APPENDIX: PUBLICATIONS

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International Conferences


Effect of polygonal pin profiles on friction stir processed superplasticity of AA7075 alloy

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A B S T R A C T

Recently friction stir processing (FSP) has shown keen interest to achieve superplasticity in different aluminum alloys. The pin profile of FSP tool is one of the important process parameter which controls the mechanical and metallurgical properties of stir zone (SZ), like other variables of tool rotational speed, travel speed, and tool tilt. The high strength 7075 aluminum (Al–Zn–Mg–Cu) alloy was subjected to FSP to investigate effects of pin profiles on the superplastic behavior. Three different polygonal pin profiles of square, pentagon and hexagon were used. Microstructure, microhardness and grain size measurements were performed for all FSP samples. Fine grain uniform microstructure without cavitation in the SZ was observed in sample produced by square pin only. All polygonal pin profiles indicated sticking of workpiece material around tool pin that resulted in non-uniform grain microstructure in the SZ. Hot tensile testing was carried out for square pin under the superplastic condition of $3 \times 10^{-6} s^{-1}$ and $400^\circ C$ to study the superplastic behavior. Uniform superplastic elongation of 227% was obtained in the gauge region of the square pin sample.

1. Introduction

Friction stir processing (FSP) is a solid state process employed to alter the mechanical and metallurgical properties of materials such as aluminum, copper, and magnesium. FSP is one of the variants of friction stir welding (FSW) which uses basic principle of FSW (Mishra and Mahoney, 2004). Fig. 1 displays the working principle of FSP in which non-consumable rotating tool plunges into a workpiece, traversed in the processing direction and finally retracted from the workpiece. During the process, FSP tool induces intense plastic deformation of the workpiece. The tool geometry mainly consists of shoulder and pin, which are responsible for frictional and plastic deformation of workpiece respectively (Patel et al., 2016c). The FSP region is divided into two different zones i.e. stir zone (SZ) and thermomechanically affected zone (TMAZ). The SZ consists of fully recrystallized, equiaxed, fine grain microstructure due to shearing and mixing of work material around the tool pin (Behbahani et al., 2012; Chauri and Mishra, 2003). Recently FSP has shown potential for applications such as surface composite manufacturing (Sharma et al., 2015), fatigue life improvements of Mg welds (Borrego et al., 2014; Costa et al., 2014), grain refinements (Patel et al., 2016d; Thompson et al., 2013), and superplasticity (Patel et al., 2016c).

Superplasticity is a property of material to achieve more than 200% uniform elongation under tensile loading. Hence, superplastic materials offer designer and manufacturer to produce complex shape components by using various types of materials including low joint strength aluminum alloys such as AA7075. The fine-grained microstructure is a preliminary requirement to obtain superplasticity. However, the fine-grained microstructure is mainly unstable at the higher temperature, which results into degraded superplasticity (Charit and Mishra, 2005). Hence, in order to achieve superplasticity, a stable fine-grained microstructure at higher temperature is necessary. The FSP has been have been investigated for superplastic behavior in different aluminum alloys. Raha et al. (2014) reported superplasticity of the friction stir processed Al–4.5 Mg–0.35 Sc–0.15 Zr alloy; Pradeep and Pancholi (2013) produced superplastic bulk area by multipass FSP in aluminum alloy; Smolj et al. (2014) produced Superplasticity in friction stir processed Al–4.5 Mg–0.35 Sc–0.15 Zr alloy.

The AA7075 alloy is high strength alloy among Al alloys which is extensively utilized for aerospace applications because of its high strength to weight ratio, good fracture toughness and high resi-
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1. Schematic illustration of friction stir processing.

Fig. 1. Schematic illustration of friction stir processing.

2. Experimental procedure

Commercial AA7075-T651 thick plate (100 × 100 × 6.5 mm$^3$) was used to perform FSP. The conventional stainless steel fixture shown in Fig. 2 was used to prevent distortion of the workpiece under action of downward forces during the process. Heat treated M2 grade tool steel was used for fabrication of all FSP tools. Three different pin profiles such as square, pentagon and hexagon were designed and manufactured as displayed in Fig. 3. The tool dimensions of shoulder diameter 20 mm and 6 mm pin length were same for all FSP tools. Pins were designed by keeping the constant dynamic volume of the pin during FSP. The thermal history of the samples was recorded by mounting k-type thermocouple 3 mm away from the shoulder surfaces on both advancing side (AS) as well as retreating side (RS) of the workpiece.

