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Effect of Tool Shoulder Diameter during Friction Stir Processing of AZ31B alloy sheets of various thicknesses

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Abstract

Friction-stir processing (FSP) is an emerging severe plastic deformation technology that is based on friction stir welding (FSW). In FSP, the tool plays a very important role in producing a defect free processed zone. The shoulder of the tool, which is the main source of heat generation, is typically either flat or tapered in shape. The typical shape of the shoulder aids in material consolidation during processing by forcing the softened material to be retained in the processed zone, as the tool traverses along the length of the work piece. The pin also plays a very important role, in refining the grain size along the through-thickness of the work piece. In this work, high carbon steel of and AZ31B magnesium alloy (6mm & 1.5 mm thick) was chosen as a tool material and work piece material respectively. The tool shoulder diameter of 18 mm and 24 mm were chosen to friction stir process the work piece material in a single pass. The possibility of Increase in the tool shoulder diameter beyond 18mm but less than 24 mm, a defect free processed zone was observed for variation in the process parameters in 6mm thick plate. Also as the thickness of work piece is reduced, the defects in the friction stir processed zone of 1.5 mm thick plate is completely eliminated. A fine equiaxed grain of average grain size less than 10μm were during friction stir processing, thus creating the material to exhibit superplasticity.

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Keywords: Friction Stir Processing, Microstructure, Macrostructure, nugget.

Nomenclature

FSP Friction Stir processing

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1. Introduction

Friction stir processing (FSP) is a new solid state technique which uses the principles of friction stir welding to process materials in a variety of other ways besides joining them. The friction stir process results in the obtaining of a very fine and equiaxed grain structure in the processed regions causing a higher mechanical strength and ductility. The microstructure in the processed region evolves through a continuous dynamic recrystallization process. Further the strong grain refinement produced by the process lead the material to exhibit superplastic properties [1]. Initially friction stir processing was used to modify the microstructure and also to eliminate the surface defects of the cast aluminium alloy. Very recently, friction stir processing has received more attention for processing the magnesium alloys that spread the usage of magnesium alloys in sheet metal industries.

Tabellenbuch [2] reported that magnesium is an attractive material for automotive use, primarily because of its light weight, 36% lighter per unit volume than aluminium and 78% lighter than iron (Fe). In the alloyed form, Magnesium has the highest strength-to-weight ratio of all the structural metals. Since the first oil crisis in the 1970s, there has been an economic and legislated move to make automobiles lighter in weight for improving improve fuel efficiency and emissions reductions. The most striking material shifts have been from iron to high-strength steel (HSS), and from iron and steel to aluminium and plastics. But magnesium offers even greater potential to reduce the weight, by replacing steel, and the additional incremental savings by replacing aluminium and plastics.

Tensile tests were carried out on A206 alloy in the cast with T4 condition as well as after FSP with different heat treatment by Kapoor et al [3]. It was stated that the cast with T4 condition had a yield strength of 270 MPa, an ultimate strength of 310 MPa and a ductility of 3%, whereas the friction stir processed alloy resulted in a substantial increase of tensile strength from 310 to 405 MPa and a simultaneous increase in ductility from 3 to 21%. In contrast, the yield strength has not improved substantially. The authors also reported that the subsequent heat treatments did not have much effect on the UTS, implying that the UTS were controlled by the intermetallic particles rather than the heat treatment conditions. The inverse behaviour of YS with ductility at different heat treatment conditions implies that the YS were controlled by the inherent matrix strength, which in turn depends on the microstructure (i.e., grain size and precipitate type). Samples with one through three passes with 100% overlap were created using friction stir processing (FSP) by Magdy El-Rayesa and Ehab El-Danaf [4] in order to locally modify the microstructural and mechanical properties of 6082-T6 Aluminum Alloy . A constant rotational speed and three different traverse speeds were used for processing. The authors addressed the microstructural properties in terms of grain structure and second phase particles distribution, and also the mechanical properties in terms of hardness and tensile strength of the processed zone with respect to the number of passes and traverse speeds. The parameter combination which resulted in highest ultimate tensile strength was further compared with additional two rotation speeds. It was reported that FSP caused dynamic recrystallization of the stir zone leading to equiaxed grains with high angle grain boundaries which increased with increasing the number of passes. Gandra et al [5] studied the effect of overlapping direction in multipass friction stir processing (FSP) on AA 5083-H111 alloy of 8mm thick plate and the structural and mechanical differences were observed when overlapping was done by the advancing side (AS) direction or by the retreating side (RS) one. It was reported that overlapping by the retreating side was found to generate smoother surfaces, while overlapping by the advancing side led to more uniform thickness layers. Hardness within the processed layer increased by 8.5% and was seen to be approximately constant between passes. The mechanical resistance and toughness under bending were improved by 18% and 19%, respectively. Hulbert et al [6] predicted the tensile behaviour of conventional FSP and actively cooled FSP on 25.4 mm thick A2519 aluminium plate and concluded that the FSP zone was much more ductile and had yield strength less than that of heat affected zone and base metal regions of the plate. The authors also identified that the FSP specimens produced enhanced ductility, which was due to increased dislocation mobility and not grain boundary sliding. The tensile behaviour of friction stir processed AZ91 alloy was investigated by Cavalier and De Marco [7]. The authors reported that friction stir processed material produced a strong increase in the mechanical properties in respect to the unstirred material with an increase in elongation to failure accompanied by a strong increase in strength due to the very fine recrystallized structure and also due to the absence of porosity in the stirred region.

