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AN INVESTIGATION ON THE EFFECT OF PROCESS PARAMETERS ON THE FORCES GENERATED AND MICROSTRUCTURE DURING FRICTION STIR PROCESSING OF ALUMINIUM ALLOYS

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ABSTRACT

Friction stir processing (FSP) is one of the new and promising thermo mechanical processing technique that alters the micro structural and mechanical properties of the material in single pass to achieve maximum performance with low production cost in less time using a simple and inexpensive tool. Preliminary studies of different FS processed alloys report the processed zone to contain fine grained, homogeneous and equiaxed microstructure. Several studies have been conducted to optimize the process and relate various process parameters like rotational and translational speeds to resulting microstructure. But there is only a little data reported on the effect of the process parameters on the forces generated during processing, and the resulting microstructure of aluminium alloys especially AA5052 which is a potential super plastic alloy. In the present work, sheets of aluminium alloys were friction stir processed under various combinations of rotational and translational speeds. The processing forces were measured during the process and the resulting microstructure was analyzed using TEM. The results indicate that the processing forces and the microstructure evolved during FSP are sensitive to the rotational and translational speed. It is observed that the forces generated increase with the increasing rotational speed. The grain refinement was observed to vary directly with rotational speed and inversely with the translational speed. Also these forces generated were proportional to the grain refinement i.e., greater refinement of grains occurred at lower forces. Thus the choice of process parameters especially the rotational speed has a significant effect on the control and optimization of the process.

Keywords: ***Friction stir processing, force analysis, process parameters microstructure, aluminium alloy.***

1. INTRODUCTION

Friction stir processing (FSP) is a solid-state process which means that at any time of the processing the material is in the solid state. In FSP a specially designed rotating cylindrical tool that comprises of a pin and shoulder that have dimensions proportional to the sheet thickness. The pin of the rotating tool is plunged into the sheet material and the shoulder comes into contact with the surface of the sheet, and then traverses in the desired direction. The contact between the rotating tool and the sheet generate heat which softens the material below the melting point of the sheet and with the mechanical stirring caused by the pin, the material within the processed zone undergoes intense plastic deformation yielding a dynamically-recrystallized fine grain microstructure. The process is suitable for joining of dissimilar metals compared to conventional fusion welding process. The advantages of this process are high quality and flexibility. It could join the materials together without melting which reduces many defects existed in fusion welding process. The process parameters such as rotational speed, welding speed, tool geometry have influence on the material flow .

Friction stir processing is an outgrowth of friction stir welding .FSP offers the ability to locally tailor the properties within a structure in order to improve its properties, because of the ability to create a fine grain micro structure and eliminate casting defects. For example, by applying FSP, local properties can be improved, such as abrasion resistance, strength, ductility, fatigue life, formability, and super plasticity. Friction stir processing is a growth technology that may become as important as FSW. Lastly, FSW and FSP are essentially new technologies not much beyond their infancy. The growth potential for the future can be considerable.

2. PROCESS & MECHANISM

Figure 1.1 illustrates process definitions for the tool and work piece. Most definitions are self-explanatory, but advancing and retreating side definitions require a brief explanation. Advancing and retreating side orientations require knowledge of the tool rotation and travel directions. In Fig. 1.1, the FSW tool rotates in the counterclockwise direction and travels into the page (or left to right). In Fig. 1.1 the advancing side is on the right, where the tool rotation direction is the same as the tool travel direction (opposite the direction of metal flow), and the retreating side is on the left, where the tool rotation is opposite the tool travel direction (parallel to the direction of metal flow). The tool serves three primary functions, that is, heating of the work piece, movement of material to produce the joint, and containment of the hot metal beneath the tool shoulder. Heating is created within the work piece both by friction between the rotating tool pin and shoulder and by severe plastic deformation of the work piece. The localized heating softens material around the pin and, combined with the tool rotation and translation, leads to movement of material from the front to the back of the pin, thus filling the hole in the tool wake as the tool moves forward. The tool shoulder restricts metal flow to a level equivalent to the shoulder position, that is, approximately to the initial work piece top surface.

