kaynak alanı genişliği ve dikey aşağıya doğru nüfuziyet arttığı için kaynak mukavemeti artarken, silindirik vidalı uç ile bunun tersi meydana geldi. Konik pim ile 51mm dak^{-1}'de yapılan kaynakta en büyük çekme yükü 13033 N, silindirik vida pimi ile ise 22 mm dak^{-1}'de yapılan kaynakta en büyük 12162,5 N çekme yükü elde edilmiştir. Üst levhanın üst yüzeyinde takım omuzundan dolayı oluşan çizgilerin küçük parçacıklara ayrılarak kaybolması her iki takım için de daha güçlü bir kaynak oluşumunun göstergesi olmuştur. Uygun takım ilerleme hızı değeri, takım uç geometrisine bağlı olarak önemli ölçüde değişkenlik gösterebilir.

1. INTRODUCTION

Aluminum (Al) alloys play a crucial role in aircraft and automotive applications thanks to their superior strength-to-weight ratio and good machinability. There are series of Al alloys having different chemical compositions have been developed for using in different applications. 7075 Al alloy is characterized by its high strength and generally used as structural material in aircraft fuselage panels [1]. 5182 Al alloy is characterized by its high Mg content and has outstanding formability and deep stretch forming and commonly utilized as structural material in automobile bodied [2]. Reliably joining dissimilar Al alloys can provide more flexible designs. But, traditional fusion welding techniques are not suitable for combining different Al alloys because porosity, hot cracks, brittle secondary phases, and residual stress often emerge [3] that degrade the mechanical properties of the joint. Additionally, welding Al alloys are hard by fusion welding methods since they have a strong oxide layer on their surface and high thermal conductivity [4]. Solid-state welding techniques have been shown for combining dissimilar metals. AISI 1010 low carbon steel and copper alloy were joined without intermetallic phases at the weld region by friction welding, a solid-state welding technique [5]. Friction stir welding (FSW), one of these methods, has demonstrated to be appropriate and effective in the welding different Al alloys [6]. As the maximum temperature in FSW process is below the melting point of the metals being joined and thus melting connected issues such as gas porosity, solidification cracking do not occur [7,8]. Moreover, FSW does not necessitate the use of mechanical joining elements like rivets, fasteners, which results in fabricating lighter bodies and faster manufacturing periods [8]. Furthermore, FSW is seen as one of the greatest alternative welding methods because it costs low, consumes low energy, provides strong joints, reduces weight of structures, is environmentally friendly, and requires less human ability [9]. Tool profile, rotation speed and feed rate speed are the main parameters of the FSW process [7,8,10]. Tool geometry can be regarded as having the greatest impact on heat generation and material mixing. Combination of tool shoulder diameter and profile, and pin diameter, length, and profile are all crucial factors in determining other welding variables such as tool rotational and feed rate and also the resulting weld quality [11]. Çevik et al. [12] investigated the FSW of 7075-T651 Al alloys using different tool rotation speeds (900, 1250 and 1600 rpm) and stated that the weld with the best mechanical properties was produced at the rotation speed of 900 rpm. 6061 T6 Al alloy sheet couples were welded with the FSW method using tools with different pin profiles, and it was stated that the pin shape significantly affects the weld microstructure and mechanical properties [13]. Cakan et al. [14] investigated the effects of tool rotation speed (660 and 920 rpm) and feed rate speed (18, 32 and 54 mm min-1) parameters on the weld quality in the FSLW of different pure copper and AA7075-T6 Al alloy materials. It was found that the rotation speed of 660 rpm and feed rate of 32 mm min-1 was the best. Lap joints are often employed, for example, in joining stringer and skin in aircraft fuselages, and for assembling components in railway tankers, goods wagons and ship decks [15,10]. Buffa et al. [10] studied on FSLW of 2198-T4 Al alloy by using three different welding tools with cylindrical, conical and cylindrical-conical pin and they determined that welds with better mechanical properties were produced by cylindrical-conical pin tool. They also stated that increasing the welding speed (50-1000 mm min-1) or decreasing the rotation speed (500-2000 rpm) improved the weld strength. Lee et al. [16] researched FSLW of 5052 Al and 6061 Al alloys using tool rotation speeds of 1250, 2500 and 3600 rpm at a constant speed of 267 mm min-1 and using welding speeds of 127, 267 and 507 mm min-1 at a fixed 1600 rpm. They claimed that increasing rotation speed decreased weld strength while increasing welding speed improved weld strength. Reducing weight and fuel consumption and increasing efficiency, and performance for land and aircraft vehicles can be achieved by combining dissimilar Al alloys in the production. According to the literature research I have done, there is a need for more studies on the understanding effect of tool pin profile along with the tool feed rate on weld quality in the FSLW of different types of aluminum alloys. Therefore, the weldability of 7075-T651 Al alloy to 5182 Al alloy was experimentally investigated by the FSLW method using two tools having different pin shapes and various welding speeds.