Darras et al [8] analysed the microstructural results of friction stir processed commercial AZ31B alloy and reported that FSP produced a more homogeneous microstructure. The author also reported that the as-received material which had a fine microstructure of 6µm has been refined into an equiaxed homogenized grain with an average size in the range of 3-4µm after FSP. The author concluded that the as received material exhibited a combination of large and small grains while the structure of the processed samples illustrated the majority of grains having almost the same grain size. Because of the finer grain size in the processed regions, an improvement in the ductility and formability of the FSP material was expected and also the material can exhibit the superplastic characteristics at elevated temperatures. Johannes [9] reported that friction stir processing can be considered as a viable technique for creating a more homogenized starting material in Al 5083 aluminium alloy. The author by examining the microstructure reported that the constituent particles are not only refined after FSP, but they are also more evenly distributed. Chang et al [10] reported that an ultrafine grain size in a solid solution hardened AZ31Mg alloy can be successfully achieved in single pass FSP coupled with rapid heat sink. The author concluded that with proper control of the working temperature history, an ultrafine grain structure with the mean grain size ranging from 100 – 300 nm can be achieved from the initial grain size of 75µm by a single pass FSP. The decrease in the grain size in the processed regions produced an abnormal increase in the microhardness from 50 Hv to 120 Hv with an increment factor of 2.4.

Though large number of investigations has been carried out on friction stir processing of aluminum alloys, the study on friction stir processing of magnesium alloys is limited. Many researchers successfully used friction stir welding to join magnesium sheets. All the above literature are related to friction stir processing of magnesium alloys in which very less information was available related to the effect of friction stir processing on tensile properties of the base metal and friction stir processed metal. In FSP, the tool plays a very important role in producing a defect free processed zone. The shoulder of the tool, which is the main source of heat generation, is typically either flat or tapered in shape. The typical shape of the shoulder aids in material consolidation during processing by forcing the softened material to be retained in the processed zone, as the tool traverses along the length of the workpiece. The pin also plays a very important role, in refining the grain size along the through-thickness of the workpiece. In this work, high carbon steel and AZ31B magnesium alloy (6mm & 1.5 mm thick) was chosen as a tool material and workpiece material respectively. The tool shoulder diameter of 18 mm and 24 mm were chosen to friction stir process the workpiece material in a single pass. The possibility of Increase in the tool shoulder diameter beyond 18mm but less than 24 mm, a defect free processed zone was observed for variation in the process parameters in 6mm thick plate. Also as the thickness of workpiece is reduced, the defects in the friction stir processed zone of 1.5 mm thick plate is completely eliminated. A fine equiaxed grain of average grain size less than 10µm were during friction stir processing, thus creating the material to exhibit superplasticity