The temperature was measured using a multipoint temperature controller with a resolution of 0.1 °C. The temperature controller was interfaced with computer and temperature was recorded at every 2 s during the process. Fig. 4 represents entire experimental setup.

Three FSP samples were produced at 765 rpm rotational speed, 31.5 mm/min$^{-1}$ travel speed, and 2" tool tilt since these parameters were indicated good thermal stability to the microstructure during high temperature tensile test (Patel et al., 2016a). Samples were cut transverse to the direction of tool travel, and ground and polished using diamond paste to obtain surface finish of 1 μm. Keller’s etchant was applied to etch prepared specimens for revealing grain boundaries. The prepared specimens were studied using an optical microscope and scanning electron microscope (SEM). Vickers hardness measurement device used to measure microhardness within the processing zone by taking indentation at a spacing of 1 mm under the testing conditions of 0.3 kgf load and 10 s loading time.

Flat tensile specimens of gage dimensions of 20 × 6 × 1 mm$^3$ were cut longitudinal to the processing zone using a wire cut electro discharge machine (EDM). Specimens were cut in consideration that gage dimensions matched with the region of SZ. High temperature tensile testing was carried out on INSTRON 5982 universal testing.
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machine to measure the superplasticity in terms of elongation. Hot tensile tests were performed at the strain rate of $3 \times 10^{-4} \text{s}^{-1}$ and temperature of 500°C. The tensile specimens were kept at 400°C in a furnace for 30 min to obtain temperature equilibrium inside the furnace.

3. Results and discussion

After FSP, all the samples were visually observed to study surface morphology and no surface defects found in any of the samples. Fig. 5 shows surface appearance for all FSP samples.

3.1. Thermal history during FSP

Temperature distributions of all samples during FSP are shown in Fig. 6.

The upward trend of the graph is heating curve while downward trend is a cooling curve. The cooling curve is little steeper than the heating curve. The thermal history on both sides of AS and RS was found almost similar. The temperature graphs do not represent the exact value of temperature at the nugget or SZ, but could be used as a comparison among the temperature profiles of different pin profile samples could be carried out. The heat index (HI)
in FSP is the ratio of rotational speed to travel speed. The value of HI was same for all the samples because they were produced under same rotational and travel speed. The temperature history of the samples during process is estimated from the frictional heat generated between tool and workpiece (Patel et al., 2016b). The frictional heat generated can be divided into two regions. First, the contact between tool pin and workpiece where the pin profile plays a significant role in heat generation. Second, the contact between tool shoulder and workpiece top surface. Maximum temperature of 379°C, 368°C, and 346°C was reported for the square, pentagon, and hexagon pin profiles, respectively during the process. Important observations are made from Table 1 that represents the effective contact area of the pin and shoulder for all polygonal pin profiles.

First, the effective shoulder area is much higher than the effective pin area for all the FSP tools. Second, the effective shoulder area decreases as we move from square to hexagon pins. Third, the effective pin area increases as we move from square to hexagon pin. Since majority of heat is produced by the shoulder region in all samples, the square pin reported the highest maximum temperature during FSP in comparison to pentagon and hexagon pin samples. Hence, the SZ is a result of severe stirring and shearing of the material by the tool which creates maximum temperature during the process at the SZ. It is understood that SZ is a reflection of the tool pin profile used because the pin is responsible for the material flow.

### Table 1

<table>
<thead>
<tr>
<th>Pin profile</th>
<th>Effective area of the pin, mm²</th>
<th>Effective surface area of the shoulder, mm²</th>
<th>Maximum temperature, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square</td>
<td>120</td>
<td>296.15</td>
<td>379</td>
</tr>
<tr>
<td>Pentagon</td>
<td>127.30</td>
<td>292.76</td>
<td>368</td>
</tr>
<tr>
<td>Hexagon</td>
<td>131.38</td>
<td>290.78</td>
<td>346</td>
</tr>
</tbody>
</table>