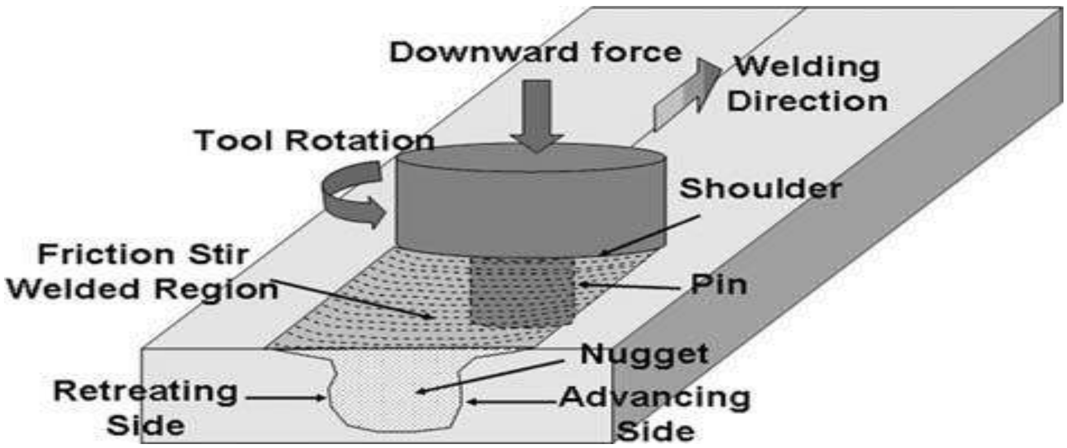

Fig 1.1 Schematic diagram of FSW

As a result of the tool action and influence on the work piece, when performed properly, a solid-state joint is produced, that is, no melting. Because of various geometrical features on the tool, material movement around the pin can be complex, with gradients in strain, temperature, and strain rate. Accordingly, the resulting nugget zone microstructure reflects these different thermo mechanical histories and is not homogeneous. In spite of the local micro structural in homogeneity, one of the significant benefits of this solid-state welding technique is the fully re crystallized, equiaxed, fine grain micro structure created in the nugget by the intense plastic deformation at elevated temperature. The fine grain microstructure produces excellent mechanical properties, fatigue properties, enhanced formability, and exceptional super plasticity. Like many new technologies, a new nomenclature is required to accurately describe observations. In FSW, new terms are necessary to adequately describe the post weld microstructures. The first attempt at classifying friction stir welded microstructures was made by Thread gill . Figure 1.2 identifies the different micro structural zones existing after FSW, and a brief description of the different zones is presented. The system divides the weld zone into distinct regions, as follows:

• ***Unaffected material or parent metal:*** This is material remote from the weld that has not been deformed and that, although it may have experienced a thermal cycle from the weld, is not affected by the heat in terms of microstructure or mechanical properties.

• ***Heat-affected zone:*** In this region, which lies closer to the weld-center, the material has experienced a thermal cycle that has modified the microstructure and or the mechanical properties. However, there is no plastic deformation occurring in this area.

• ***Thermo mechanically affected zone (TMAZ):*** In this region, the FSW tool has plastically deformed the material, and the heat from the process will also have exerted some influence on the material. In the case of aluminum, it is possible to obtain significant plastic strain without re crystallization in this region, and there is generally a distinct boundary between the re crystallized zone (weld nugget) and the deformed zones of the TMAZ.

• ***Weld nugget:*** The fully re crystallized area, sometimes called the stir zone, refers to the zone previously occupied by the tool pin. The term *stir zone* is commonly used in friction stir processing, where large volumes of materials are processed.

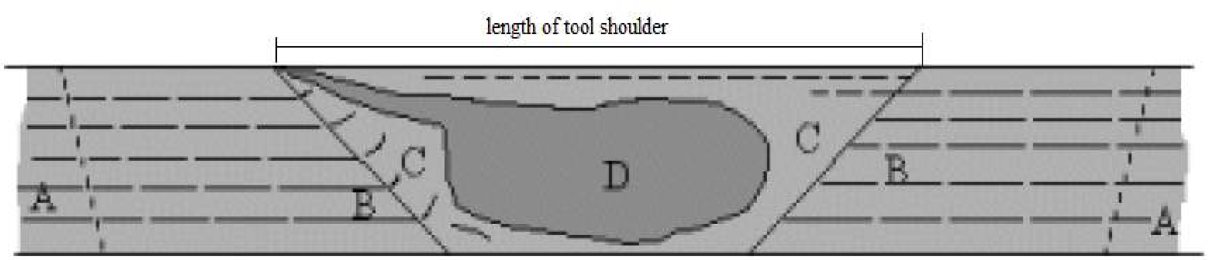

Fig.2.1 Various micro structural regions in the transverse cross section of a friction stir welded material. A, unaffected material or parent metal; B, heat-affected zone; C, thermo mechanically affected zone; D, weld nugget

