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The Effect of Pin Shape and the Ratio of Tool Rotational Speed to Welding Speed on the Mechanical Properties

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Abstract: In the present study, the effect of two different pins which shaped in the triangular and straight helical threaded were associated with the ratio of the tool rotational speed to the welding speed on the mechanical properties of dissimilar friction stir welding (FSW) of EN AW 6082 and EN AW 5754. The responses of FSW process were investigated by the UTS, Ɛ% and hardness of weld joint. The results showed that the ratio of the tool rotational speed to the welding speeds have a dominant effect on the weld joint strength.

Keywords: Friction stir welding, Pin shape, Mechanical properties

Takım Dönme Hızının Kaynak Hızına Oranı ve Pim Şeklinin Mekanik Özellikler Üzerine Etkisi

Özet: Bu çalışmada EN AW 6082 ve EN AW 5754 malzemelerin birbiri ile FSW kaynağında helisel diş açılmış ve üçgen şekilli iki farklı pim ile takım dönme hızının kaynak hızına oranının mekanik özellikler üzerine etkisi incelenmiştir. FSW işleminin sonuçları kaynaklı bağlantının maksimum çekme mukavemeti, % şekil değiştirme ve sertliği ele alınarak incelenmiştir. Sonuçlar takım dönme hızının kaynak hızına oranının kaynaklı bağlantının mukavemeti üzerine çok önemli bir etkiye sahip olduğunu göstermiştir.

Anahtar Kelimeler: Sürtünme karıştırma kaynağı, Pim şekli, Mekanik özellikler.

1. Introduction

The use of aluminum alloys in the automotive, shipbuilding, aerospace, etc. industries is growing increase due to its inherent properties [1]. In these industries, the welding process is highly used in joining of sheets for body parts. Some of aluminum alloys are not joining by fusion welding because, it is well known that the fusion welding techniques take place at the melting temperature of the related metals and the welding condition should be arranged considering the parameters to achieve high strength joint. The main problems to reach high strength joint are the loss of elements, mismatch of filler material to the base material, defects like porosity, hot cracking, oxide et [2].

EN AW 6082 – T6 aluminum alloy is the highest strength of the 6XXX aluminum alloys and the major alloying elements are magnesium and silicon. It has higher corrosion resistance and is used generally as plate and sheet [3]. Although the EN AW 6082 has very good weldability, the strength of the weld joint decreases in the weld zone. EN AW 5754 aluminum alloy has also high corrosion resistance and high strength compared to the other 5XXX aluminum alloys [4]. The weldability of EN AW 5754 plates by fusion welding is good, but magnesium loss cause to reduce in the strength

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of the weld joint. For the dissimilar welding of these alloys by fusion welding, selection of appropriate filler material and heat is the most influential factors. The solid state welding techniques have overcome the mismatch problem and reduction in strength due to defects in the weld zone. The friction stir welding (FSW) process is one of the solid state welding techniques and takes place below the melting temperature. Due to carry out in the solid phase, some of welding defects occurring in fusion welding process cannot be observed. The heat for welding process is provided by a tool consisting of two parts which named as shoulder and pin. By the movement and the rotation of the tool, the welding process occurs. The tool pin is placed on a butted surface and also, helps to produce heat and forging force. The welding process is simple. Firstly, the tool shoulder is contacted on the plates and pin is rotated on the butted surface of plates, second is that the plasticized material by the effect of frictional heat produced by the tool shoulder and pin is transferred from the front of the pin to the trailing edge and finally the plasticized material is translated towards to the weld direction [5]. By the effect of tool rotation, the stirring action of pin cause to stir of materials at the butted surface and mix the material at the both sides of the pin. In the weld joint performed by FSW, three distinct zones named as nugget zone (NZ), thermo-mechanically affected zone (TMAZ), heat affected zone (HAZ) at two sides of the pin are occurring.