#### 3.2 Macrostructure and microstructure observations

Figs. 7 and 8(a), (b) represent the macrostructure and microstructures of square, pentagon and hexagon pin samples, respectively. The micrographs at the top of the macrostructure represent the TMAZ/SZ interface while those at the bottom of the macrostructure represent SZ. Macrostructures are categorised in three regions of top, middle and bottom for better understanding. Also, the microstructures based on each region at TMAZ/SZ interface and SZ are shown in Figs. 7 and 8. The macrostructure of all three samples has revealed complete penetration of the tool pin in the SZ. From the macrostructure interesting observation can be made about the material flow for all the samples. The material flow was shoulder driven at the top region while pin driven at the middle and bottom region. Microstructures of all three samples have revealed the transition in the microstructure between TMAZ and SZ. TMAZ consisted of slightly elongated pancake grain microstructure while SZ exhibited fine equiaxed grain microstructures in all samples. The fine grain microstructures in the SZ are the result of the dynamic recrystallization during FSP (Su et al., 2005). For square pin samples, the macrostructure as well as the microstructures at all regions have reported a defect free SZ.
In case of pentagon pin samples, the little cavitation was observed in the macrostructure at the middle region as shown in Fig. 8(a). For hexagon pin sample, cavitation was also observed in the macrostructure at the bottom of TMAZ/SZ interface as revealed in Fig. 8(b). Additionally, the SZ microstructure reflects the material flow around the pin during the plastic deformation. For polygonal pin, the pulsating actions give rise to the turbulence in stirring and mixing of the material. As number of faces in pin increases the level of turbulence also raises, which may lead to inadequate material movement around the pin. Therefore, pentagon (5 faces) and hexagon (6 faces) pins having more faces generated cavitation due to inadequate material flow around the pin. The square pin (4 faces) sample with less number of faces could have provided the best pulsating action followed by better stirring and mixing of material. Hence, square pin sample has produced the defect free SZ.

The noticeable observation was made for all three samples that tool pin became cylindrical in shape after the FSP as shown in Fig. 9. The tool pin was altered due to sticking of the work material around the tool pin. The sticking of aluminum around tool pin was also observed in the microstructures of the samples that resulted into interrupted shearing and mixing of the work material and hence non-uniform microstructure in the SZ. Sticking of the work material around tool pin is mainly due to the high heat input and could be minimized by adopting low tool rotation or high traverse speed during FSP.

Microhardness distribution in all FSP samples along the processing zone is displayed in Fig. 10. The center portion of the graph represents microhardness in the SZ of respective samples. The maximum value of the microhardness in the SZ was observed of 107, 130, and 128 for square, pentagon and hexagon pin samples respectively. The average hardness in the SZ was found of 103, 116 and 115 HV for the square, pentagon, and hexagon pin sample respectively.

In case of pentagon and hexagon pin samples the hardness values were found almost similar. Moreover, the polygonal pin generates excess turbulence of the plasticized materials due to pulsating actions generated by pin during the process. Hence, the material flow is greatly influenced by number of faces in polygonal pin. More number of faces in pin increases the pulsating actions and consequently intensity of plastic deformation. This increased plastic deformation also increases the material dislocation density which leads to higher hardness for pentagon and hexagon pin samples. Square pin sample generated the highest peak temperature during the process and that would have dissolved the precipitates as the AA7075 alloy is precipitate hardening alloy. This could have resulted into the low value of maximum as well as average hardness in the SZ for square pin sample. In the case of pentagon and hexagon pin samples, the hardness values were found almost similar. The hardness distribution in the SZ was found more uniform in case of square pin sample than pentagon and hexagon pin samples as shown in Fig. 10.

Since square pin generates less pulsating actions, the level of turbulence in the plastic deformation is moderate in comparison to pentagon and hexagon pins. Hence, uniform hardness distribution in the SZ could have resulted because of adequate material flow around the square pin. For precipitation hardening Al alloys, hardness enhancement in SZ is also influenced by the re-precipitation after completion of the process (Can et al., 2014).

### 3.3 Hot tensile testing in order to investigate superplastic behavior

The pentagon and hexagon pin samples have reported cavitation in the SZ that hinders elongation during the high temperature testing. Hence, only square pin sample has been studied for the
Fig. 8. A montage of optical macrostructure and micrographs of the FSP samples: (a) pentagon pin, and (b) hexagon pin.
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Fig. 9. Pin shape after FSP: (a) square, (b) pentagon, and (c) hexagon.

Fig. 10. Microhardness measurement in processing zone of FSP samples.