3. LITERATURE REVIEW

Darras et al (2015) [1] studied the effect of various friction stir processing parameters on the thermal histories and properties of commercial AZ31B-H24 magnesium alloy sheet. They refinement and homogenization of microstructure is more an observation in a single pass. Fine grain size can be obtained in a single pass friction stir processing through severe plastic deformation and control of heat input during processing.

Fadhel A. et.al (2015) [2] performed friction stir process (FSP) to enhance surface properties of AA2024-T3 alloy. The effect of friction stir shoulder rotation in addition to its pressing effect on surface topography and mechanical properties was studied. Samples were FS processed with a flat pinless cylindrical shoulder of 10mm diameter with a constant rotational and travel speeds 945 rpm and 85mm/min respectively. The maximum hardness increment is about 40-45% and the maximum value obtained at the surface is 190Hv compared to 130Hv before processing. A little bit increase was recorded in yield and tensile strengths by an amount of 15% and 9% respectively after FSP.

Ranjit Bauri et al (2015) [3] recently reported the optimisation of process parameters for fabricating metal particles reinforced 5083 Al composite by FSP. A wide range of parameters covering tool rotation speeds from 1000rpm to 1800rpm and arrange of traverse speeds from 6mm/m into 24mm/min were explored in order to get a defect free stir zone and uniform distribution of particles. The right combination of rotation and traverse speed was found from these experiments. Both as-received coarse particles (70 μm) and ball-milled finer particles (10 μm) were incorporated in the Al matrix using the optimized parameters.

Karthikeyan et al (2009) [5] investigated the effects of Friction stir processing on Cast 2285 alloy and concluded that due to FSP the mechanical properties and microstructure are improved. 30% improvement in yield and tensile strengths were recorded and ductility increased around 4 times. He concluded that this improvement in mechanical properties was due to reduced porosity and grain size.

Elangovan and Balasubramanian (2008a) [6] studied the influences of tool pin profile and tool shoulder diameter on the formation of friction stir processing zone in AA6061 aluminum alloy. They reported that, of the five tool pin profiles used (straight cylindrical, tapered cylindrical, threaded cylindrical, square and triangle) to fabricate the FSW joints, square pin profiled tool produced defect free FSP zone , irrespective of the shoulder diameter of the tools. They also reported that, a tool with 18mm shoulder diameter produced defect free FSP region, irrespective of tool pin profiles used. The FSW joint fabricated using square pin profiled tool with shoulder diameter of 18mm showed superior tensile properties.

Basil M Darras et al (2007) [7] performed the friction stir processing of AZ31 Mg alloy. They examined the possibility of using FSP to modify the microstructure and properties of commercial AZ31B-H24 magnesium alloy sheets. The effect of various process parameters on thermal histories, resulting microstructure and properties were investigated. They found promising results and their results proved that FSP leads to finer and more homogenized grain structure.

Itharaju et al. (2004)[8] investigated the microstructure at different combinations of rotational and translational speeds and tried to relate the resulting grain sizes to the generated forces in friction stir processed 5052 aluminum sheet. They observed that the resulting average grain size of the FS processed AA5052 sheet were between 1.5 and 3.5 μm depending on the process parameters, compared to 37.5 μm for the unprocessed sheet, which mean that great refinement has been achieved. Itharaju et al also concluded that, in general, the plunging force increases with increasing rotational speed and it is almost independent of the translational speed.

Kwon et.al (2003)[9] studied the FS processed Al 1050 alloy. The hardness and tensile strength of the FS processed 1050 aluminium alloy were observed to increase significantly with decreased tool rotation speed. It was noted that, at 560 rpm, these characteristics seemed to increase as a result of grain refinement by up to 37% and 46% respectively compared to the starting material.