2. EXPERIMENTAL WORK

The base metal used in this investigation is the extruded AZ31B grade magnesium alloy. The extruded AZ31B alloy was received in the form of a plate of dimensions 300 x 150 x 6 and 300 X 150 X 1.5 mm respectively. Friction stir processing on the wrought magnesium alloy was done along the longitudinal direction in friction stir welding machine with the following specification, a spindle motor capacity of 15 hp, maximum tool rotational speed of 2500 rpm, maximum traversing speed of 135 mm/min and maximum axial load of 25 kN. The two friction stir tool composed of a pin with a diameter of 6mm, pin length of 5.8 mm and shoulder diameter of 18 mm and 24 mm respectively. The Processing parameters, such as the tool rotational speed and tool traversing speed for the experimental study are given in Table 1, 2 and 3 respectively, for various thickness sheet materials and tool shoulder diameter. Table 1 shows the process parameters used for the 6 mm thick plate with a tool shoulder diameter of 18 mm. Since visible surface defects and excessive flash were observed during the tool translational speed of 22 mm min $^{-1,}$ the experiments were conducted for only three tool rotational speeds, and for processing along the transverse direction; this parameter has not been taken into consideration due to visual surface defects. A similar case was identified, when the tool rotational speed was increased beyond 1200 rpm, and the tool translational speed was 105 mm min^{-1}. Since the tensile properties were less for processing along the transverse direction, the successive experiments were done only along the longitudinal direction or along the length of the workpiece. Due to more defects observed in the processed region, the tool shoulder diameter was increased to 24 mm. Table 2 shows the process parameter ranges used during friction stir processing on a 6 mm thick plate with a tool shoulder diameter of 24 mm. Since to perform the superplastic forming on the sheet material with a thickness less than 1.5 mm, friction stir processing was done on the 1.5 mm thick sheet, with the tool shoulder diameter of 24 mm. Table 3 shows the process parameter ranges used during the friction stir processing of a 1.5 mm thick sheet with a tool shoulder diameter of 24. All these parameters have been frozen after conducting some trial experiments.

Table 1. Process parameter values for 18 mm tool shoulder diameter on 6mm thick plate.

S.No	Tool rotational speed, (rpm)	Tool translational speed, mm min^{-1}			
		22	40	75	105
1	1000	√	√	√	√
2	1200	√	√	√	√
3	1400	√	√	√	√
4	1600	-	√	√	√
5	1800	-	√	√	√

Table 2. Process parameter values for 24 mm tool shoulder diameter on 6mm thick plate.

S.No	Tool rotational speed, (rpm)	Tool translational speed, mm min^{-1}		
		40	75	105
1	600	√	√	√
2	800	√	√	√
3	1000	√	√	√
4	1200	√	√	√

Table 3. Process parameter values for 24 mm tool shoulder diameter on 1.5 mm thick plate.

S.No	Tool rotational speed, (rpm)	Tool translational speed, mm min^{-1}		
		40	60	75
1	400	√	√	√
2	500	√	√	√
3	600	√	√	√
4	700	√	√	√