Fig. 11. Square pin sample SZ (a) SEM image, (b) EDS analysis.
superplastic behavior by hot tensile testing. Fine grain microstructure is the preliminary requirement to obtain superplasticity. Fig. 11(a) shows the SEM image of the square pin sample SZ that revealed uniform fine grain microstructure without any partial melting in the SZ where the process temperature is maximum. The average grain size of 6.90 μm was measured using linear intercept method. Energy dispersion spectroscopy (EDS) analysis was performed on the square pin sample to find the presence of the secondary phase particles to form various strengthening phases. Fig. 11(b) reveals the EDS of the square pin that indicated the comparable weight percentage of Al(95%), Zn(4.22%), Mg(1.73%) and Cu(1.19%). Furthermore, X-ray diffraction (XRD) was performed for the square pin SZ to know the presence of strengthening phases. Fig. 12 shows the XRD pattern of square pin SZ, which represented the different phases such as MgZn2 and Al12Mg17. This analysis has confirmed the presence of second phase strengthening particles in the SZ microstructure which are responsible for the enhanced mechanical properties. Fig. 13 represents the superplastic deformation of the square pin sample at a strain rate of $3 \times 10^{-4} \text{s}^{-1}$ and a temperature of 400°C. Uniform elongation (>200%) was observed in the gage region that ensured the superplastic behavior. The sample was deformed at the high temperature and necking was observed at the fracture surface. Fig. 13(b). Hence, Square pin generated fine grain microstructure having thermal stability since the fine grain microstructure with thermal stability is the foremost requirement for achieving superplasticity.

The stress-strain diagram of the hot tensile test is displayed in Fig. 14. The flow stress is reduced at higher temperature. The maximum flow stress of around 12 MPa was reported to obtain an elongation of 227%. The superplastic behavior can be enhanced by minimizing the flow stress during the forming. The low value of the superplastic elongation could have resulted due to the instability of the microstructure at high temperature. It can be observed in the stress-strain curve that after the maximum flow stress value the elongation as not in steady-state. The formation of larger size dimples were observed in the fractography of the fractured surface as shown in Fig. 15. The large size of the dimples were formed due to the higher ductility during high temperature deformations.

4. Conclusions

By this investigation the following points are summarised:

- The square pin sample generated the highest maximum temperature during FSP due to the larger effective shoulder area available to the tool geometry.
- The square pin sample was produced without any cavitation but the pentagon and hexagon pin samples have reported cavitation in the SZ due to inadequate material flow around pin.
- The lowest value of maximum as well average microhardness in uniform manner was obtained in the SZ produced by square pin. The lowest value and uniform distribution of hardness was characterized by the highest temperature and adequate material flow, respectively.
- Defect free sample of square pin exhibited superplastic behavior by achieving 227% uniform elongation in gage region. Square pin is recommended among the polygonal pins for FSP in AA7075 to obtain superplasticity.
Fig. 15. Factography of the fractured surface during the high temperature deformation.

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References

Appendix

APPENDIX B: PAPER 2

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Influence of Friction Stir Processed Parameters on Superplasticity of Al-Zn-Mg-Cu Alloy

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Friction stir processing (FSP) is a novel technique for refining the microstructure. In this study, the effect of FSP process parameters such as tool rotation, traverse speed and tool tilt on resulting grain size, microstructure and superplastic behavior of high-strength thick Al-Zn-Mg-Cu alloy is reported. The microstructure examination of the stir zone (SZ) was performed by optical as well as scanning electron microscope. Microstructure variation attributed to different process parameters is reflected in the SZ. It is observed that grain size increases with increasing tool rotation speed, and decreases with increasing traverse speed. However, tool tilt has no significant effect on grain size. Moreover, at higher tool tilt distorted grains were observed in microscopic images. The highest average value of hardness in the SZ is obtained for low heat input value corresponding to higher tool rotation and traverse speed. In this study, hardness has shown no dependency on the grain size of the SZ due to the strengthening of phase particles. Process parameter of 1500 rpm, 31.5 mm/min and 2° tool tilt (low heat input) only exhibited superplastic elongation of 225% at a superplastic condition of 400°C and 3×10^-4 s^-1 because of an appropriate material flow without any defect.

Keywords: 7075; Electron microscopy; Friction; Microstructure; Superplasticity.

INTRODUCTION

Superplasticity is the ability of a polycrystalline material to obtain more than 200% uniform tensile elongation before the fracture takes place. There are two basic requirements for superplasticity: one is fine-grain microstructure and the other is thermal stability of fine-grain microstructure at higher temperature. In precipitate strengthening alloy, size and distribution of second-phase particles after processing play an important role in governing microstructure features to achieve superplastic behavior. Fine-grain microstructure without thermal stability will not exhibit superplasticity. Superplastic forming (SPF) has emerged as an attractive, commercial, cost-effective, near-net-shaped forming process to produce complex shaped unitized structures [1]. However, SPF has not become popular as expected because of its high material cost. Attempts over the years have been made to reduce the overall cost in metallurgical and manufacturing aspects.

