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Effect of Friction Stir Welding on Mechanical properties of Zn-22Al Superplastic Alloy

[1] Hamed Mofidi Tabatabaei, [2] Tadashi Nishihara
[1] Graduate School of Engineering, Kokushikan University
[2] Department of Mechanical Engineering, Kokushikan University

Abstract: -- **Present study discusses the trials of friction stir welding (FSW) on Zn-22Al superplastic alloy. The effect of different process parameters of FSW tool on mechanical behavior of the welded zone has been discussed. The results are discussed in terms of mechanical properties and microstructure observations. A new developed FSW tool which was investigated in our laboratory was used in the experiments to investigate the structural changes of microstructures of the material as well. Results revealed a fine grain structure after FSW within the stir zone.**

Index Terms— Friction stir welding, Mechanical properties, Superplastic alloy, Zn-22Al.

I. INTRODUCTION

Friction stir welding (FSW) is a solid-state joining process using friction heat. This method was developed at TWI in Cambridge, England and patented in 1991 [1]. Because FSW is particularly appropriate for aluminum alloys, which tend to be problematic for standard welding, initial research efforts concentrated on these alloys. Copper alloys and magnesium alloys were also examined and possible applications to titanium alloys, stainless steels, and metal matrix composites (MMCs) are currently being explored [2]-[7]. However, only a few studies of FSW on superplastic alloys have been conducted [8]. The Superplastic alloys have gathered interest in many different fields of studies. Weight saving is the most important requirement in the area of aircraft industry, There is a need for devices fabricated by superplastic forming in medical and biomaterial fields, like dentistry. For many reasons like problems with casting with titanium [9] fabrication by superplastic forming has been attracting interests [10], [11]. However, very little information is available regarding friction stir welding of superplastic alloys.

Zn–22Al is a well-known superplastic material that has been widely used in different fields of studies. Zn–22Al can be obtained as sheet for thermal forming and is often useful in low-volume applications where tooling costs must be kept low. It is also used for electronic enclosures, cabinets and panels, business machine parts, and medical and other laboratory instruments and tools. [12] Studies of controlling and improving the mechanical properties of this alloy have been conducted in our laboratory. It has been reported in a previous study that the tensile strength increases after FSP. Additionally, in friction stir-processed Zn–22Al, a high strain rate sensitivity exponent m of 0.59 was observed on the high strain rate side at 250 °C, and the possibility of grain refinement by FSP has been indicated. [13] Microstructural changes in superplastic Zn–22Al alloy caused by FSP were also investigated in another study [14] In particular, the change in the average grain size was experimentally determined and grain refinement of the Zn–22Al alloy by FSP was proved to be possible. Nishihara has reported initial results for the FSW of superplastic Zn–22Al eutectoid alloy, which demonstrated that FSW produces a fine grain structure within the joint part. [8] In the present study, trials of FSW on Zn-22Al superplastic alloy are carried out in different process parameters of FSW tool.

II. EXPERIMENTAL PROCEDURE

Fig.1 (a) shows the experimental setup. A vertical milling machine was set up to perform FSW trials. Different parts of the FSW system are shown in Fig. 1 (a). The Shoulder part of the FSF tool with a diameter of 15mm and an angel of -5° is made of Inconel 625 because of its heat resistance, while a high-speed steel forming tap (M6×1) with a height of 1.5mm is used as the probe part of the tool to improve the stirring performance. This particular tool which is shown in Fig.1 (b) was first developed in Kokushikan University. [13] Experiments are performed on 3 mm thick Zn-22Al eutectoid superplastic alloy. Two phases of Zn-22Al superplastic alloy are used in this study. Starting microstructures of studied alloy is shown in Fig.2 (a) is the as-received Zn-22Al without any heat treatment and Fig.2 (b) shows the Lamellar grain structures of Zn-22Al which was achieved after heat treatment. Table I shows the chemical composition of the material. Experiments are performed on various process parameters of FSW tool for each phase of Zn-22Al alloy. Table II shows the process parameters for as-received material and table III shows the parameters for annealed material.

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III. RESULTS AND DISCUSSIONS

A. Microstructural Observation

Fig. 3 shows the appearance of a friction stir welded material. Rotation of the tool is counterclockwise and direction of the process is as shown in the photo.