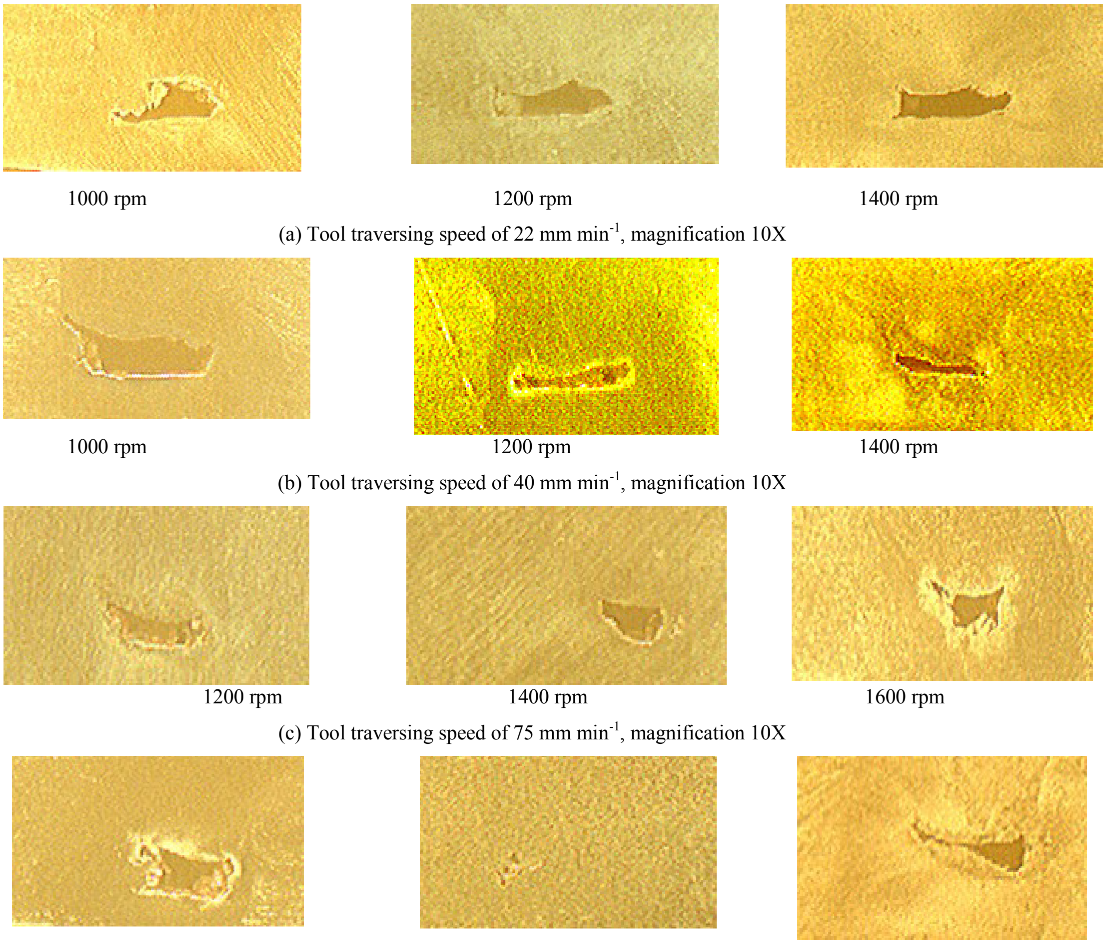
Note : √ - selected process parameters

The friction stir processed workpieces were later subjected to a macrostructural examination to identify defects, such as pin, void and tunnel in the processed zone and tensile test were carried out on defect free specimens. To perform the macrostructure analysis, the friction stir processed AZ31B magnesium alloy was cut in a direction perpendicular to the processing direction, and polished with diamond paste. The samples were etched with a mixture consisting of 10% of picric acid mixed with absolute ethyl alcohol along with 3ml of acetic acid and 2 ml of hydrogen peroxide. An optical microscope interfaced with a digital camera was used to record the macrographs with an optical zoom of 10X. The specimens for the tensile test were sliced in the direction parallel to the direction of processing and then machined to the required dimension according to ASTM E8M-04 standard for sheet type material with a gauge length of 50 mm and a gauge width of 12.5 mm. The Tensile test was carried out in a computer interfaced 10 kN universal testing machine, and parameters such as the yield strength, ultimate tensile strength, percentage of elongation were evaluated.

3. RESULTS AND DISCUSSIONS

3.1 Effect of tool shoulder diameter of 18 mm on 6mm plate

The macrostructure of all the processed specimens with a tool shoulder diameter of 18 mm they are presented in Figure 1 (a-d). It is found from Figure 2 (a,b) that for a combination of translational speed of 40 mm min-1 and tool rotational speed of 1600 rpm, and for a translational speed of 75 mm min^{-1} and tool rotational speed of 1000 rpm, the processed zone developed a minimum defect.