The literature review showed that there is limited study on dissimilar FS welding of EN AW 6XXX to EN AW 5XXX. Aval et al. [6] have studied on the effect of dissimilar FSW parameters for the weldability of EN AW 6061 to EN AW 5086 aluminum alloys. The tool with a conical probe with three grooves were associated with welding parameters (rotational and welding speeds) to investigate the effect of FSW tool on residual stress profile and also the produced microstructures and precipitation distribution have investigated. Peel et al.[7] have studied on the effect of tool rotational and welding speed on microstructure of welding zones and weld properties of dissimilar FSW EN AW 5083- EN AW 6082 joints. Palanivel et al. [8] have studied the influence of tool rotational speed and pin shape on microstructure and tensile properties of dissimilar FSW EN AW 5083-H111 and EN AW 6351-T6 aluminum alloys. The selected pin shapes are tool pin profiles of straight square (SS), straight hexagon (SH), straight octagon (SO), tapered square (TS), and tapered octagon (TO). Kasman [9] has investigated the effect of the shoulder diameter-to-pin diameter (D/d) ratio, TRS, and WS on the UTS and elongation (ε, in percent) on the tensile properties. Alvarez et al. [10] has carried out dissimilar FSW with right-hand threaded cylindrical pin shape on EN AW 6082-T6 and EN AW 5754-H111 aluminum sheets.

The open access literature reviews showed that the dissimilar FSW of AA6082 to AA5754 aluminum alloys by triangular shaped pin and at the different ratio of the tool rotation speed to the welding speed (υ) have not studied before. Therefore, this study contributes with a different attribute by using pin shapes and different υ ratios to the related fields. In the present study, the aim is to determine the effect of tool pin shape and the ratio of the tool rotational speed to the welding speed on the ultimate tensile strength (UTS), percentage of elongation (Ɛ%) and changing of hardness in the weld zone. Also, macrostructural and microstructural investigations were done.

2. Experimental

The FSW experiments were performed on the EN AW 6082 and EN AW 5754 aluminum alloys. The chemical composition and mechanical properties were listed in Tab. 1 and Tab. 2, respectively. The welding plates were cut in the size of 100 mm in width, 200 mm in length and 5 mm in thickness. Before welding experiments, the butted surfaces of plates were cleaned from dust and any residue.

Table 1. The chemical composition of aluminum alloys used in the present study (wt. %)

Alloy / Elements	Cu	Si	Mg	Mn	Zn	Ti	Cr	Fe	Al
EN AW 6082	0.23	0.98	1.02	0.6	0.21	0.01	0.03	0.6	Bal.
EN AW 5754	0.04	0.11	2.96	0.27	0.02	0.007	0.03	0.29	Bal.

FSW parameters which are welding speed (WS), tool rotation speed (TRS), pin shape and process conditions were given in Tab. 3. Two different tools, three tool rotational speeds and a welding speed were used FSW experiments. The FSW parameters were associated with two different pin shape and totally, six experiments as shown in Tab. 4 were performed. The dissimilar FSW were performed with a universal milling machine. For the welding experiments, a backing plate was used to place and clamp the plates. A schematic FSW experiment and components are shown in Figure 1. The welding direction was set as the parallel to the rolling direction of plates and the tool was tilted at the 2º to the normal direction of the plates. A sample figure for FSW experiments is given in Figure 1.

Table 2. Mechanical properties of aluminum alloys

Alloy	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)	Hardness ($HV_{0.1}$)
EN AW 6082 – T6	293.21	251.89	8.12	98
EN AW 5754 – H111	211.5	122.1	26.5	61

A joint fabricated by the FSW process was characterized with the ultimate tensile strength (UTS) and percentage of elongation (Ɛ, %). The tensile test specimens were prepared according to the ASTM E8M-04 specification and tests were performed at room temperature at a cross-head speed of 2 mm min-1 on a 500 kN universal testing machine. The results were listed in the Tab. 4. The variations in hardness were investigated and measurements were performed on the cross-section of joint. A load of 100 gr. was applied 10 s for the performing of tests.

Table 3. FSW process parameters and their levels

Parameters (unit)	Symbol	Levels		
Tool Rotational Speed (rpm)	*TRS*	400	630	800
Welding Speed (mm min^{-1})	*WS*	40		
Tool Rotational Speed -to- Welding Speed	υ	10	15.75	20
Pin shape	*PS*	T	SC	-
Fixed parameters				
Tool shoulder diameter (mm)	D	20		
Tool tilt angle (°)	α	2		
Dwell time (s)	t	20s		

Table 4. FSW experimental layout with responses (UTS, Ɛ%)