2. MATERIAL AND METHOD

On a Falco FMH-4 brand universal milling machine, a 2 mm thick 7075-T651 Al alloy sheet was put on a 5 mm thick 5182 Al alloy plate and then tightly fastened. Then, they were welded by friction stir lap welding (FSLW). FSLW experiments were carried out by conical pin tool and cylindrical screw pin tool at tool feed rates of 22, 37 and 51 mm min-1 and at a constant tool tilt angle of 2 degrees clockwise and tool rotational speed of 980 revolutions per minute (rpm). Chemical composition and mechanical features of the alloys are given in Table 1 and 2, respectively. FSLW experiment variables and configuration with dimensions are given in Table 3 and Figure 1, respectively. FSLW experiment and welding tools are shown in Figure 2. Tools were manufactured from a bar made of H13 hot work tool steel material. Conical pin tool has a conical pin with a length of 3 mm, tip diameter of 3 mm and root diameter of 5 mm and a shoulder with a diameter of 16 mm while cylindrical screw pin tool has a cylindrical screw pin right hand thread pitch 0.8 mm with a length of 3 mm and a diameter of 5 mm and a shoulder with a diameter of 16 mm. The produced FSLWed samples were presented in Figure 3. After the welds were produced, they were cut on KMYDG 280 brand semi-automatic rotary belly band saw machine to acquire tensile test and macro and microstructure samples. Tensile test samples with 25 mm width based on AWS D17.3M:200X standard [17] were given in Figure 4. Cross-sectional areas of welds were ground by sandpaper up to 1500 grit and then etched by Keller's reagent (1 ml HF, 1.5 ml HCl, 2.5 ml HNO3, and 95 ml H2O) for 10 s to examine macro and microstructures in the welds. The etched cross-sections of the welds were presented in Figure 6. Macro and microstructures of the welds were examined on an AOB brand inverse metal optical microscope. The hardness of the welds was attained from their cross-sections by an AOB model micro Vickers hardness tester and utilizing a 200 g load and 10 seconds dwell time. Tensile strength of the welds were obtained on SHIMADZU model 250 kN universal tensile tester by utilizing 2 mm min-1 constant cross-head speed at room temperature. Fracture surfaces of the joints were observed on JEOL JSM6510 model scanning electron microscope (SEM). X-ray Diffraction (XRD) analysis was conducted on the Rigaku MiniFlex machine using X-Ray generator (40 kV, 15 mA) and Scan speed/Duration time (4.00 °/min).

Table 1. Chemical composition of Al alloys (wt. %)

Material	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
7075-T651	0.4	0.5	1.2-2	0.3	2.1-2.9	0.18-0.28	5.1-6.1	0.2	Balance
5182	0.2	0.35	0.15	0.2-0.5	4-5	0.1	0.25	0.1	Balance

Table 2. Mechanical properties of Al alloys

Material	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)
7075-T651	470	550	10
5182	140	300	25

Table 3. FSLW experiments with variables

Sample	Welding tool with	Tool tilt angle clockwise (degree)	Tool rotation speed (rpm)	Tool plunge depth (mm)	Tool feed rate (mm min^{-1})
S1	Conical pin	2	980	3.6	22
S2		2	980	3.6	37
S3		2	980	3.6	51
S4	Cylindrical screw pin	2	980	3.6	22
S5		2	980	3.6	37
S6		2	980	3.6	51