1000 rpm 1200 rpm 1400 rpm

(a) Tool traversing speed of 22 mm min^{-1}, magnification 10X

1000 rpm 1200 rpm 1400 rpm

(b) Tool traversing speed of 40 mm min^{-1}, magnification 10X

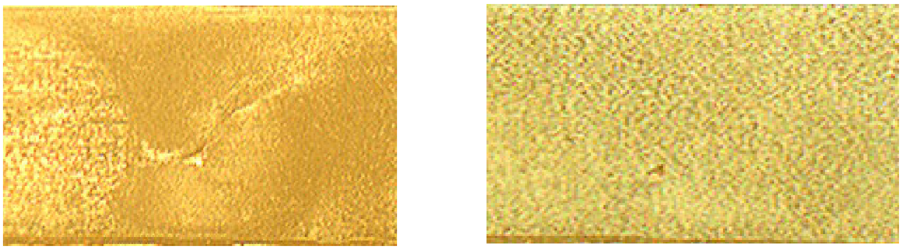
1200 rpm 1400 rpm 1600 rpm

(c) Tool traversing speed of 75 mm min^{-1}, magnification 10X

1000 rpm 1200 rpm 1400 rpm

(d) Tool traversing speed of 105mm min^{-1}, magnification 10X

Figure.1 (a-d) Defects in the processed nugget zone at various tool traversing speed with a tool shoulder diameter of 18 mm at axial load of 8kN

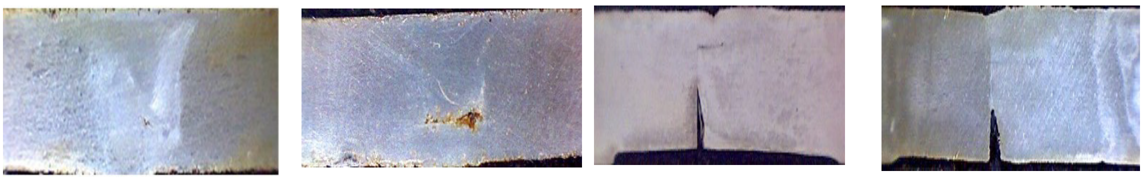


(a) 40 mm min^{-1}-1600 rpm (b) 75 mm min^{-1} – 1000 rpm

Figure 2 (a,b) Minor defects in the processed zone with a tool shoulder diameter of 18mm

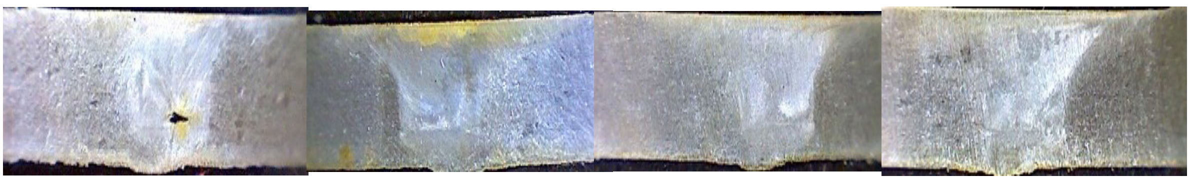
3.2 Effect of tool shoulder diameter of 24 mm on 6 mm plate

It is observed from the macrostructure, as shown in Figure 1 and 2, for a tool shoulder diameter of 18mm, that for all the selected process parameters, various defects mentioned above were observed. All the defects occurred at the bottom of the plate. These defects occurred due to insufficient heat input at the interface between tool shoulder and workpiece and severe twinning of the base material due to the original manufacturing process, and non relieving of internal stresses. Hence, to overcome these defects, the tool shoulder diameter was increased to 24 mm to maintain the tool shoulder diameter to the pin aspect ratio as 4. Figures 3(a-c) and 4 (a-c) show the macrostructure of the friction stir processed AZ31B magnesium alloy for different tool rotational speed with a tool shoulder diameter of 24 mm and for an axial load of 6kN and 8kN respectively.