Thomas et al.(2001)[10] presented a review of friction technologies for stainless steel, aluminum, and stainless steel to aluminum, which are receiving widespread interest. Friction hydro pillar processing, friction stir welding (FSW), friction plunge welding are some of these unique techniques. They observed that this technology made possible the welding of unweldable aluminum alloys and stainless steel feasible. Using this technology sheets up to 75mm thickness can also be easily welded.

Mishra et.al (1999)[11] investigated the FSP of a commercial 7075 Al alloy that resulted in significant enhancement of superplastic properties. The optimum superplastic strain rate was observed to be 10-2 s-1 at 490 °C in the FSP 7075 Al alloy, and the maximum elongation was observed to be about 1000%. Also, the average grain size was determined by mean linear intercept technique (grain size = 1.78 × mean linear intercept), and was approximately 3.3±0.4μm.

4. EXPERIMENTAL SETUP

One of the advantages of FSP as mentioned earlier is that it can utilize the existing machine tool technology and requires a simple tool. The experimental setup required to FS process aluminum alloys is discussed in this section.

- HAAS VF-0F vertical milling machine.
- Most important element in FSP is the tool. The tool assembly designed consists of a pin and a shoulder. It is made of ¼ -20, 01 tool steel nib Rockwell hardness of 62C with right hand threads,

nominal shoulder diameter of ½”, and pin diameter of ¼” slightly force shortened and rounded. The height of the pin is equal to the thickness of the sheet to be processed.

- A 3-component piezoelectric KISTLER dynamometer to measure the forces in three axes namely, X, Y, Z. This dynamometer is placed on the bed of the machine
- Backing plate made of steel is placed on the dynamometer to support the FS processed sheet during the process.

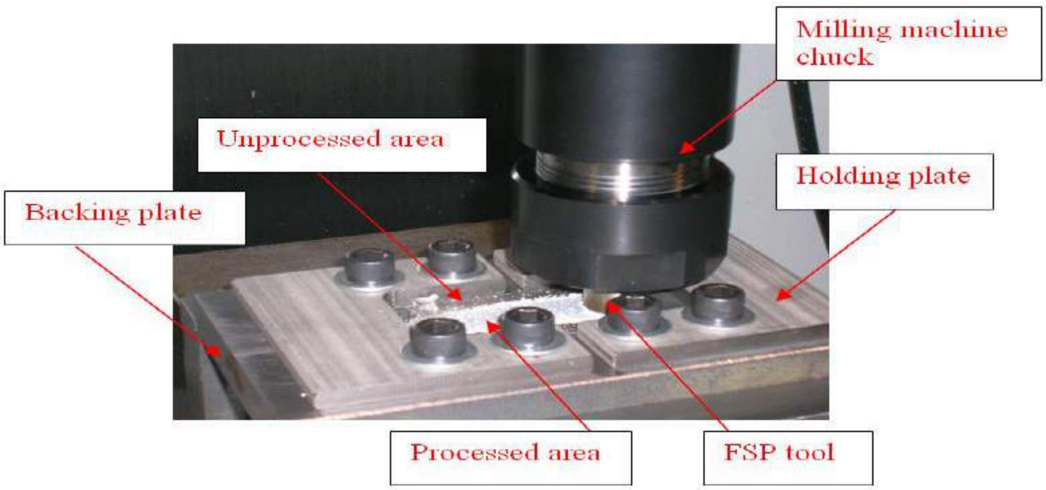

Fig. 4.1 Experimental Setup for FSP

5. EXPERIMENTAL PROCEDURE

As received AA5052 sheets are used for FSP Table 3.1. The process of FSP begins with the work piece being firmly clamped to a worktable via backing plate which is placed on the dynamometer. A small hole is drilled at the beginning of the sheet to initiate the penetration of the tool. The rotating pin is forced into the work piece and moved along the desired direction with a specific combination of rotational and translation speeds. Frictional heating is produced from the relative motion of the rotating shoulder with respect to the sheet being processed, while the rotating pin deforms rather generates a ‘stirring’ action which locally heats up and creates severe plastic deformation in the material. FSP can be considered as a hot working process in which a large amount of deformation is imparted to the work piece than the rotating pin and the shoulder.