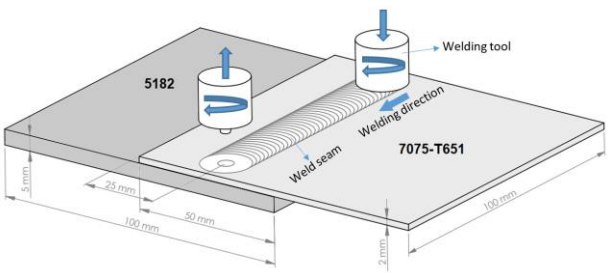

Figure 1. FSLW configuration with dimensions

Figure 2. FSLW of alloys and the used welding tools

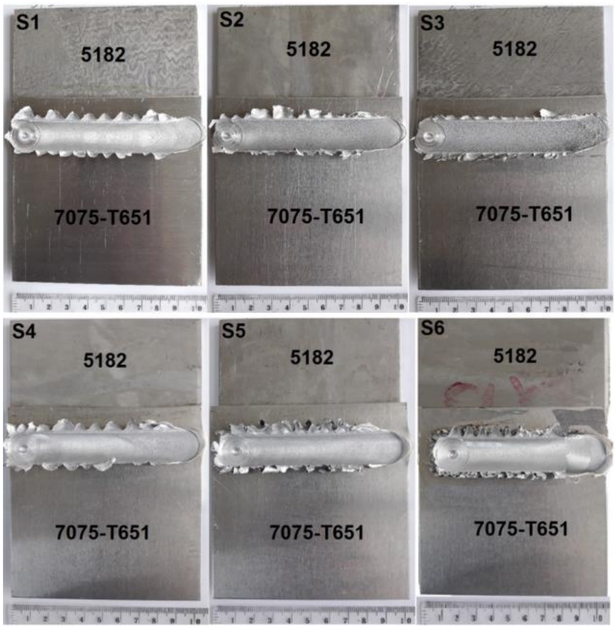

Figure 3. The FSLWed samples

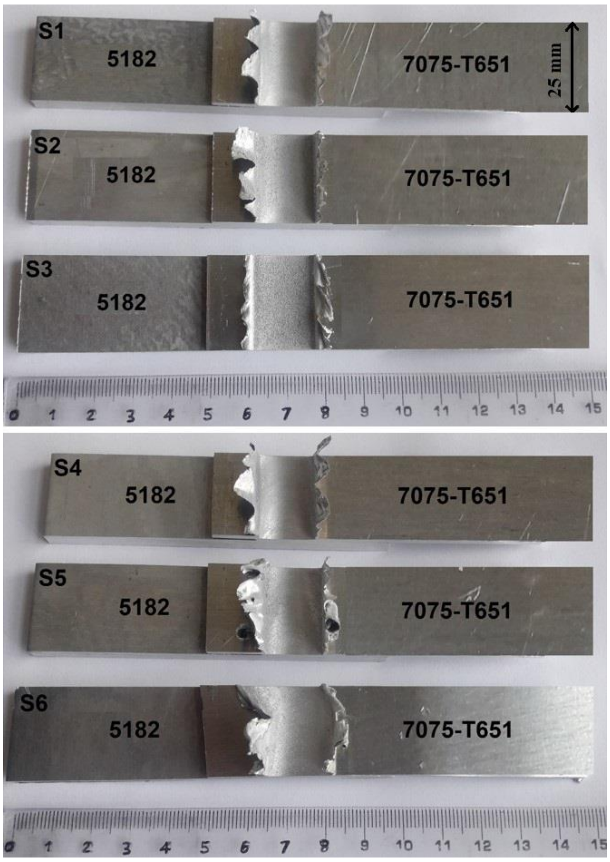

Figure 4. The tensile test samples cut from the FSLWed samples

3. RESULTS AND DISCUSSION

3.1. Macrostructural Analysis

Figure 5 illustrates the top surface appearance (weld beads) of FSLWed samples. The lines formed by the tool shoulder on the top surface of the upper sheet were broken into small particles and disappeared with the increasing tool feed rate (from weld S1 to S3) for the conical pin tool. On the other hand, the lines started to form more with increasing the welding speed (from S4 to S6) for the cylindrical screw pin tool. There are no lines formed by the tool shoulder on the top surface of weld S3, whereas slightly more than half of the top surface of weld S4 had lines formed by the tool shoulder. Figure 6 displays the macro views of the cross-sections of the FSLW joints. Figure 7 represents optical microscope images of the cross-sections. It can be seen in Figure 7 that the effective welded area width and vertical downward penetration gradually enhanced by enhancing the tool welding speed from weld S1 to S3 made through the conical pin tool. However, for the cylindrical screw pin tool, the effective welded area width and vertical downward penetration decreased when the tool feed rate was boosted from weld S4 to S6, and also voids appeared. While increasing the tool feed speed gave good results for the conical pin tool, it had negative results for the cylindrical screw pin tool. There are formations of voids observed under the weld S6 made at the highest tool feed rate for the cylindrical screw pin tool. At this highest feed rate, heat input may have been insufficient to adequately soften, plasticize and stir the material because a higher feed rate provides less heat input. The heat on the lower side of the screw pin is less than on the upper side due to the tool shoulder contacting the upper sheet generating heat. Thus, the screw cut the material rather than mixing and allowing it to flow, leaving voids behind at the bottom. According to [18], in the FSW, a cavity takes place behind the welding tool and then filled with plasticized material that moves from the pin's front to its back.