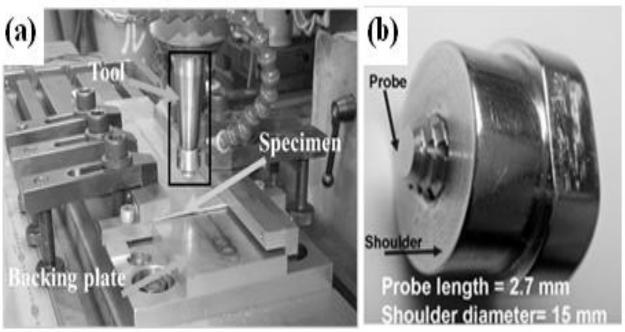

Fig. 1 (a) FSW machine with jigs, backing plate (b) FSW tool showing probe and shoulder part

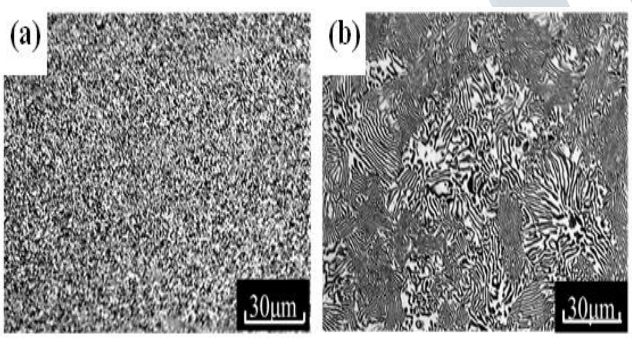

Fig. 2 Starting microstructure of the Zn-22Al alloy as-received (b) annealed

Table I Chemical composition of Zn-22Al alloy

Cu	Al	Mg	Ti	Zn
0.52	21.1	0.010	0.034	Bal.

Table II Process parameters of FSW tool during the process for as-received Zn-22Al

Rotation speed [rpm]	Travel speed [mm/min]	Plunge depth [mm]	Tilt angle [°]
880	400–1200	2.7	3

Table III Process parameters of FSW tool during the process for annealed Zn-22Al

Rotation speed [rpm]	Travel speed [mm/min]	Plunge depth [mm]	Tilt angle [°]
440	50–800	2.7	3

Fig. 4 and Fig. 5 show the macro photos of the cross-section for both as-received and annealed materials. Cross-sections are perpendicular to the direction of processing and are etched with sodium-hydroxide. It can be confirmed that FSW has significantly changed the structure of base metal. Affected area decreases as travel speed increases, also a larger un-joined part between butted sheets was observed as the travel speed increased. The amount of created heat-input during the FSW process is thought to be the reason of change in length of the un-joined part. Heat input increases as the travel speed decreases [15], therefore weld becomes deeper for parameters which have smaller heat-inputs. Stirring time becomes longer as travel speed decreases, therefore FSW tool has more time to push the material which is soften by friction heat. This could be another reason of having smaller un-joined part as travel speed decreases. Fig. 6 shows the microstructural observations for different part of annealed material after FSW. It makes a comparison between the microstructures of a low and a high travel speed. It can be confirmed that un-joined part between sheets disappears as the travel speed is decreases. Microstructure of stir zone, TMAZ (thermo mechanically affected zone) and unaffected area are shown in the figure.

As Nishihara had suggested about finer grain size within the stir zone after FSW [8], it can be confirmed that finer grain structures have been achieved after FSW. It can be confirmed from Fig. 7 that FSW has significantly changed the structure of base metal. Secondary electron microscopy photos of base metal, heat affected zone (HAZ), thermo mechanically affected zone (TMAZ) and stir zone are shown in figure. Notably finer grain structures after FSW process is obtained within the stir zone. A study on effect of friction stir process on the grain refinement of Zn-22Al alloy has been published earlier. [14] It revealed that depending on the process parameters of FSW tool during the process, a grain size of 0.3 µm and a high superplasticity could be obtained.