FS processed zone is characterized by dynamic recrystallization which arises through either localized or large scale instabilities forming narrow or extended adiabatic shear bands. There is an apparent extrusion like behavior of material around the pin tool, the process is more characteristic of solid state flow facilitated by the adiabatic shear creating recrystallization regimes to accommodate the large deformations at high deformation rates. The result of this process is a homogeneous, equiaxed, dynamically recrystallized, fine grained material. In order to process the complete sheet, overlapping passes are used. The process is initiated by drilling a hole in the work piece, as it allows the pin to easily penetrate into the work piece as there is not enough heat generate at the beginning of the process to make the material soft.

The forces generated during the entire process are recorded using the data acquisition system. The processed sheets are then prepared for microstructural and mechanical testing.

Table 5.1 Composition of AA5052 by % weight

Alloy	Al	Cr	Cu	Fe	Mg	Mn	Si	Zn
% Wt	97.5	0.15-0.35	Max 0.1	Max 0.4	2.2-2.8	Max 0.1	Max 0.25	Max 0.1

6. FORCE ANALYSIS PROCEDURE

As the process of FSP is similar to a machining process one of the best methods to control and optimize the process is through studying the forces generated during the process and controlling these forces by controlling the process parameters.

Thus the forces generated especially the processing forces (Fx, Fy, Fz) are recorded during FSP of Al 5052 under various combinations of rotational and translation speeds using a 3-component piezoelectric KISTLER dynamometer which is connected to a DAQ system. The force data obtained is transferred into an Excel spread sheet and are sample using the root mean square (RMS) and averaging techniques (example 1).

$Fz = (\sqrt{(\sum fzi^2)})/ N$ …… where fz force at a particular instance N number of data points

$i = 1, 2 ...N$

These sampled force data are plotted with respect to the time of FSP. The average force data is also plotted with respect to the rotational and translational speeds. These plots give clear idea of the trends of the force with respect to speeds which can be used to control the process parameters and thus optimize the process.

7. MICROSTRUCTURAL ANALYSIS PROCEDURE

As received AA5052 samples are cold mounted, polished to 1µm flat and are finally anodized and observed under the polarized light optical microscope. After FSP, the surface of the sheet is cleaned and samples are cut for micro-structural study from three different locations of the processed sheet. The samples are cut across the cross section of the processed zone. They are cold molded and mechanically and electro polished to study under a polarized light optical microscope which would enable us to qualitatively comment on the grain refinement by friction stir processing. Further to quantify this refinement, the samples are prepared for TEM analysis.

8. RESULT AND DISCUSSION

Initial FSP experiments were performed on AA 6061-T6 and AA 2024-O alloy sheets in order to understand the process, choose the right dimensions and design of the tool and other process parameters. From these initial FSP experiments standardized procedures for processing and analysis i.e. both microstructure and force analyses were established. Further experiments were conducted on AA5052 as it was recently established that this alloy exhibits a super-plastic like behavior (190% elongation) at room temperature even with a coarse grained structure (~50µm). Hence with a finer grain this alloy might exhibit an enhanced super-plastic behavior

In the present section, the FSP tool design development and different modes of failure observed are also discussed along with the results for single pass friction stir processed AA5052 and some results of the initial experiments conducted on AA6061-T6. Adapting the procedure as explained above, sheets of aluminum alloys are friction stir processed. These results are presented mainly as two different sections which include 1) force analysis (for AA5052 and AA 6061) 2) micro-structural analysis (for AA5052) during FSP. Finally a correlation is established between the forces generated and microstructure evolved.

8.1 FSP tool design

The crucial part in this project was to design an experimental setup which would fit in the available machine tool. Understanding the tool design plays a very important role in friction stir processing. The initial FSP tool designed was a simple cylindrical tool with 1" shoulder diameter, diameter and height of the pin equal to the thickness of the sheets processed i.e., ¼". The forces generated using this tool especially during the penetration of the tool into the wok-piece, which were very high and beyond the capability of the dynamometer to measure.

Then we threaded the pin in order to reduce the initial high forces during penetration. This resulted in the reduction of forces but the forces seemed still higher to be measured. This led to the reduction in thickness of the work-piece. The sheets selected for processing where now 1/8” and accordingly the height of the pin was reduced to match the thickness of the sheet i.e., the height of the pin was reduced to 1/8”. And also a small hole was drilled to initiate the penetration of the tool and thus decrease the forces generated. It was the observed that the heat generated was very high and in order to reduce this frictional heat the shoulder diameter was reduced to ½”. Hence, we finally came up with a design that resulted in good processed zone at reduced forces. The tools design development discussed above is shown in Figure 4-1.