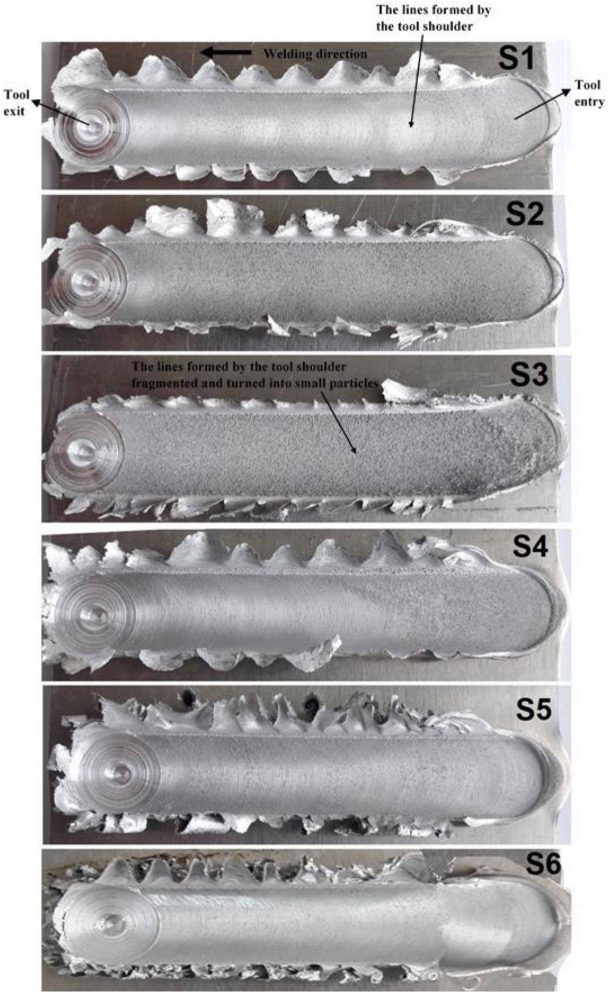

Figure 5. The top view of the FSLWed samples

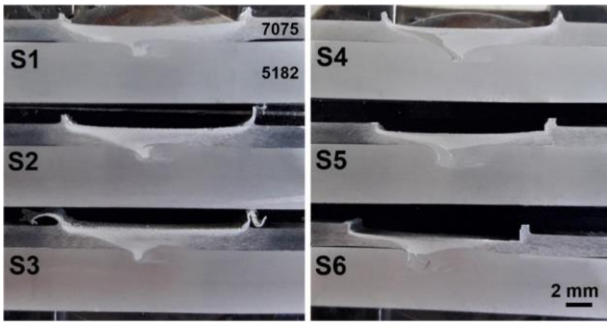

Figure 6. Cross-sections of the FSLWed samples

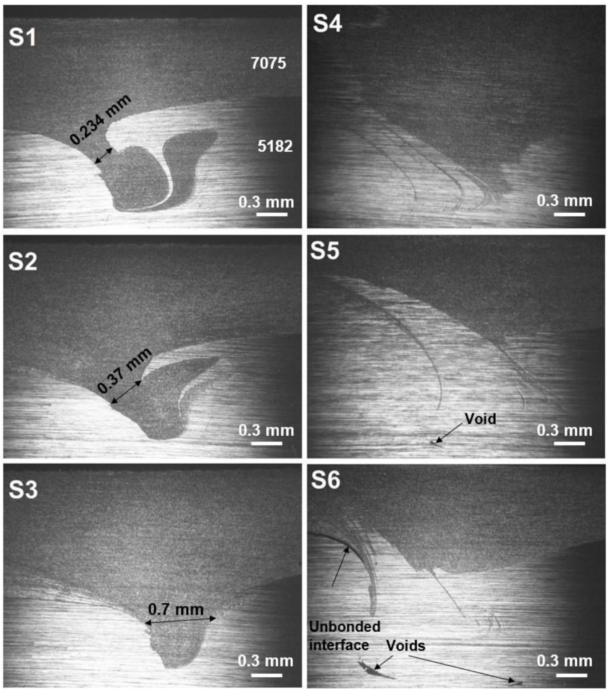

Figure 7. Optical microscope images of the cross-sections of the FSLWed samples

3.2. Microstructural Analysis

Microstructures of welds S3 and S4 are presented in Figure 8 as these are the strongest ones made employing the conical pin tool and cylindrical screw pin tool, respectively. Figure 8a, b and c show the microstructures of a, b and c regions on cross-section of the weld S3, respectively. a, b and c regions represent the welded area right at the interface of the sheets, the welded area just below the interface and thermo-mechanically affected zone (TMAZ) just next to the weld zone (stir zone), respectively. As can be seen that the microstructure of the region b contains the smallest grains and slightly smaller than the grains of the region a, however, region c has a mcirostructure with elongated and the largest grains. The width of region c (TMAZ) began to narrow from weld S1 to S3 with increasing welding speed for the conical pin tool since heat input decreased. On the other hand, Figure 8d and e indicate the microstructures of d and e regions on cross-section of weld S4, respectively. Region e consists of grains slightly smaller than that of region d. In general, the microstructures of the weld S3 had finer grains (denser) than that of weld S4. Hence, it can be said that the conical pin tool mixed the alloys better than the cylindrical screw pin tool. The fine-grained microstructure was formed because of intense plastic deformation and recrystallization. Similar observations were obtained in terms of grain size and orientation formed in the microstructures of the SZ and TMAZ during the FSLW of 7075 and 2024 Al alloys [19].