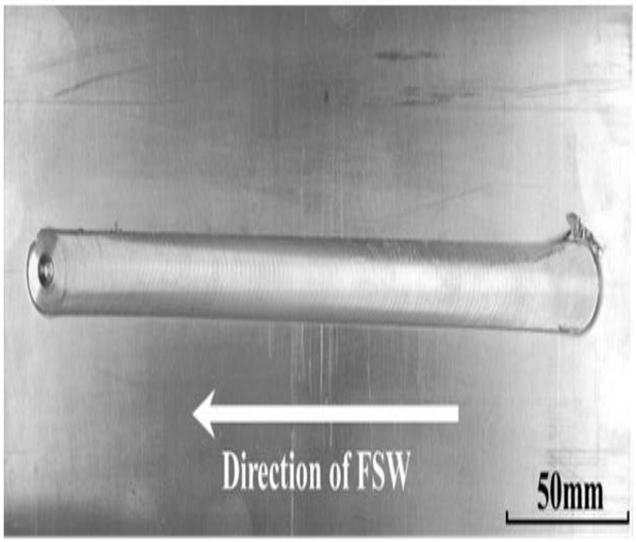

Fig. 3 Appearance of a friction stir welded Zn-22Al alloy

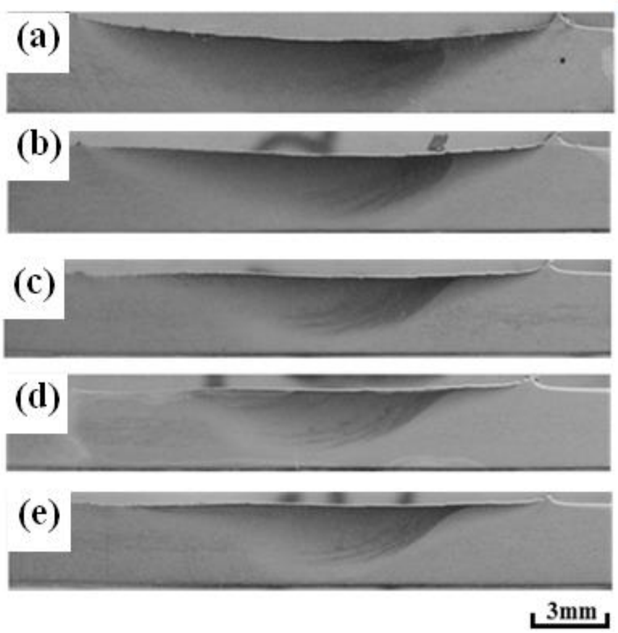

Fig. 4 Macro photos of cross-section after FSW in as-received alloy for a rotation speed of 880 rpm and a travel speed of (a) 400 mm/min (b) 600 mm/min (c) 800 mm/min (d) 1000 mm/min (e) 1200 mm/min

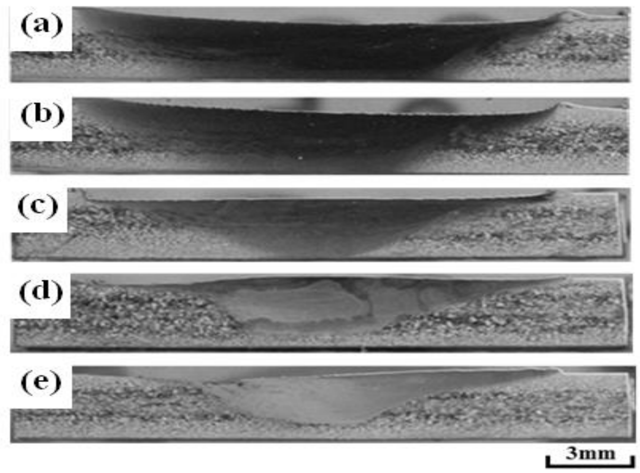

Fig. 5 Macro photos of cross-section after FSW in annealed alloy for a rotation speed of 440 rpm and a travel speed of (a) 50 mm/min (b) 100 mm/min (c) 200 mm/min (d) 400 mm/min (e) 800 mm/min

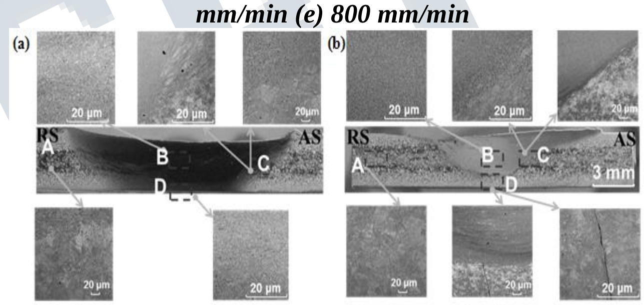

Fig. 6 Microstructure observation of friction stir welded annealed Zn-22Al for (a) travel speed of 50 mm/min (b) travel speed of 800 mm/min showing: A. unaffected zone B. stir zone C. TMAZ D. interface area