Over the last decade friction stir processing (FSP) has emerged and developed as a novel technique to obtain superplastic behavior in various aluminium alloys. FSP comprises a rotating tool, featured by shoulder and pin inserted in a work material to modify the microstructure for specific property enhancement rather than joining the metals [1]. Figure 1 illustrates the basic working principle of FSP. During FSP, intense plastic deformation of the work material occurred due to friction between the tool and work. This FSP region results in a stirred zone (SZ) with a fully recrystallized, equiaxed and very fine-grained microstructure [2–4] and refinement of constituent particles [5].

The aerospace sector finds a large number of applications for high-strength aluminium (Al) alloys having superplasticity. 7xxx series Al alloys are the commercial heat-treatment alloys. 7075 (Al-Zn-Mg-Cu) Al alloy is aircraft material and widely used for aero structures such as airframe and airfoil because of its good mechanical properties such as strength, hardness and fracture toughness [6–9]. 7075 Al alloy is susceptible to hot cracking, which led to very poor joint strength [10]. Moreover, as a primary alloying element, zinc creates problems such as porosity, lack of fill and fumes due to oxidation and vaporization of zinc. Hence, this alloy has a very few applications where fusion welding is involved [11]. Achieving superplasticity (>200% uniform elongation) in 7075 Al alloy eliminates the need for joint, which allows the production of complex-shaped unitized structures [12]. Hence, during the past few years 7075 alloy has been subjected to FSP and superplastic investigations by researchers [13–24]. Table 1 is a summary of FSP of 7075Al alloy to achieve superplastic behavior in terms of high strain rate superplasticity, low-temperature superplasticity, multiple passes and FSP parameters such as tool rotation and traverse speed. As per the author’s best knowledge, no literature is available describing the effect of FSP parameters on superplasticity. Thus, the aim of this study is to investigate the combined effect of FSP process parameters such
Influence of Pin Profile on the Tool Plunge Stage in Friction Stir Processing of Al–Zn–Mg–Cu Alloy

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Abstract Friction stir processing (FSP) is a solid state process for refining the microstructure. Though FSP has shown significant impact in manufacturing industry, a detailed investigation is needed for further development of the process. The current article presented an experimental investigation on tool plunge stage by using different pin profiles such as conical, square, pentagonal and hexagonal. Influence of pin profiles on the temperature distribution around the tool during plunge has been studied. Thermocouples were placed at two different locations around the tool in the workpiece of Al–Zn–Mg–Cu alloy and temperatures were measured simultaneously at both the locations. FSP tools with different pin profiles under same process parameters were used to study the effects of pin profile on the temperature of the workpiece. Temperature profile was found to be asymmetric around the tool. During plunging stage, it was observed that the temperature due to plastic deformation at pin was less than the temperature caused by friction on the workpiece. Compared to other pin profiles, pentagon pin generated more temperature during the plunging. Further, tool shoulder had significant influence on the workpiece temperature compared to tool pin.

Keywords 7075 · Conical · Friction · Hexagon · Pentagon · Pin · Plunge · Square · Temperature

1 Introduction

Friction stir processing (FSP) is derived from the friction stir welding (FSW). FSW, invented at The Welding Institute (TWI) of UK in 1991, is a solid-state joining process [1]. FSP has been developed by Mishra and Mahoney [2] based on the basic principles of FSW. FSP is also a solid-state process in which the properties of the material are altered, rather than joining of materials in case of FSW [3]. FSP have been demonstrated as a generic process to modify the microstructure (grain refinement) [4]. Apart from grain refinement, FSP has been found to enhance mechanical properties such as tensile strength, ductility, hardness, fatigue strength and tribological properties such as wear and corrosion resistance [5, 6]. Recently, FSP of cast aluminium alloys has reported enhanced mechanical properties [6–8] and tribological properties [9–12]. Due to the solid state nature, FSP is more popular in aerospace, marine and shipping industries.