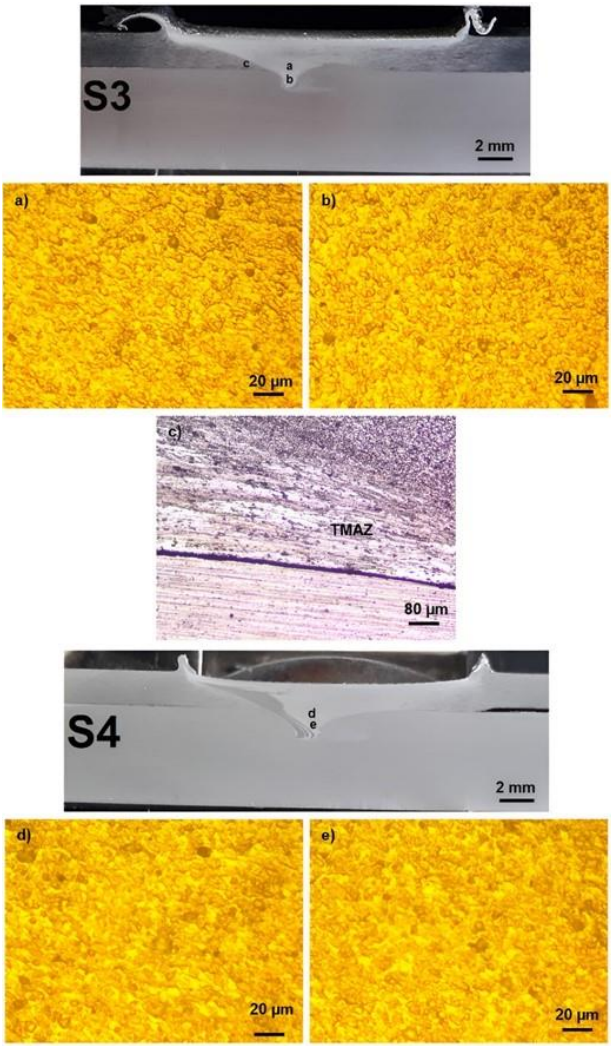

Figure 8. Microstructures of weld S3 and S4

XRD analysis of the welds S1 and S3 were presented in Figure 9. Al2Cu2Fe phases were determined in both welds. However, the Al2Cu2Fe phase formation was higher in the S1 weld probably because of more heat input since S1 was produced at a lower tool feed rate. According to Bayazid et al. [20], Al7Cu2Fe is a brittle material and can seriously impair mechanical characteristics, particularly ductility. Cu increases hardness [21].

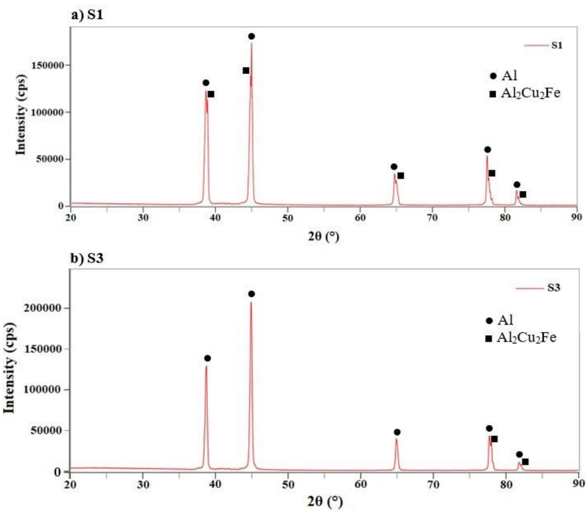

Figure 9. XRD analysis for the welds S1 and S3

3.3. Microhardness

The hardness values of the welds attained from the top 7075 sheets (just above the interface of sheets) and bottom 5182 sheets (just below the interface of the sheets) are presented in Figures 10a and b, respectively. The hardness of 7075 and 5182 metals ranged between 167 to 170, and 78 to 82 HV, respectively. It was found that there is a first decrease in the hardness and then an increase and reached a maximum in the weld center when moving on the upper sheet from 7075 base metal to the weld center, but lower than the hardness of the 7075 metal (Figure 10a). Moreover, the hardness of the weld S4 was lower than the weld S3. This is because S4 was produced at an approximately 2.3 times lower tool feed rate, which generates more heat input, resulting in the formation of bigger grains in the weld microstructure, as shown in Figure 8. On the other hand, when going from the 5182 base metal to the weld center, the hardness on the lower 5182 sheet first decreased slightly and then significantly increased and became the highest in the weld center above the hardness of the 5182 base metal (Figure 10b). The reason for the much higher hardness of the weld center than the 5182 base metal is because the 5182 material mixed with the harder 7075 material in the weld center. In general, the weld center just above the interface of the sheets had higher hardness than the weld center just below the interface of the sheets. This is because the 7075 material mixed more with the softer 5182 lower sheet material in the weld center at the bottom. In addition, while the lowest hardness values were acquired in the HAZ regions, the hardness of the TMAZ regions was slightly higher than the HAZ regions. The hardness in the weld, HAZ, and TMAZ areas appeared to be slightly lower when the weld was produced at a smaller tool feed rate. This is probably because heat input increased with a smaller tool feed rate resulting in grains growing. The weld region had higher hardness when compared to the HAZ and TMAZ regions due to most likely the smaller grains in its microstructure, as shown in Figure 8. The hardness in the weld areas where 7075 and 5182 metals were mixed became lower than that of the 7075 base metal and higher than that of the 5182 base metal. Similar results were observed in friction stir butt welding (FSBW) of 7075 and 5182 alloys, where the hardness first decreased and then increased from the base material to the weld zone [22]. Çetkin et al. [23] studied friction stir welding of 5182 alloys and they found that the hardness from the 5182 base metal to the TMAZ decreased, and later increased in the weld zone. Furthermore, it was observed that the welds made by the cylindrical screw pin tool possessed a slightly lower hardness value. This could be because this tool generated more heat input.