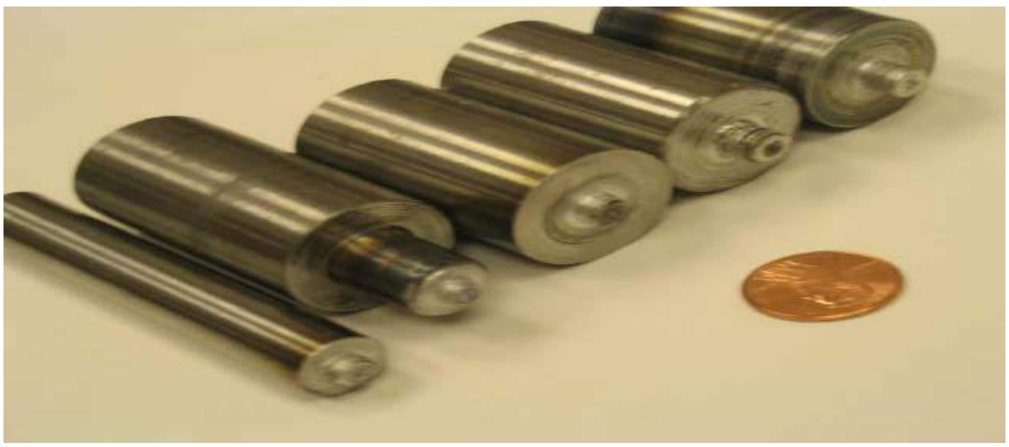

Figure 8.1 FSP tool designs latest to the oldest (left to right)

8.2 Modes of failure in FSP

FSP depends greatly on the amount of frictional heat generated during the process. The factors influencing the frictional heat generated during FSP include the processing conditions, tool design, use of backing plate and depth of penetration of the tool. Some of the modes of failure observed during FSP are shown in Figure 4-2. Tool design and alignment during processing are very important in order to obtain a good processed region. The ratio of shoulder and pin diameters is an important aspect of consideration. As this ratio increases the amount of frictional heat generated also increases and as a results of too much of heat generated at the shoulder-sheet interface the sheet material starts melting. Also it has been observed that the backing plate though increases the forces generated, supports the material to flow and beneath the pin and reduces the defects at the rare side of the processed sheet. This defect is also reduced by the using a smaller clearance between the tool tip and the lower surface of the sheet. Choice of process parameters like rotational and translational speeds also plays a crucial role.

At lower rotational speeds the frictional heat generated is insufficient and produces a defective processed zone which can be attributed to the process similar to that associated with the built-up edge formation in metal cutting process.

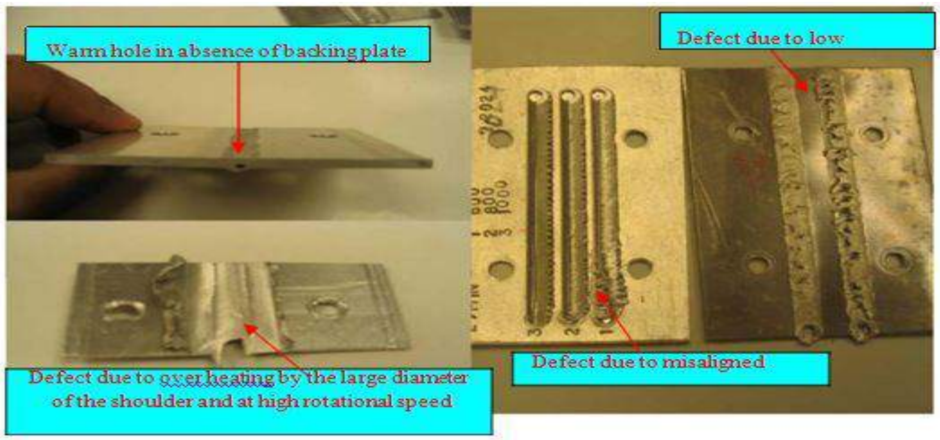

Figure 4-2 Failure modes observed during FSP of aluminum sheets

8.3 Force analysis

Aluminum alloy sheets are friction stir processed at various speeds and feeds and the processing forces (Fx, Fy, Fz) are measured using a 3-component piezoelectric KISTLER dynamometer for each combination of rotational and translational speeds.

