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Fracture Mechanism in Friction Stir Processed Annealed Pure Copper Samples

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Abstract: Fracture mechanism in metals using Friction Stir Processing (FSP) is a challenging investigation and is made by means of a rotating tool inserted in a work piece providing heat transfer and plastic deformation. In this paper, improving ductility during FSP was determined as a purpose and the microstructure and fracture mechanism of samples were investigated during Friction Stir Processing (FSP) of pure copper. Ductility was measured using tensile elongations at temperature of 20°C. By varying the traverse speed from 40 to 100 mm/min at rotation speeds of 300 and 600 rpm, the ultrafine grain microstructure was achieved. Defects were observed in rotational speed of 300 rpm. By increasing traverse speed at constant rotational speed of 600 rpm grain size of the nugget zone decreased and ductility increased. Despite the cavity formation during process, friction stir processing technique was successfully applied to acquire samples with high ductility and certain minimum grain sizes for copper plates.

Key words: Friction stir processing . annealed pure copper . ductility . fracture mechanism

INTRODUCTION

Friction Stir Welding (FSW) is a promising choice for joining particulate reinforced aluminum matrix composites, pure copper and magnesium alloys. FSW is a solid state welding process, where a rotating non-consumable tool with a pin extending from a larger shoulder is translated along the weld line. During welding, the rotating tool produces frictional heating with temperature below the melting point of material and plastic deformation due to stirring of material around the pin, which forms the weld. This solid state joining process avoids the formation of shrinkages, porosity and segregation of the ceramic reinforcements and significantly reduces the thermal stresses [1].

Based on the principles of friction stir welding and closely with similar features to Modified Friction Stir Channeling (MFSC), Friction Stir Processing (FSP) was invented by charit and mishra [4-6] for microstructural modification of metal materials. In FSP, a rotating tool is inserted into a material and high plastic deformation is produced. Unlike its pioneers, FSP is used to enhance ductility, induces super plasticity and improve corrosion. Dynamic recrystallization of the deformed zone forms an ultrafine-grained structure. FSP has been successfully applied to various cast aluminum and magnesium alloys to eliminate casting defects and thereby improve their mechanical properties.

Copper has been widely applied in many areas for its high electrical and thermal conductivities, favorable combinations of strength and ductility and excellent resistance to corrosion [7, 8]. In order to enhance the mechanical properties of copper joints, FSP has been regarded as an effective method. Okamoto *et al*. [9] fabricated a copper back plate for cooling by FSW at a tool rotation rate of 1300 rpm and a welding speed of 170 mm/min. Similarly, Lee and Jung [10] reported that 4-mm-thick copper plate was successfully welded at a rotation rate of 1250 rpm and a traverse speed of 61 mm/min.

Two modes of metal transfer during friction stir processing have been reported. The first mode of metal transfer is generated between the tool shoulder and the plate and takes place as layer-by-layer deposition of metal one over the other. The second mode of metal transfer is generated by the extrusion of metal around the tool pin, when it reaches a state of sufficient plasticity. Metal transfer, generated between the tool shoulder and the plate, plays an important role in influencing the mechanical properties during friction stir process [11]. Modes of metal transfer are clearly visible in the microstrurcture characteristics, but they are not too distinct in macrostructure of most processed samples. Friction stir processing can be applied as a single-pass for processing a small area. For large engineering components in which the contact areas are relatively large, single pass FSP may not be adequate. Multi-pass FSP with a certain level of overlap between the successive passes is required for large contact areas. For both single and multi-pass processes, it is important to assess the microstructural evolution and its influence

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on the mechanical properties. For example, Surekha and Els-Botes [12] obtained a high strength, high conductivity copper by friction stir processing. To obtain fine grains, they friction stir processed a 3mm thick pure copper plate to a depth of 2.8 mm at low-heat input conditions by varying the travel speed from 50 to 250 mm/min at a constant rotation speed of 300 rpm.

However, a comprehensive investigation on fracture mechanism in friction stir processing of pure copper is lacking. In this study, the ductility and fracture mechanism were investigated during Friction Stir Processing (FSP) of pure copper.