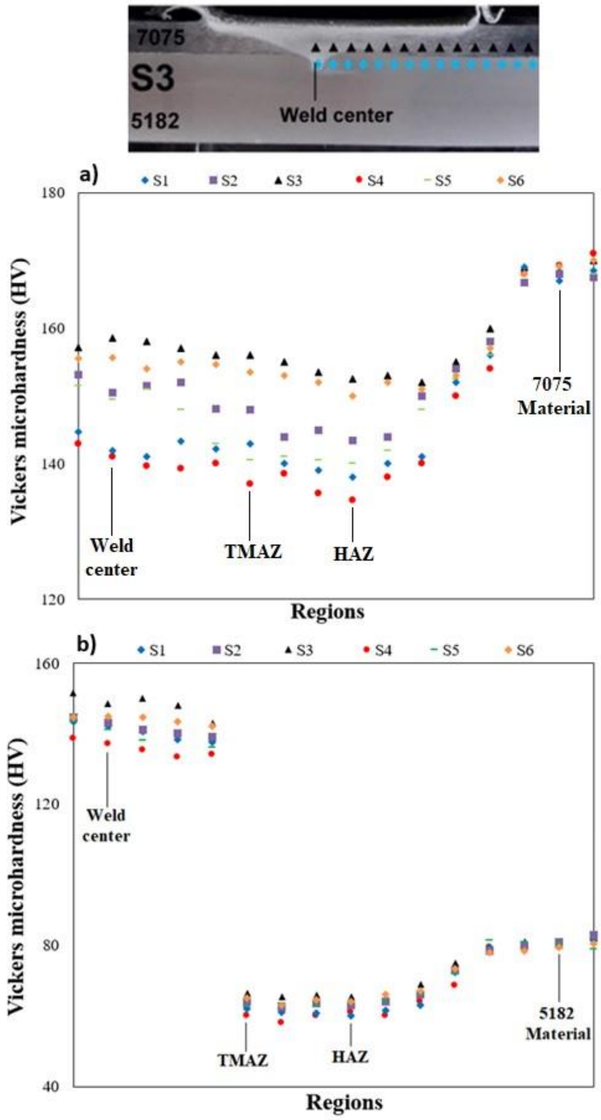

Figure 10. Hardness of the weld S3 and S4

3.4. Tensile Load Determination

Figure 11 demonstrates the tensile test results of the FSLW joints generated by the conical pin and cylindrical screw pin tools at 22, 37, and 51 mm min-1 feed rates. The tensile load of the joint fabricated through the conical pin tool gradually increased with increasing of the tool feed rate, whereas the opposite of this was seen for the cylindrical screw pin tool. Welding area width and vertical downward penetration increased with an increase in the conical pin tool feed rate as seen in Figure 7, and accordingly the weld strength increased. However, when increasing the cylindrical screw pin tool feed rate speed led to a decrease in the welded area width and penetration as well as voids formed as can be seen in Figure 7, and as a result of these, the weld strength reduced. The strongest weld S3 with a tensile load of 13033 N was fabricated via the conical pin tool at 51 mm min-1 while via the cylindrical screw pin, the strongest weld S4 with a tensile load of 12162.5 N was produced tool at 22 mm min-1. These welds performed better strength as they had larger welded areas and higher penetration. In general, stronger joints were created by the conical pin tool. Because higher vertical downward penetration with finer grain microstructure took place in the welds of the conical pin tool. Additionally, the concave shoulder of the conical pin tool might have assisted in more powerful weld production. Buffa et al. [10] investigated FSLW of 2198-T4 Al alloy utilizing three different welding tools with cylindrical, conical and cylindrical-conical pin. They reported that the cylindrical-conical pin tool produced stronger welds and also stated that increasing the welding speed improved the weld strength. Song et al. [19] studied the FSLW of 2024 and 7075 Al alloys and they found that the weld strength enhanced with an increase in the welding speed. Lee et al. [16] investigated the FSLW of different 5052 Al and 6061 Al alloys. They reported that higher welding speed improved the weld strength.