The processing forces during FSP were observed to be very high during penetration of the tool but later as there was sufficient amount of frictional heat generated, the forces tend to decrease and then remain almost constant throughout the process. Figure 4.1 show the variation of the processing forces (Fx, Fy and Fz) with respect to rotational and translational speeds respectively. From these figures it can be observed that there is a significant variation in the plunge force Fz with the variations in the other process parameters Hence the behavior of plunging force (Fz) is studied with the variation of the process parameters such as rotational and translational speeds. Figure 4-5 shows the variation of Fz with the rotational speed for different constant translational speeds for AA5052. It is observed that at low rotational speed of 400 rpm the forces generated are very high and the process zone is also not defect free. As the speed is increased to 600 rpm the force generated is very low at all the translational speeds. A better and almost defect free process zone was obtained as the rotational speed was increased from 600-1000 rpm, for all translational speeds. However, it was observed that the forces generated during the process significantly increased as the rotational speed was increased from 600-1000rpm.The variation of Fz with translation speed at constant rotational speeds during FSP of AA5052 was also observed. At 1.5in/min the forces generated are high in comparison to the other conditions. As the speed increases to 2.5in/min the forces generated decreases. As the speed further increases from 2.5-3in/min the forces generated increase significantly at 800 and 1000rpm. However, at 600 rpm the forces generated decreases as the speed increases from 1.5 to 2in/min and there after the forces generated increase with the increasing speeds.But, it is also observed that the force generated at 400 rpm increased as the translational speed was increased from 1.5-2.0in/min and further increase in speed to 2.5 in/min decreased the force. Further increase in speed to 3in/min resulted in increase of the force. It is also observed at low translation speed the surface of the processed sheet is not defect free. Good surface finish is observed at higher translational and rotational speeds. Thus, from above it is concluded that the ideal combination in terms of plunge forces used is 600 rpm and 2in/min. It can also be concluded that very low speeds - both translational and rotational speeds result in very uneven forces and a bad process as there is not enough frictional heat generated for the softening the material and allowing the flow of the material.

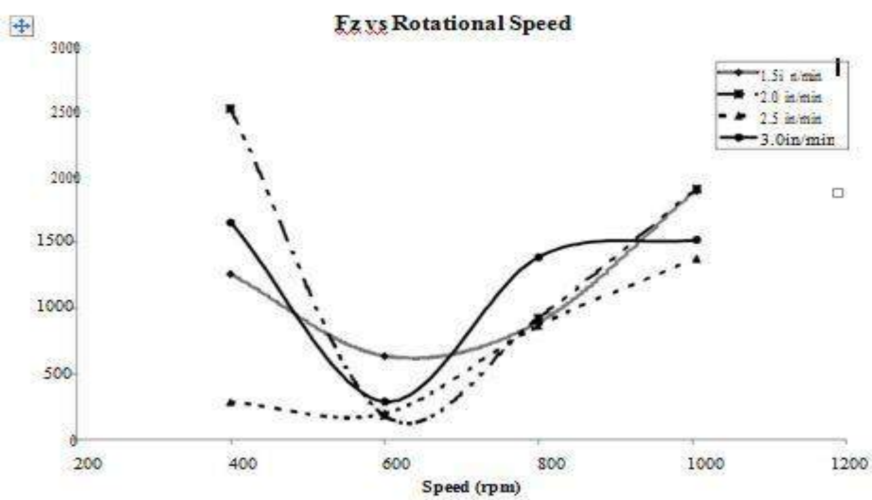

Fig. 8.2 The plunging force Fz vs. rotational speed at different translational speeds

8.4 Micro-structural analysis

The microstructure of the AA5052 unprocessed was observed under polarized light of an optical microscope and FS processed zone under Jeol-2000FX TEM. AA5052 sheets FS processed at various combinations of rotational and translational speeds are cut along the cross section and are prepared for metallographic study (to observe under both the optical microscope and also under transmission electron microscope for qualitative and quantitative analysis respectively. The grain refinement as a result of FSP can be qualitatively analyzed using these optical microscope pictures. In order to quantify this refinement the processed zone is observed under TEM.