EXPERIMENTAL PROCEDURE

5 mm pure copper plates, with the nominal composition shown in Table 1, were friction stir processed with a CNC milling machine with a maximum force of 30 KN, tool rotational speed of 2500 rpm and power of 13 HP. Because of high hardness and coarse-grained structure, caused by cold rolling process, mentioned copper plates were annealed in furnace at the temperature of 700°C for 1 hour to reach a fine-grained structure with desirable hardenability. A special fixture was used to keep the work piece during FSP. A high carbon steel cylindrical tool, with 14 mm shoulder diameter,8 mm pin diameter and pin length of 4 mm was used. The FSP tool as shown in Fig. 1b, was made of H13 tool steel and was heat treated to about 58 HRC. The samples were processed to a depth of 4 mm at different process conditions by varying the traverse speed from 40 to 100 mm/min at rotation speeds of 300 and 600 rpm. The detailed parameters are summarized in Table 2. Single stir passes were used. Defect-free sample achieved by FSP is shown in Fig. 1c. The friction stir direction was normal to the rolling direction in the rolled plates. Olympus optical metallurgical microscope was applied to investigate microstructural characteristics of the samples. Specimens were grounded, polished and etched using Keller's etchant before the examination. Tensile tests were carried out at room temperature using Shimadzu universal testing machine at constant crosshead speed of 1 mm/min. Tensile specimens were electrical discharge machined into a gauge normal to the FSP progression direction and the gauge was exactly located in the nugget zone as shown in Fig. 1a.

Table 1: Chemical composition of base metal

Sn (%)	Pb (%)	Zn (%)	Mn (%)	P (%)	Fe (%)	Ni (%)	Cr (%)	Mg (%)	Si (%)	As (%)
<0.001	<0.001	0.041	0.006	<0.001	0.006	0.08	<0.001	<0.001	0.007	<0.001
Be (%)	S (%)	Zr (%)	B (%)	Ti (%)	Cd (%)	Co (%)	Sb (%)	Al (%)	Cu (%)	
<0.001	<0.001	<0.001	0.002	<0.002	<0.001	<0.001	0.001	0.006	99.85	

Table 2: Different experimental process conditions and mechanical test results

Specimen number	Tool rotation speed (Rpm)	Traverse speed (mm/min)	Ultimate tensile strength (MPa)	Elongation (%)
1	300	40	207	58
2		100	214	64
3		40	240	61
4		55	251	67
5	600	70	256	70
6		85	265	73
7		100	271	81

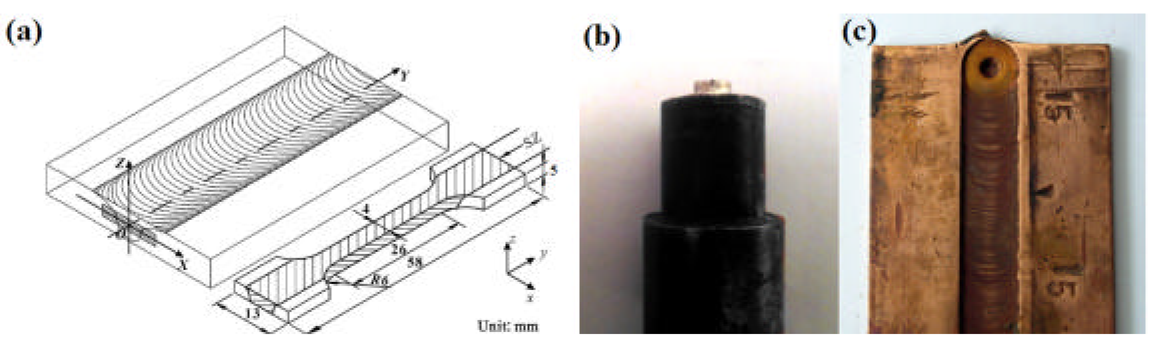

Fig. 1: (a) Process illustration and tensile test specimen [13] (b) high carbon steel cylindrical tool applied for FSP (c) Defect-free sample

RESULTS AND DISCUSSION

Microstructural characterization: The cross-section images of FSP samples are shown in Fig. 2. The base metal microstructure consisted of large elongated grains with an average grain size of 75µm is shown in Fig. 2a. As shown in Fig. 2b, microstructure in the nugget zone (SZ) is completely different from that of the base material. Using two different rotation speeds of 300 and 600 rpm grain size variation was observed. Insufficient heat input to the material affected the microstructure and caused formation of ultrafine grains, as shown in Fig. 2c. Also, in samples processed at rotation speed of 300 rpm due to low plastic deformation during process, cavity defects and porosities were formed. However, low hardness and defect formation in 300 rpm rotation speed convinced us to use 600 rpm tool speed for fabricating samples with high ductility. Figure 2d indicates that in tool rotation speed of 600 rpm, defect formation decreased due to sufficient heat input.Adequate plastic deformation in the stir zone led to finer grains and higher hardness value as shown in Fig. 2f. It was observed that higher heat input in tool speed of 600 rpm relative to 300 rpm, increased the grain size of NZ and led to lower dislocation density of samples. Dislocation density is a key factor for determining the mechanical properties of materials. Lower dislocation density decreases the hardness, tensile strength and tensile elongations of samples processed in 600 rpm. In order to improve tensile elongations in FS processed samples, traverse speed as second process parameter was applied. Due to decrease in heat input at higher traverse speeds, grain size in NZ decreased and dislocation density increased. Samples with high ductility were achieved in high traverse speeds of 85 and 100 mm/min.