600 rpm 800 rpm 1000 rpm 1200 rpm

(a) Tool traversing speed 40 mm min^{-1}, magnification 10X



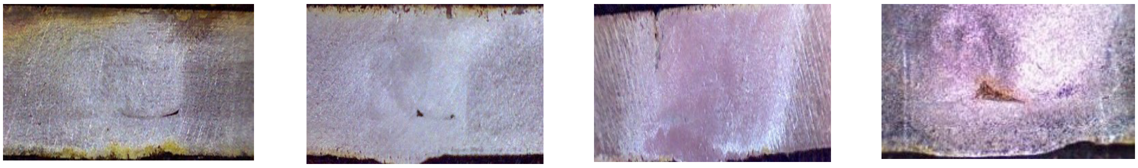
600 rpm 800 rpm 1000 rpm 1200 rpm

(b) Tool traversing speed 75 mm min^{-1}, magnification 10X

600 rpm 800 rpm 1000 rpm 1200 rpm

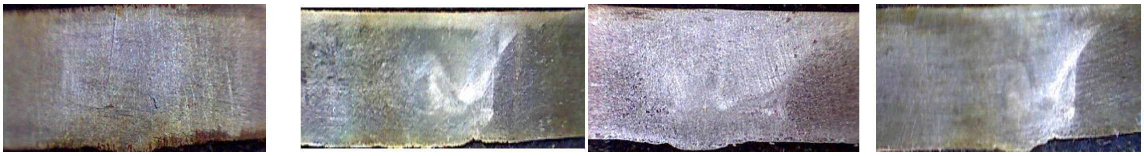
(c) Tool traversing speed 105 mm min^{-1}, magnification 10X

Figure 3 (a-c) Macrostructure of the friction stir processed specimens at an axial load of 6 kN



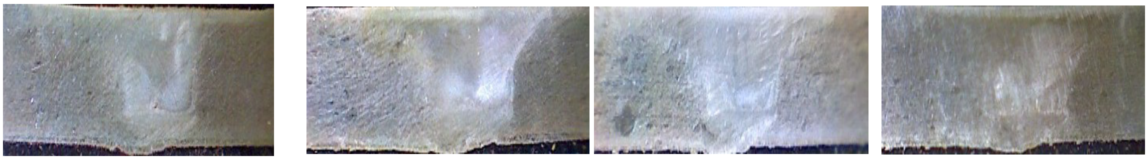
600 rpm 800 rpm 1000 rpm 1200 rpm

(a) Tool traversing speed 40 mm min^{-1}, magnification 10X



600 rpm 800 rpm 1000 rpm 1200 rpm

(b) Tool traversing speed 75 mm min^{-1}, magnification 10X



600 rpm 800 rpm 1000 rpm 1200 rpm

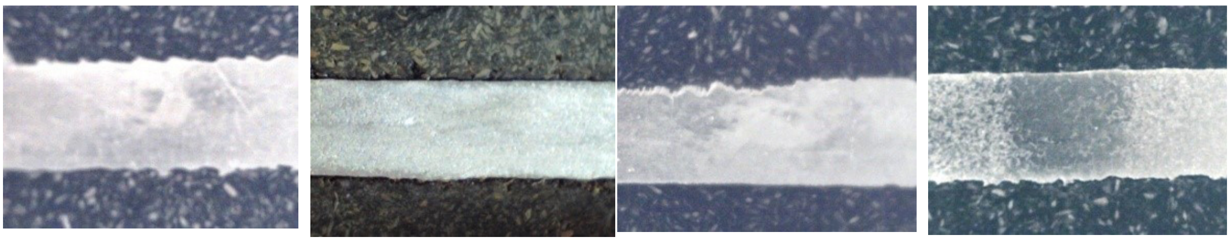
(c) Tool traversing speed 105 mm min^{-1}, magnification 10X

Figure 4 (a-c) Macrostructure of the friction stir processed specimens at an axial load of 8 kN

It can be observed from the above macrostructure that, when the tool axial force was 6kN, the defects occurred in the processed regions for most of the process parameters. The defect in the processed zone is reduced when the axial force is increased from 6kN to 8kN for the same combination of tool traversing and rotational speeds. Hence, it can be concluded that an increase in the tool axial force and increase in the tool shoulder diameter decreases the possibility of defects in the processed regions.

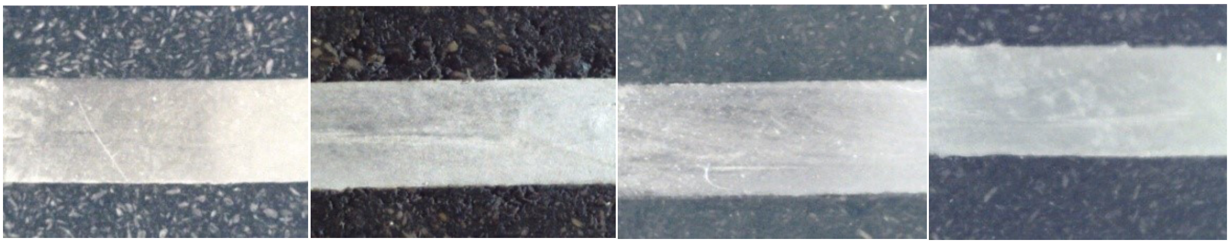
3.3 Effect of Tool shoulder diameter of 24 mm on 1.5 mm thick sheet

The macrostructure of the friction stir processed specimens on a sheet thickness of 1.5 mm and with a tool shoulder diameter of 24 mm is shown in Figure 4.