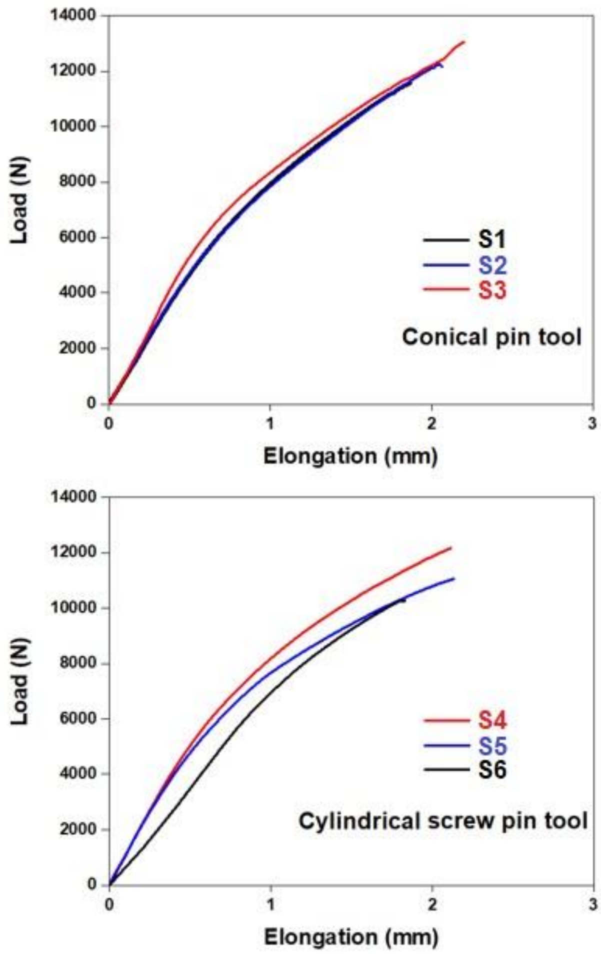

Figure 11. Tensile load-elongation curve of the FSLW welds

Cakan et al. [14] studied the FSLW of different pure copper and AA7075-T6 Al alloy materials using different tool feed rates (18, 32 and 54 mm min-1) and the best joint was created at 32 mm min-1. Xie et al. [24] studied the FSLW of dissimilar 304 austenitic stainless steel and Ti6Al4V alloy and they achieved a maximum tensile shear strength of 7507 N for the joint produced at the welding tool rotation speed of 600 rpm and with the feed rate of 30 mm min-1.Top surface appearance of the welds in Figure 5 is giving a clue about the weld strength. When the lines formed by the tool shoulder on the top surface of the upper sheet were broken into small pieces, higher weld strength occurred. When the conical pin tool feed rate increased from 22 to 51 mm min-1, the lines formed by the tool shoulder on the top surface of upper sheet started to break into small pieces. For example, there are no tool shoulder lines formed on the top surface of the upper sheet of weld S3, the lines were totally broken into small pieces and disappeared and thus weld S3 had the highest tensile strength. Additionally, the microstructures of the conical pin welds had finer grains as can be seen in Figure 8. On the other hand, when the cylindrical screw pin tool feed rate was increased, clearer and more tool shoulder lines began to form resulting in a decrease in the weld strength. The tensile strength of the welds was found by proportioning the tensile load to the cross-sectional area. The cross-sectional area is obtained by multiplying the effective weld thickness or sheet thickness by the weld width. The effective weld thickness of the welds failed from the weld region was found by measuring the distance from the interface of the sheets to the bottom of the weld as shown in Figure 12a. For the welds broken from the upper 7075-T651 sheet, the effective sheet thickness was measured from the broken area as shown in Figure 12b. Approximately tensile strengths and efficiency of the welds are shown in Table 4. As the upper 7075-T651 sheet is thinner and failure took place from this during the tensile test, the weld efficiency was calculated based on the upper sheet with a tensile strength of 550 MPa. When looking at the tensile strength and efficiency of the welds, it generally improved with increasing tool feed rate, and maximum efficiency of 81.08 and 87.09 % were achieved at 51 mm min-1 for the conical and cylindrical screw pin tools, respectively. 5182 alloy sheet has a tensile strength of 330 MPa. All the welds had a higher tensile strength than the 5182 alloy. Generally, better welds were acquired via the tool having a conical pin. Cetkin et al. [25] investigated friction stir welding of 7075 aluminum alloys by tools with conical and triangular pins. They reported that stronger welds were made by the tool with the conical pin.

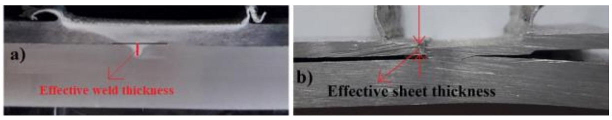

Figure 12. Representation of measuring effective weld and sheet thickness

Table 4. Tensile strength and efficiency

Weld sample	**Effective weld or sheet thickness (mm)**	**Width of weld sample (mm)**	**Failure load (N)**	**Tensile strength (MPa)**	**weld efficiency (%)**
S1	1.077	25	11564.45	429.506	78.09
S2	1.108	25	12242.19	441.956	80.35
S3	1.169	25	13033	445.953	81.08
S4	1.395	25	12162.50	348.745	63.40
S5	1.011	25	11057. 42	437.484	79.54
S6	0.857	25	10262.50	478.996	87.09