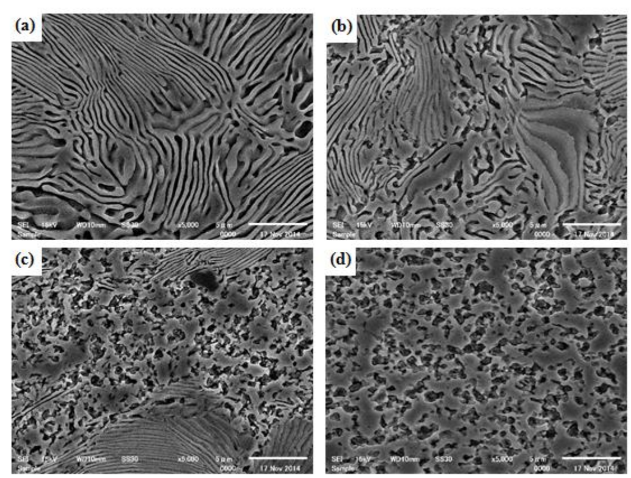

Fig. 7 SEM photos of friction stir welded Annealed Zn-22Al (a) unprocessed annealed Zn-22Al with lamellar structure

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(b) HAZ (c) TMAZ (d) SZ

A. Bend Test

Face and root bend test were carried out after applying FSW for different tool process parameters.

Face bend test results revealed that maximum load increases as revolutionary pitch increases (Fig. 8 (a)). Lower strength for lower travel speeds could be attributed to the high heat input when decreasing the travel speed. Material gets soften as a result of high heat-input; therefore a lower load is attained. For as-received alloy maximum load starts to decrease as travel speed reaches 1000 mm/min (revolutionary pitch of 1.1). For annealed alloy maximum load stops increasing when travel speed reaches 400mm/min (revolutionary pitch of 1.1). It could be confirmed from root bend tests Maximum load decreases as travel speed increases (Fig. 8 (b)). This is contributed to a larger Un-joined part at higher travel speeds. As mentioned before as travel speed increases, due to the lack of heat input, a bad fellow of material happens during the process which leads to a larger un-joined part which affects the strength. Fig. 9 shows the macro-photo of cross-section after bending tests for as-received alloy. As it can be confirmed from Fig. 9 (a), in root bend test, for a high travel speed the crack starts from the un-joined part and continues throw the stir zone. Lack of material flow causes larger interface which affects the strength. As the travel speed decreases, crack tends to start from the boundary between stirred and un-affected area and continues throw the stir zone (Fig. 9 (b)) For face bended Zn-22Al, for lower travel speeds specimens seemed to be brittle and crack tended to start from the retreating side and went through the stir zone (Fig. 9 (c)). The reason for this fact could be the grain refinement of stir zone which makes the material harder but also more brittle. For higher travel speeds the specimens tended to be more ductile and broke in a sharper angle. This can be attributed to the lower hardness of stir zone in a high travel speed specimen which makes it less brittle. Cracks tended to start from the retreating side and went around the stir zone (Fig.9 (d)). As travel speed reaches 1200 mm/min, no crack was seen and the sample specimen was bended till in U-shape form (Fig.9 (e)).

Fig. 10 shows the macro-photo of cross-section after bending tests for annealed alloy. Same phenomenon for annealed alloy was observed as for the as-received alloy. It can be observed in Fig. 10 (a) that for a low travel speed, crack occurs in the middle and travels throw the stir zone in both root and face bend tests. As travel speed increases (to 200 mm/min in this case) crack occurs and starts in the un-joined part and travels around the stir zone in root bend test (Fig. 10 (b)). After face bend test for higher travel speeds (200 to 800 mm/min), crack starts from the boundary between stirred and un-affected area or rather no crack was observed. However, crack occurred in un-joined part and continued throw stir zone after the root bend test. Larger un-joined part in a higher travel speeds is the reason for the mentioned result (Fig. 10 (c)).