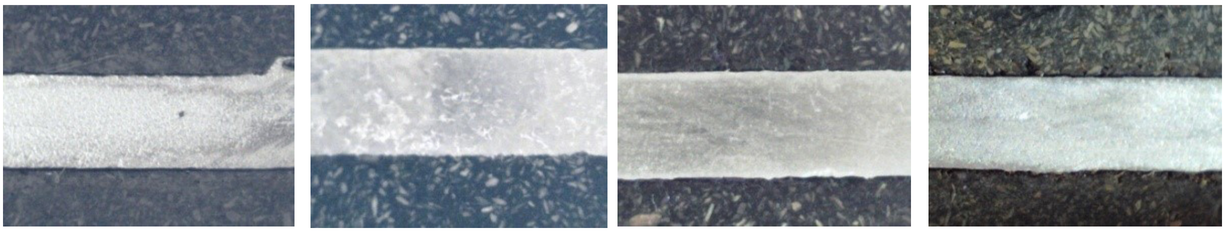
400 rpm 500 rpm 600 rpm 700 rpm

(a) Tool traversing speed 40 mm min^{-1}, magnification 40X



400 rpm 500 rpm 600 rpm 700 rpm

(b) Tool traversing speed 60 mm min^{-1}, magnification 40X



400 rpm 500 rpm 600 rpm 700 rpm

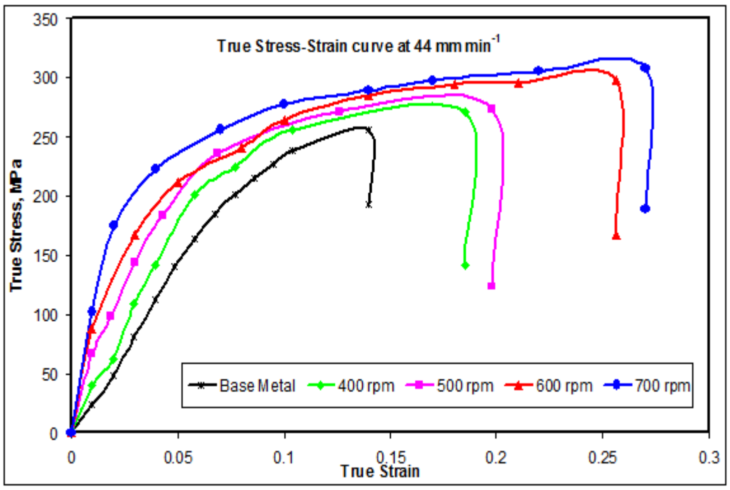
(c) Tool traversing speed 75 mm min^{-1}, magnification 40X

Figure 5 (a-c) Macrostructure of 1.5 mm thick friction stir processed specimens

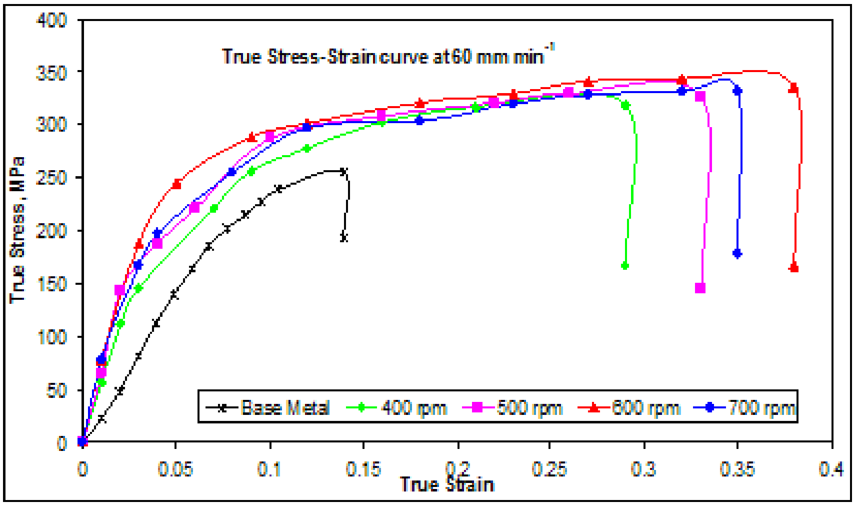
From the Figure 5(a-c), it is inferred that defect have not been observed in the processed regions. The Macroscopic examination revealed that the above defects can be completely eliminated as the sheet metal thickness is decreased. Hence, it can be concluded that as the sheet thickness decreases for a given tool shoulder diameter, enough heat input and proper stirring is provided by the tool in the processed regions, and because of this, defect is not observed in the processed regions.