Figure 1 represents the working principle of FSP, in which the process is carried out in three stages called plunge, feed and tool retraction [13]. At the first stage of plunging, the non-consumable tool with set rotational speed penetrates into the workpiece by applying downward force. Tool geometry consists of shoulder and pin profile as shown in Fig. 1. Tool keeps penetrating into the workpiece until the full penetration of pin and shoulder makes contact with the top surface of the workpiece. Heat is generated and temperature of workpiece is raised due to friction between tool and work interfaces. Initial temperature rise is attributed to plunge stage where friction occurs between tool pin and workpiece. Further increasing the plunge depth, more friction is generated and hence temperature rises gradually. During second stage, feed is applied after the contact is established between tool shoulder and
APPENDIX D: PAPER 4

Friction Stir Processing as a Novel Technique to Achieve Superplasticity in Aluminum Alloys: Process Variables, Variants, and Applications

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Abstract This article provides an overview of the potential for superplasticity of aluminum alloys using friction stir processing (FSP). FSP is a variant of friction stir welding (FSW), and FSP is an effective technique to alter the metallurgical and mechanical properties of the material, which results in superplastic properties at high strain rate and low temperature. This makes FSP as an attractive and cost-effective method to produce superplastic materials. A detailed summary of previously reported superplasticity in all aluminum alloys using FSP is tabulated in this review. It reveals the influence of tool design, machine variables, number of passes, active cooling, grain size, superplastic temperature, strain rate, and elongation on the superplastic properties of FSP aluminum alloys. Variants of FSP to achieve superplasticity at optimized conditions are proposed based on dual rotation of tool and additional cooling during the process. Applications of superplastic forming in aerospace and automotive are discussed. The direction of research in friction stir-processed superplasticity is covered in future scope.

Keywords Aluminum · Forming · Friction · Processing · Recrystallization · Strain · Stir · Superplasticity

Introduction to Achieve Superplasticity in Aluminum Alloys

Superplastic forming (SPF) is able to produce simple to complicated parts without the requirement of having a joint present. However, the high starting cost of superplastic material has restricted its application in many industrial applications. For the past few years, efforts have been made to reduce the cost of the superplastic materials in metallurgical and manufacturing contexts. Metallurgists have been working to reduce cost of basic materials, while manufacturing engineers have been working to increase the productivity by optimizing superplastic conditions such as the lowest temperature and the highest strain rate.

Principle of Superplasticity

Superplasticity is the ability of any metallic material to exhibit more than 200% uniform elongation under tension prior to failure [1]. A fine grain microstructure is a key factor to obtain superplasticity. This microstructure consists of the following elements [2]:

- Fine grain size (<15 µm)
- Equiaxed grain arrangement
- High-angular grain boundaries
- Presence of fine second-phase particles to hinder the grain growth

The aforementioned properties are important because the dominant mechanism in superplasticity is grain boundary sliding (GBS). Deformation at high temperature based on GBS can be described by a generic constitutive relationship [3]:

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Effect of velocity index on grain size of friction stir processed Al-Zn-Mg-Cu alloy

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Abstract

Friction stir processing is an effective tool for microstructure modification by refining the microstructure in aluminum alloys. In this study, the effect of velocity index (tool rotation speed /traverse speed) on resulting grain microstructure of friction stir processed high strength Al-Zn-Mg-Cu alloy is reported. The velocity index is a key factor to decide the heat input during the process. Three samples were manufactured at different velocity index. The hardness measurement was performed to understand the hardness distribution in the processed region at different velocity index. The microstructure examination of the stir zone was performed by optical microscope. All the samples exhibited the stir zone with fine equiaxed grain microstructure. It is observed that grain size decreased with decrease in the value of the velocity index.

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Keywords: 7075 aluminum; friction stir processing; grain size; microstructure; process parameters; velocity index.

1. Introduction

Friction stir processing (FSP) was developed by Mishra et al. [1, 2] based on the basic principles of friction stir welding (FSW). Like FSW, FSP comprises a rotating tool, which is inserted in a monolithic workpiece to modify microstructure for specific property enhancement rather than joining the metals as shown in Fig. 1. The rotating tool consists of shoulder and pin region. The pin is responsible for plastic deformation of the workpiece material, while shoulder is responsible for frictional deformation. The stirring action of the pin generates fine grain microstructure zone, which is called the stir zone (SZ).

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Cavitation in Friction Stir Processing of Al-Zn-Mg-Cu Alloy

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Abstract—Friction Stir Processing (FSP) is a solid state process to modify the microstructure of the metals. FSP was carried out on the high strength aluminium alloy to investigate the defects such as cavitation. Temperature profiles were recorded to evaluate the maximum temperature during FSP. Macro and Microstructure examination was performed after FSP using optical microscopy. Cavitation was observed in all FSP samples at different locations and amount within the processing zone. High heat input samples reported more cavitation volume compared to low heat input sample. Pin geometry was found the governing factor for material flow and consequently the level of the cavitation during FSP.