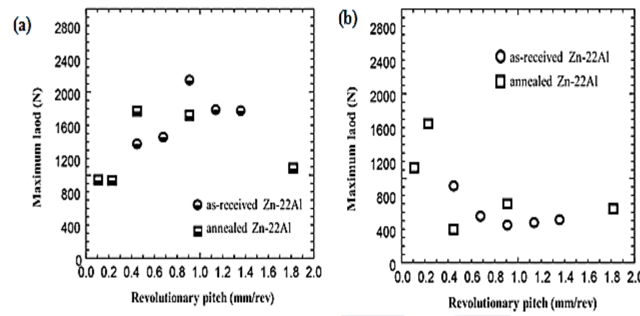

Fig. 8 Effect of travel speed on maximum load in friction stir welded Zn-22Al after (a) face bend test and (b) root bend test

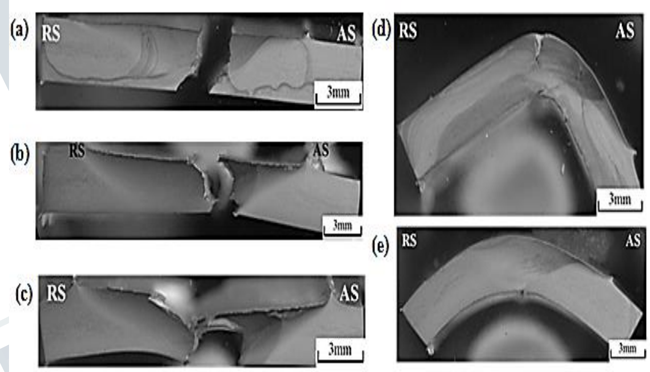

Fig. 9 Cross-section photos of friction stir welded Zn-22Al after bend tests showing (a) root bend test (travel speed: 1200 mm/min) (b) root bend test (travel speed 400 mm/min) (c) face bend test (travel speed: 400 mm/min) (d) face bend test (travel speed: 1000 mm/min (e) face bend test (travel speed: 1200mm/min)

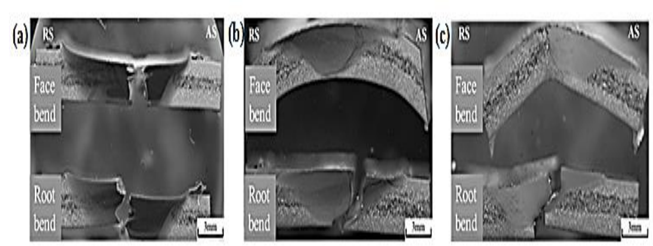

Fig. 10 Cross-section photos of friction stir welded Zn-22Al after bend test for a tool rotational speed of 440 rpm and (a)

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travel Speed: 50 mm/min (b) travel speed= 200 mm/min (c) travel speed= 800 mm/min

C. Tensile Test

Tensile tests were carried out after the process to confirm the effect of different tool process parameters on the strength of friction stir welded alloy. As it can be confirmed from Fig.11 (a), tensile strength has a decreasing tendency as the travel speed and rotational pitch (the ratio of rotation speed to travel speed) increases. As it was discussed in earlier section, un-joined part becomes larger due to lack of heat-input for a higher travel speed, which results in decreasing the strength and also joint efficiency (Fig. 12). Based on the bending and microstructural results higher elongation must have been observed as the tool travel speed increases, however, as it can be confirmed from Fig. 11 (b), a scattered results have been obtained for the elongation after tensile test. One reason that can be argued is that the un-joined part in higher travel speeds act to weaken strength also prevents the specimen to be elongated. Another reason is that for lower tool travel speeds a fine-grain structure has been obtained within the stir zone, which makes the specimen tougher and more ductile as well. It was published in another study that the superplasticity characteristics of Zn-22Al and strain rate sensitivity exponent (m-value) increases after the friction stir process [14]