3.4 Variation of tensile Properties of 1.5 mm thick FSP specimens

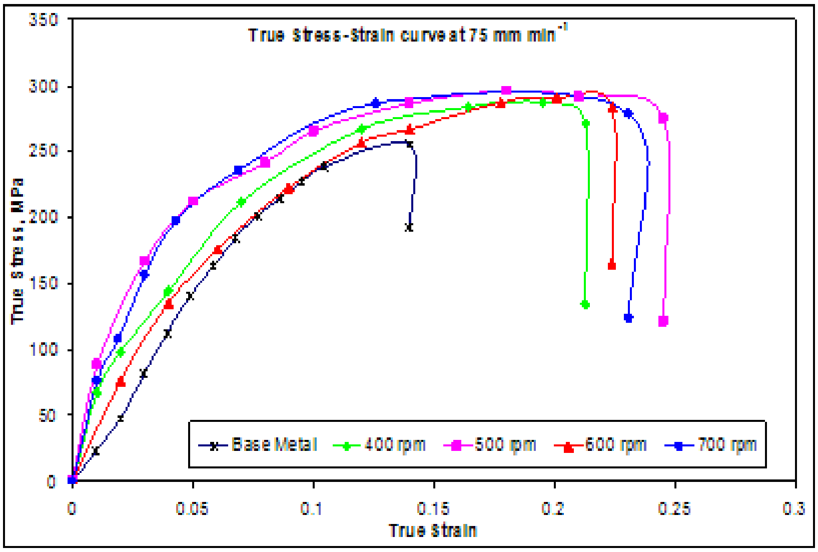
The tensile properties have been evaluated for the 1.5 mm thickness FSP specimens, and are shown in Figure 6(a-c) for various combinations of tool traversing and rotational speeds.



(a) 44 mm min^{-1}



(b) 60 mm min^{-1}



(c) 75 mm min^{-1}

Figure 6 (a-c) True stress-strain curve of the 1.5 mm thick FSP specimens for various tool traversing speeds

Hence, from the above tensile properties it can be concluded, that the friction stir processed material produced a strong increase in the mechanical properties in respect of the unstirred material. This increase in elongation to failure accompanied by a significant increase in strength is due to the very fine recrystallized structure and also due to the absence of porosity in the stirred region. Moreover, the finer grain size in the stirred regions was attributed to the increase in the tensile strength and percentage of elongation.

4. CONCLUSION

The following conclusion was drawn from the experimental study of on the friction stir processed AZ31B magnesium alloy.

1. Irrespective of the tool shoulder diameter, FSP can refine and homogenize the grains at the selected region within the material.
2. The various defects and tensile strength of the friction stir processed material depends upon the combination of tool axial force, tool rotational speed, tool traversing speed and tool shoulder diameter. To eliminate the defects in the processed region, tool shoulder diameter is more significant and for the maximum tensile strength and microhardness, tool traversing speed is the most significant parameter.
3. The tool shoulder diameter of 18 mm produced the defects such as tunnels, voids and pin holes in the processed region for different parameter variations in 6 mm thick plate.
4. Increase in the tool shoulder diameter beyond 18mm but less than 24 mm, a defect free processed zone was observed for variation in the process parameters in 6mm thick plate.
5. As the thickness of workpiece is reduced, the defects in the friction stir processed zone of 1.5 mm thick plate is completely eliminated.
6. A fine equiaxed grain of average grain size less than 10µm were observed in the nugget region, irrespective of workpiece thickness during friction stir processing, thus creating the material to exhibit superplasticity.

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