<table>
<tr><th rowspan="2">Exp. No</th><th colspan="4">Process parameters</th><th colspan="2">Welding responses</th></tr>
<tr><th>PS</th><th>TRS</th><th>WS</th><th>υ</th><th>UTS (MPa)</th><th>Ɛ (%)</th></tr>
<tr><td>1</td><td>T</td><td>400</td><td rowspan="6">40</td><td>10</td><td>188.26</td><td>8.16</td></tr>
<tr><td>2</td><td>T</td><td>630</td><td>15.75</td><td>184.85</td><td>7.31</td></tr>
<tr><td>3</td><td>T</td><td>800</td><td>20</td><td>184.08</td><td>7.36</td></tr>
<tr><td>4</td><td>CS</td><td>400</td><td>10</td><td>182.66</td><td>7.84</td></tr>
<tr><td>5</td><td>CS</td><td>630</td><td>15.75</td><td>185.64</td><td>7.69</td></tr>
<tr><td>6</td><td>CS</td><td>800</td><td>20</td><td>186.9</td><td>7.62</td></tr>
</table>

3. Results and Discussion

The present study was performed to determine the effect of the ratio of the tool rotational speed to the welding speed on the microstructural alterations, tensile properties and hardness.

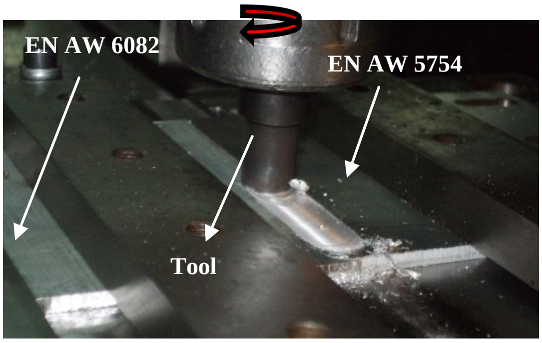

Figure 1. A sample FSW experiment and components.

3.1. Microstructural and Macrostructural analysis

The transverse cross section of the weld joints was shown in Figure 2. As seen in the macrographs, the effect of the tool pin shape can be clearly detected. For two type pins, the impact of υ ratio on the shape of the nugget zone can be distinguished by the effect of different etching behaviors. The structures were formed according to the flow behavior of materials and associated with the pin shape. The onion ring can be detected as vaguely. When compared the acceleration of material flow, it is showed that the υ ratio of 15 cause to decrease in the flow of material for triangular shaped pin. This is detected from the volume of material on the retracting side of the pin tip. A distinctive feature in the NZ of the FSW joints performed by the triangular shaped pin was detected and compared with the straight helical threaded pin. This feature is that the dark region like a teeth of comb at the retracting side and close to the bottom of NZ. Also, vaguely onion rings were observed under the dark region. The distance between the rings decreases with decreasing the υ ratio. As for the weld joint performed by the straight helical threaded pin, the distinct onion rings were observed at the υ ratio of 10. Also, the width of NZ was increased with the increase of the υ ratio. A weld joint consisting from the onion rings is shown in Figure 3.

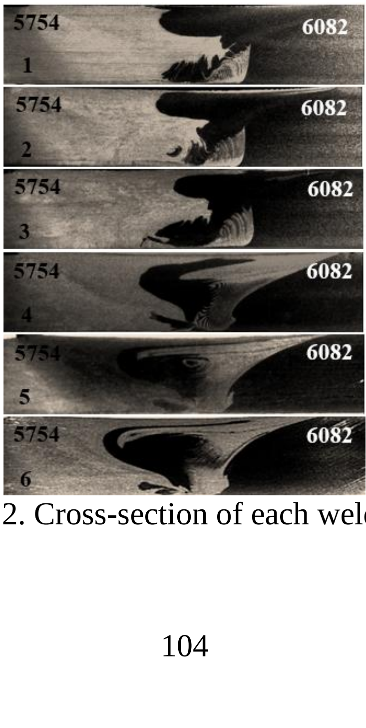

Figure 2. Cross-section of each weld joints

The microstructural examinations were done in the higher magnified cross section of the weld joint. The small cavity and tunnel type defects in the weld area was detected by the investigations. A sample defect is shown in Figure 3. The selected micrograph was taken from the Exp. 5. A tunnel and cavity like defects was shown in a dashed circle. All the joints contain small defects.