Index Terms—aluminium, cavitation, friction, parameters, process, stir

I. INTRODUCTION

Friction stir processing has gained popularity in material processing industries due to its solid state nature. FSP consists of the non-consumable rotating tool, which is inserted in workpiece to modify the microstructure for specific property enhancement [1]. Fig. 1 shows the schematic of the FSP. FSP tool possesses geometry in form of shoulder and pin as shown in Fig. 1. During FSP the heat is generated due to plastic and frictional deformation of workpiece by tool. The temperature of the process is always remain below the melting point of the workpiece material. Tool pin and shoulder geometry are responsible for plastic and friction deformation respectively. This intense plastic and friction deformation of the workpiece results in a stirred zone (SZ) with a fully recrystallized, equiaxed and fine grain microstructure [2]-[6]. The pin is responsible for the generation of the SZ and the shoulder generates the thermo mechanically affected zone (TMAZ) near to the SZ [7].

Fine grain microstructure is a preliminary requirement to obtain the superplasticity behavior. Superplasticity is an ability of metallic material to achieve more than 200 % uniform elongation before fracture takes place. Superplastic material offers designer to design complex geometry which can be formed without need of any joint. 7075 (Al-Zn-Mg-Cu) alloy possesses the highest strength among all aluminum alloys. It is widely used in the aerospace industries due to its good mechanical properties such as strength, hardness and fracture toughness. Welding of 7075Al alloy is difficult because of its poor joint strength [9]. Hence, by achieving superplasticity in 7075Al using FSP eliminates need of the joint to manufacture unitized structure [10]. Researchers have reported superplastic behavior in different aluminum alloys through fine grain microstructure using FSP [8], [11]-[16]. The SZ of friction stir processed material consists of the fine grain structure. The characteristics of SZ depend on the pin geometry and the process parameters such as tool rotation and traverse speed during FSP. Cavitation in the SZ is considered as prominent defect which hinders the superplastic behavior of friction stir processed material even though having fine grain microstructure. The aim of the present investigation is to find the effects of process parameters on cavitation during FSP of 7075Al.

II. MATERIALS AND METHODS

Aluminium 7075 plate of 100 mm long, 100 mm wide and 6.5 mm thick was processed by using heat treated tool of tool steel material. Chemical composition of AA 7075 is mentioned in Table I. Tool geometry comprise shoulder diameter of 20 mm, pin length of 6 mm having tapered threaded cylindrical pin of top diameter 6 mm and bottom diameter 3 mm as shown in Fig. 2(a). Contact type thermocouple was used by drilling 1 mm hole at center and distance of 3 mm from the processed region to measure the temperature on advancing side (AS) as well as Retreating Side (RS) as shown in Fig. 2(b). The fixture of stainless steel was used to prevent deflection of the workpiece during FSP. Three samples were prepared at different process parameters as shown in Table II. Tool tilt angle was maintained at 2° for all the samples. Transverse cross section of processed samples were cut to prepare specimens for microstructure study. FSP samples were cut, ground and polished for optical microscopy.
APPENDIX G: PAPER 7

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Title: Influence of pin profile on friction stir processing of Al-Zn-Mg-Cu alloy

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SYNOPSIS

Friction stir processing (FSP) as a variant of friction stir welding is a solid state process for refining the microstructure. FSP has shown significant impact in manufacturing industry, a detail investigation is needed for further development of the process. This article attempts an experimental investigation to study effects of pin profiles on temperature distribution around the tool and resulted microstructure during FSP. FSP tools with different pin profile such as threaded conical, square, pentagon and hexagon under same process parameters were used to perform FSP of high strength Al-Zn-Mg-
Cu alloy. Thermocouples were placed at four different locations around the tool in the work material and temperature at the all four points were measured simultaneously. Temperature profile was found asymmetric around the tool for respective pin profile. Polygonal pin profiles became circular in shape after FSP due to sticking of the work material around the pin. The sticking of the work material played significant role in the resulting microstructure of the stir zone. The threaded conical pin obtained uniform equiaxed fine grain microstructure, while polygonal pin profile exhibited non uniform fine grain microstructure due to sticking of the work material around the pin inhibited the plastic deformation by the pin. This investigation concluded the approach towards the pin profile and process parameters to perform FSP. Different pin profiles require the different process parameters to obtain defect free FSP sample.