D. Hardness Test

Hardness tests of the cross-sections were carried out for different distances under the surface. The measurements have been taken at 1.0 mm intervals extending horizontally. Fig. 12 shows the hardness distribution for different travel speeds. It can be confirmed that FSW has a high effect on hardening the material within the stir zone. Comparing to the hardness of 150 HV for annealed Zn-22Al, maximum hardness of 300 HV is achieved within the stir zone for a travel speed of 50 mm/min (Fig. 12 (a)). This can be attributed to the grain refinement due to stirring. Hardness tends to slightly increase as we get closer to the surface. Hardness decreases as the travel speed of the tool increases (comparing the maximum hardness of 300HV within the stir zone for travel speed of 50 mm, hardness of about 230HV is achieved for the travel speed of 800 mm/min). Although hardness increase within the stir zone is still observed for higher travel speeds comparing to the hardness of base metal, no significant change in hardness was observed and it can be contributed to the insufficient grain refinement during the process. Base on the Hall-Petch relation [16], [17], hardness increases as the grain size decreases. It can be concluded that stirring performance of probe decreases as the rotation pitch (travel speed/ rotation speed) increases, therefor it can be predicted that there will be a not sufficient grain refinement within the stir zone.

III. CONCLUSION

Trials of friction stir welding on Zn-22Al superplastic alloys were carried out and the effect of different process parameters of FSW tool (travel speed and rotation speed) on mechanical behavior of the welded zone has been discussed. It could be confirmed that process parameters determines the microstructural evolution and mechanical properties of the processed zone. Present study could give readers an indication of the proper parameters during the FSW process. These parameters could affect the temperature of the processed zone. The knowledge of the processed zone temperature in FSW is of great interest as well which could be one of the important future investigations for researchers. Below are the main points obtained in present study,

1. Microstructural observations revealed that finer grain size was achieved after FSW within the stir zone. The lamellar structure of annealed Zn-22Al was changed into a fine equiaxial grain structure within the stir zone.

2. Tensile strength increased as the revolutionary pitch

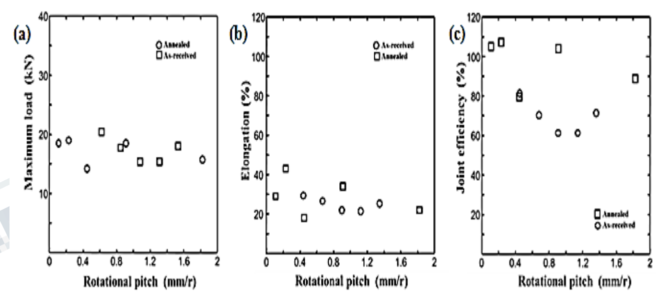
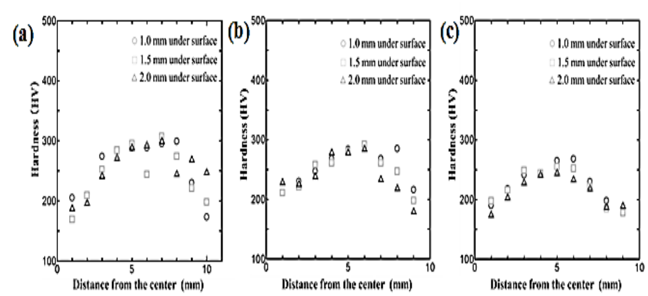


Fig. 11 Effect of revolutionary pitch on (a) tensile strength and (b) elongation (c) joint efficiency after FSW for as-received and annealed Zn-22Al alloy



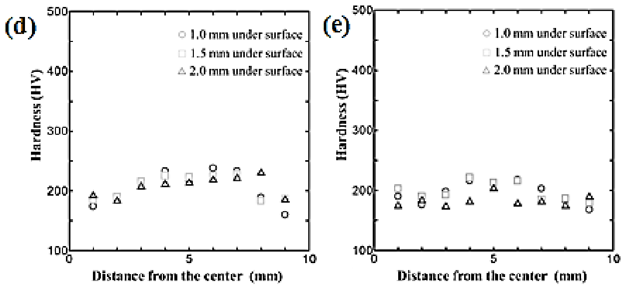


Fig. 12 Hardness distribution for tool rotation speed of 440 rpm and travel speed of (a) 50 mm/min (b) 100 mm/min (c) 200 mm/min (d) 400 mm/min (e) 800 mm/min

decreased. Higher joint efficiencies were achieved for lower revolutionary pitches as well.

3. Hardness of Zn–22Al increased toward the stir zone as a result of grain refinement. Hardness increased as the travel speed of the tool decreased. Considering the relation between hardness and grain size, it can be concluded that higher revolutionary pitch results in a finer grain structures within the weld and stir zone.

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