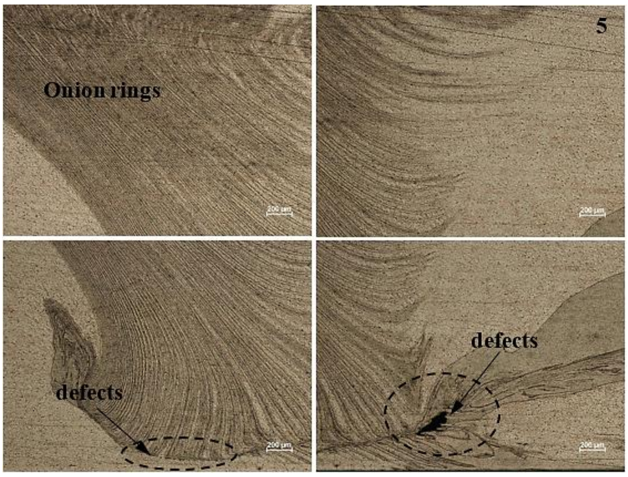

Figure 3. Samples for defective weld joints (Exp. 5) and the onion rings at the nugget zone.

3.2. Tensile Test

The tensile test results (UTS and Ɛ) were depicted as shown in Figure 4 and Figure 5, respectively. A remarkable result for welding performed by the triangular shaped pin was found, that is the variation in UTS values between the υ ratios of 15 and 20 is not significant. While the UTS value for the ratio of 15 is 184.85 MPa, the UTS value for the υ ratio of 20 is 184.08 MPa. Also, a same result was observed for Ɛ values, and the difference between two Ɛ values are merely 0.05. The highest UTS and Ɛ values is 188.26 MPa and 8.16%, respectively, which was obtained at the υ ratio of 10 for the joints performed with the triangular shaped pin. As for the straight helical threaded pin, while the UTS value is increased with the increase in υ ratio, the Ɛ value decreases with increase in υ ratio. The reason of increase in the UTS is the higher heat input that occurs by the effect of higher TRS. As known that an increase in TRS causes an increase in heat input and the reason is increase in the frictional heat. According to the tensile tests, the highest UTS value was obtained from joint fabricated at the υ ratio of 20 and the UTS value is 186.9 MPa. The highest Ɛ value which obtained at the υ ratio of 10 is 7.84%. This inverse effect was caused a change in the Ɛ value and this is 0.22 and correspond to as a percentage is merely 2.8%. It clearly appears that any change in the υ ratio is not caused major change in both the UTS and the Ɛ values.

3.3. Hardness

Microhardness distributions on the transverse cross-section of each welding experiment are shown in Figure 5. The hardness of EN AW 6082 and EN AW 5754 is 98 HV and 61 HV, respectively. As clearly seen in Figure 5, the side of EN AW 5754 has lower hardness compared to the side of EN AW 6082 because of the initial hardness value. For the side of EN AW 5754, the hardness of both TMAZ and NZ is slightly higher than base metal hardness. As for changing in hardness of EN AW 6082, the hardness distribution shows almost similar trend when compared with the hardness of EN AW 5754. On both sides, the hardness of HAZ is lower than those of other zones. The decreasing in hardness is attributed to the coarsening of precipitates due to thermal gradient [12]. As a general trend, hardness value of weld zones fabricated by the straight helical threaded pin is higher than the other welds fabricated by the triangular pin. The results illustrated in Figure 6 show that the variation of hardness in each zone is not constant.

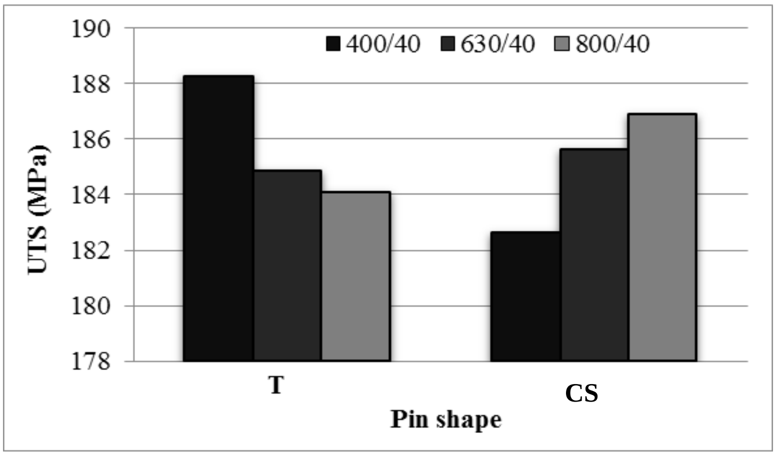

Figure 4. Tensile test results for ultimate tensile strength (UTS).