Mechanical properties and fracture mechanism: At tool speed of 300 rpm, cracks and cavities are the key factors determining the ductility of samples. As shown in Fig. 3, stress-strain curve indicates that Low heat input and low plastic deformation decreases the Ultimate Tensile Strength (UTS) and Tensile Elongation (TE) in low rotation speeds. In tool speed of 600 rpm mechanical properties is improved by higher plastic deformation during process and adequate heat input.By increasing traverse speed from 40 to 100 mm/min mechanical properties improved. The highest ductility was reached at samples with traverse speed of 100 mm/min. Figure 4a indicates optical micrograph of FS processed sample after tensile test in grip region.

In samples processed at tool speed of 600 rpm and traverse speed of 40 mm/min fracture location was near the gage point.This mechanism of failure was also observed in samples processed at tool speed of 300 rpm. It is revealed that due to low heat input in mentioned samples, cavity and porosities form and during tensile test these cavities become a severe location of stress concentration and cause the samples to fail in gage point, as shown in Fig. 4b. Ultimate Tensile Strength (UTS) of the samples was higher compared to the base metal.UTS increased with the increase in traverse speed. In specimen with tool rotation speed of 300 rpm due to insufficient heat input,

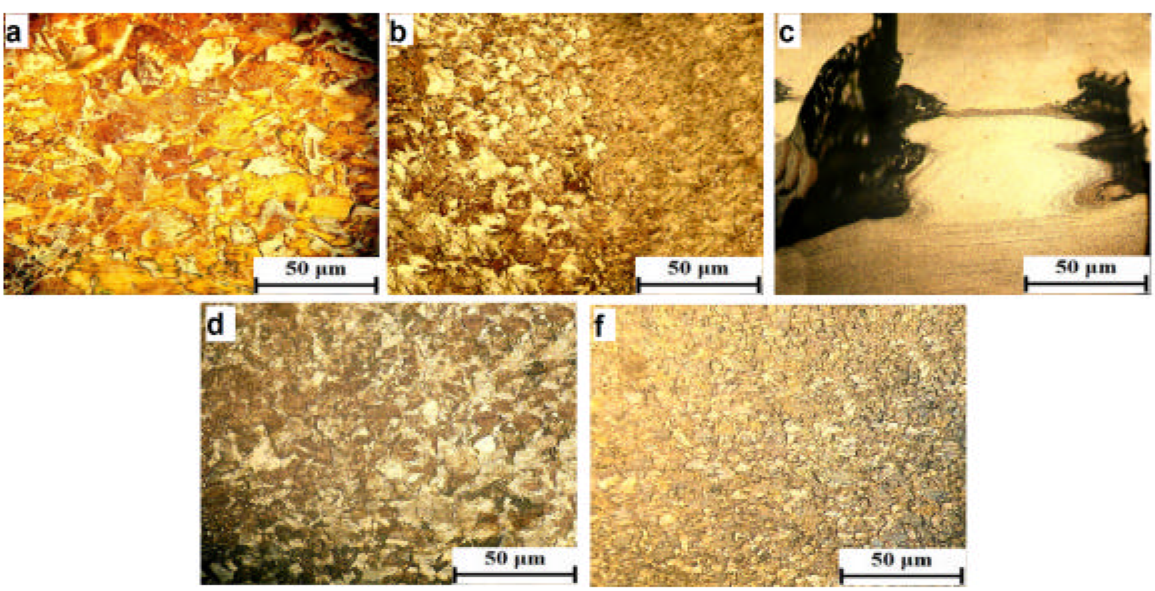

Fig. 2: (a) Base metal microstructure (b) Boundary between NZ and HAZ in sample processed in adequate heat input (c) Cavities and cracks in samples processed at tool speed of 300 rpm, (d-f) Microstructure of NZ in sample processed at tool speed of 600 rpm and traverse speed of (d) 40 mm/min (f) 100 mm/min