KEYWORDS

7075, friction, microstructure, pin, stir,
APPENDIX H: PAPER 8

Experimental Investigation on Hybrid Friction Stir Processing using compressed air in Aluminum 7075 alloy


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Abstract

Aluminum 7075 alloy is a popular candidate material in aerospace industries due to its excellent strength to weight ratio among the aluminum alloys. Friction stir processing (FSP) is a solid state process to refine the microstructure that results into enhanced mechanical properties such as hardness and superplasticity. FSP of 7075Al has proven to obtain superplasticity, which eliminated need of joint in structural applications. The thermal history during the process greatly affects the resulting microstructure. By reducing the process temperature, the grain growth of 7075Al gets inhibited and hence very fine grain microstructure can be produced, which is a primary requirement for obtaining superplasticity. Even though FSP maintains the process temperature below the melting point, the approach of hybrid FSP with active cooling offers further reduction in the generation of process temperature. Hybrid FSP with active cooling is one of the variant of FSP. In this study, 7075Al was subjected to normal FSP and hybrid FSP with compressed air cooling. Experiments were conducted on graphical abstract under constant process parameters. Active cooling FSP sample reported considerable reduction in the temperature in comparison to normal FSP. No surface defect was observed in the processed zone for both the samples. The optical micrograph revealed fine equiaxed grain structure in the stir zone for both the samples. Hybrid FSP samples reported elongated fine grain microstructure in comparison to the normal FSP due to less heat input during the process.

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Keywords: 7075; FSP; grain; hybrid; microstructure

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EFFECT OF VARIOUS COOLING TECHNIQUES ON GRAIN REFINEMENT OF ALUMINUM 7075-T651 DURING FRICTION STIR PROCESSING

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ABSTRACT
Aluminum 7075 alloy (AA 7075) is one of the prime materials used in the aviation and automotive industry because of its high strength to weight ratio, good amount of fatigue strength and high machinability. Friction stir processing (FSP) is one of the emerging solid state process that refines the microstructure and hence improved mechanical properties are obtained. The process temperature during FSP affects the resulting microstructure so the attempt for reducing the process temperature can result into reduction in the grain size. The fine grain size microstructure delivers high percentage of elongation which reduces the number of joints and welds in the critical structural applications. So, by implementing coolants such as water and carbon dioxide (CO2) during this process had hindered the grain growth and very fine grained microstructure was obtained. The fine grain microstructure offers higher elongation and hardness as deformation starts from the grain boundaries. In this experimental investigation we intended to keep the temperature generation during the process as low as possible by keeping the process parameters of 765 rpm, 31.5 mm/min feed rate and 20 tilt of the tool (optimized for tapered threaded cylindrical pin tool) constant. All the samples were examined by metallographic characterization using optical microscope. The grain size measurements for all three FSP samples were carried out. Water and CO2 cooled FSP samples reported much more fine grain as compared to naturally cooled sample because of the less heat input during the process.

Keywords: 7075; aluminum, FSP; grain; hybrid; microstructure

INTRODUCTION
Aluminum 7075 alloy (AA 7075) is one of the prime materials used in the aviation and automotive industry because of its high strength to weight ratio, good amount of fatigue strength and high machinability. Friction stir processing (FSP) is a variant of the friction stir welding (FSW). FSP uses same basic principles of the FSW for modifying the mechanical and metallurgical properties of the base material. During FSP the process temperature is always maintained below the melting point of base material and hence it is considered as solid state material processing technique. Mishra et al. invented FSP as material processing technique to enhance superplasticity for forming process [1]. Figure 1 represents the working principle of FSP with necessary nomenclatures. FSP involves non-consumable rotating tool having two main features in form of shoulder and pin. Shoulder consists of larger dimension than the pin and shoulder to pin ratio is kept in a range of 2.5-3.5. The shoulder is responsible for frictional deformation and pin is for plastic deformation. The heat generated during the FSP is due to friction and plastic deformation of the base material. FSP can be described in the three stages to understand its basic principle. First, the rotating tool is plunged into the base material till the shoulder makes the contact with the base metal. Second, the feed rate is applied in the processing direction which decides the other process nomenclatures such as advancing side (AS), retreating side (RS), leading edge, and trailing edge (Figure 1).
APPENDIX J: PAPER 10

Title: Hybrid friction stir processing with active cooling approach using compressed air, water, and CO$_2$ to enhance superplastic behavior of AA7075 alloy.

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