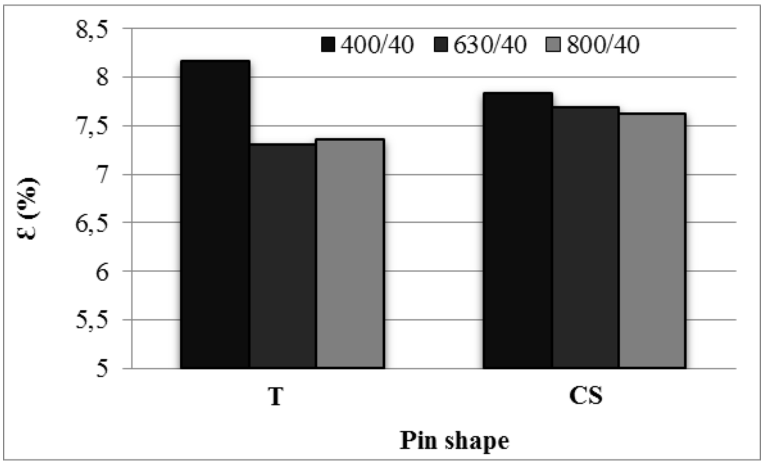

Figure 5. Tensile test results for percentage of elongation (Ɛ).

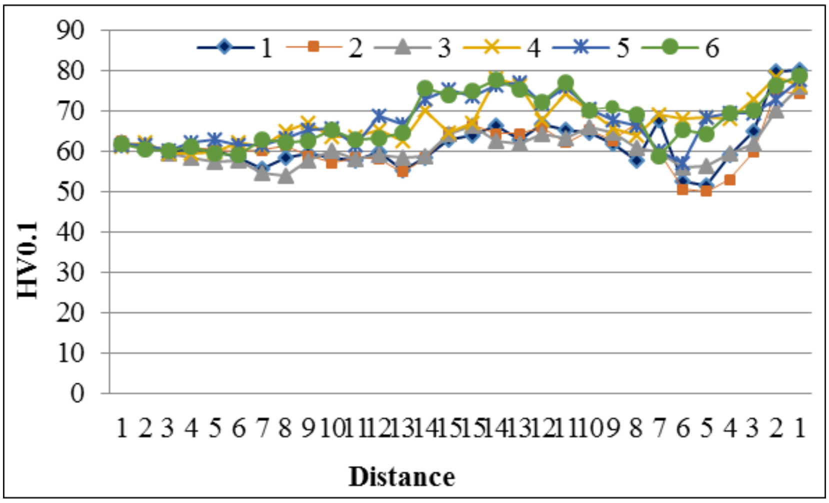

Figure 6. Hardness distribution as a function distance.

4. Conclusion

The present study contains experimental studies about the effect of the ratio of the tool rotation speed to the welding speed (υ ratio) on the tensile properties, hardness and microstructure in the dissimilar friction stir welding of EN AW 6082 to EN AW 5754 aluminum alloys. Two different pin shape associated with the υ ratio. With the help of a series of tests and investigations, the following conclusions were drawn.

- The pin shape has a significant effect on the tensile properties and hardness value.
- The highest tensile strength was obtained from the weld joint fabricated by a triangular shaped pin and the strength value is 188.26 MPa. At this condition, the measured Ɛ% value is the highest one of the all welding and the Ɛ value is 8.16.
- The UTS efficiency of each weld joint was investigated. It was found that the UTS efficiency for EN AW 6082 is changed between 63-64% and for EN AW 5754 is 86-89%. For dissimilar welding, the efficiency is located in an acceptable range.
- The minimum hardness was observed in the HAZ for both sides and it shows an increase towards the NZ.
- The nugget zone profile was also affected by the pin shape. The nugget zone profile of welds fabricated by the straight helical threaded pin have onion rings and the rings can be clearly distinguished. In the welds fabricated by the triangular shaped pin, the onion rings were detected vaguely.
- The overall results of the present study revealed that the FSW process is the best alternative for dissimilar welding of EN AW 6082 to EN AW 5754 by selecting correct parameters and their values.

5. Acknowledgement

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