It is observed that the grain refinement decreases at any particular translational speed with increasing rotational speed, which is accordance to the observations made by Sato et.al.

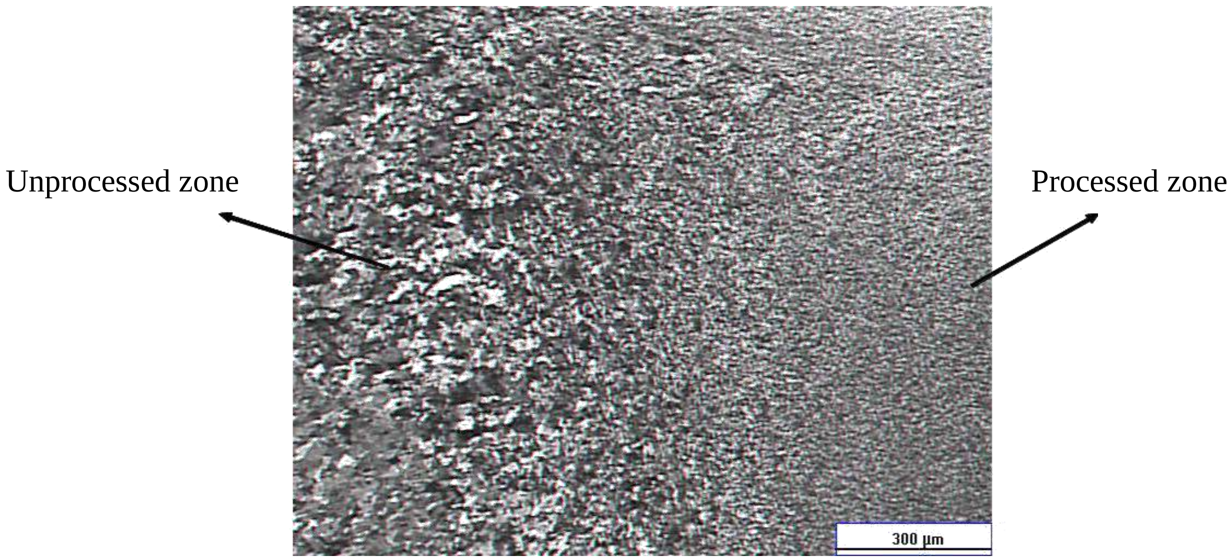

Figure 8.3 Transition zone from unprocessed to FS processed AA5052

According to this observation of Sato et.al, the grain size increase was exponential with the maximum temperature which was proportional to the increase in the rotational speed. Thus it is very evident that as either rotational speed increases the frictional heat produced increases and thus is the maximum temperature in the processed zone leading to the increase in the grain size.

9. CORRELATION BETWEEN THE FORCES AND THE MICROSTRUCTURE

From the above two sections we can observe that there exists a relationship between the grain size, plunging force Fz and rotational speed i.e. it is observed that as the rotational speed increases the forces increase and also the resulting grain refinement decreases. The increase in force with respect to the rotational speed seems to be exponential where as the grain size seems to be linear. And also the grain refinement is more at higher translational speeds though there is no significant influence of the translational speed on the plunging force. This might be because of lack of sufficient time available for the temperature increase and thus the grain growth of the refined grains at higher translational speeds.

10. CONCLUSIONS

The friction stir processing is an efficient technique for grain refinement; it reduced significantly the average grain size for AA5052 sheet from 13.41 μm to 1.67 μm at certain processing parameters. The resulting grain size depends on the processing parameters, and it is shown in this work that grain size decreases as the translation and rotation speeds are reduced.

The relation between the forces generated and the processing parameters (rotational and translational speeds) is presented in this work, and generally as the rotational speed increased the plunging force increases. Additionally, it was observed that the finest grain structure and the minimum plunging force were achieved under the same processing condition. This is a preliminary result and more tests and data are needed to develop a more general correlation. However, if a correlation between the forces and the resulting microstructure can successfully be developed, it would be then possible to control the microstructure during processing by monitoring the forces generated.

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