3.5. Fracture Area Examination

Photographs of the fractured welds during tensile testing are given in Figure 13. S1, S2, S3 and S6 welds failed from the weld area and exhibited tensile shear fracture while S3 and S4 failed from the heat-affected zone (HAZ) away from the weld area and showed tensile-type fracture. It can be seen when looking at the top of the 5182 bottom sheets of the welds made by the conical pin tool in Figure 13 that the S3 weld had a larger fractured weld area than the S1 and S2 welds. A bigger fractured weld area was observed with an increase in tool feed rate, also seen in Figure 7. Figure 14 shows the weld fracture surfaces of the strongest S3 and S4 welds produced by the conical and cylindrical screw pin tools, respectively. As can be seen, weld S3 has smaller and denser dimples than weld S4, which indicates a higher-quality weld. Weld S4 contains larger dimples. Song et al. [19] reported ductile fractures in tensile tests of FSLW welds of 2024 and 7075 Al alloys.

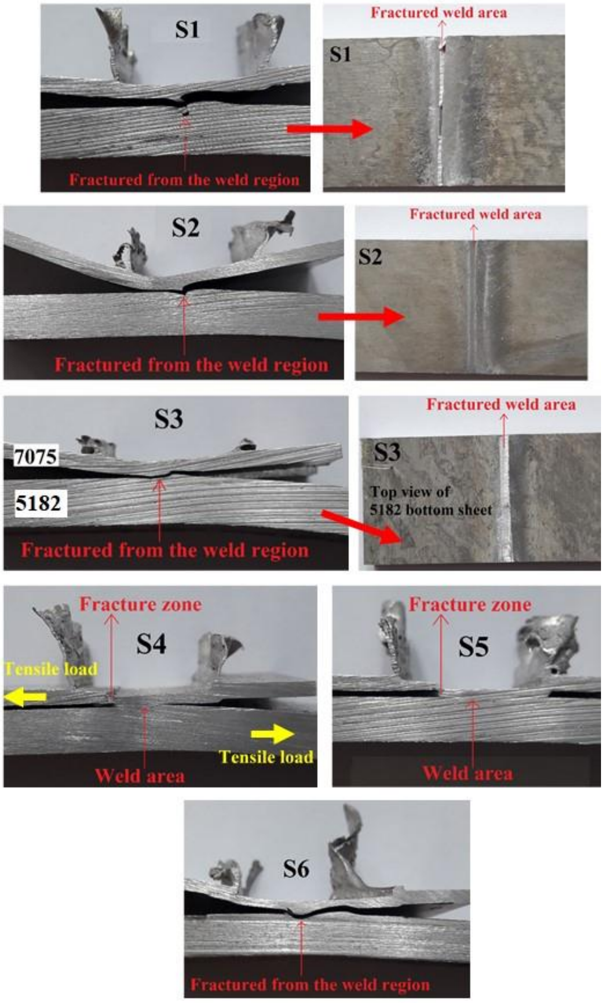

Figure 13. Photographs of the fractured welds during tensile testing

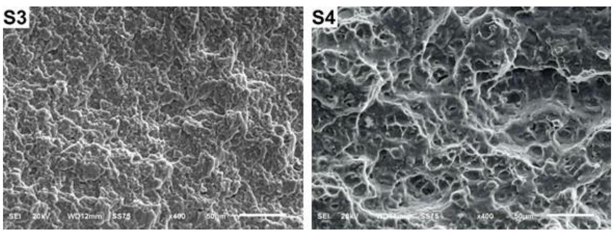

Figure 14. Fracture surface SEM images for weld S3 and S4 after tensile test

4. CONCLUSIONS

Strong FSLW welds between 7075-T651 and 5182 aluminum alloys were achieved. The results obtained are provided below.

1. The strongest weld with a tensile load of 13033 N was obtained at the welding speed of 51 mm min-1with the conical pin tool. By cylindrical screw pin tool, the weld having highest tensile load of 12162.5 N was obtained at 22 mm min-1 welding speed.
2. In FSLW welding with tapered pin tools, when the feed rate was increased from 22 to 51 mm min-1, the weld strength increased due to the increase in joint area and vertical downward penetration. However, exactly the opposite of this was observed for the cylindrical screw pin tool. While the strongest weld was obtained at the highest welding speed with the conical pin tool, the strongest weld was acquired at the lowest welding speed with the cylindrical screw pin tool.
3. Better welds were produced through the conical pin tool. Because the materials were stirred better via the conical pin tool and thus the joints with higher penetration, denser and harder microstructures were created. Additionally, smaller and denser dimples were seen in the weld fracture surface of the conical pin tool.
4. The more disappearance of the lines formed by the tool shoulder on the top surface of the upper sheet by breaking up into small particles meant the formation of a stronger weld.
5. All welded samples were ductile fractured, but the fracture areas of conical pin tool welds exhibited smaller and denser dimples. Both tool pin profile and feed rate showed to have a great impact on the weld quality.

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