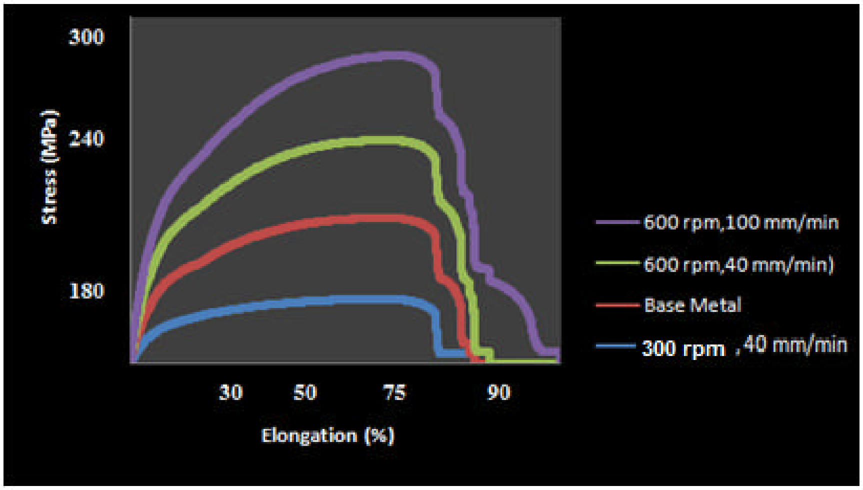

Fig. 3: Stress strain curves for different specimens and base metal

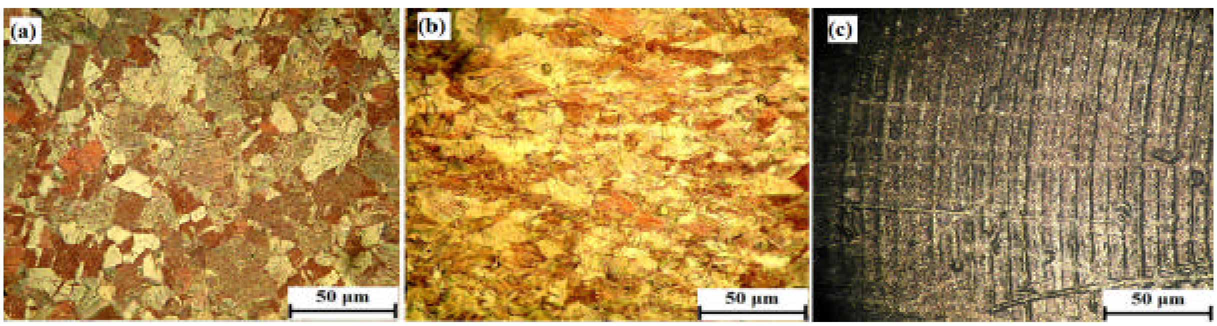

Fig. 4: Optical micrograph of FS processed sample after tensile test (a) grip region (b) elongated microstructure in gage point far from failure end (c) cavity bands in failure end

continual weld defects lead to low tensile strength. At constant rotation speed of 600 rpm, with the increase in traverse speed, the heat input and the grain size decreased and hence the mechanical properties improved.

Tensile specimen with tool speed of 600 rpm and traverse speed of 40 mm/min failed with moderate necking and the neck region was not thinned to a point. This mechanism of failure suggests the formation of cavities and porosities due to excessive heat input. Tensile specimens with tool speed of 600 rpm and traverse speed of 70, 85 and 100 mm/min failed by necking to a point. This characteristic was formerly, considered as a necking behavior of some AL-Mg alloys and revealed their superplasity in high temperatures. In this investigation it can be inferred that texture in mentioned samples was defect-free and no porosity was formed. Further investigation can be made to reveal the superplasity behavior of pure copper by FSP.

Low ductility in samples processed at tool speed of 300 rpm is related to cavity bands formed during the tensile test, as shown in Fig. 4c. Cavity locations, elongated during tensile test, lead to wide cavity bands and are usually detected as black lines in micrographic pictures.

CONCLUSION

At tool rotation speed of 300 rpm insufficient heat input and low plastic deformation generates cavities and cracks and leads to low ductility in FS processed samples. In samples processed at tool rotation speed of 600 rpm removal of defects leads to higher ductility of samples.

Fracture mechanism of FS processed pure copper significantly depends on grain size and cavity formation during process. Grain size is controlled by heat input and cavity formation decreases with higher plastic deformation, produced by tool.

Due to incapability of becoming thin to a point most of tensile test specimens had limited elongation. Ductility is controlled by cavity formation during process.

Fracture mechanism of FS processed pure copper was fairly ductile and increasing traverse speed at moderate and constant tool speed of 600 rpm was found as an effective method to increase ductility.

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