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Research Article

Developing α/β Laminar Composite Structure in CuZn Alloy by Heat Treatment and Submerged Friction Stir Processing

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ABSTRACT

A laminar composite structure was developed in a CuZn alloy plate by non-equilibrium heat treatment and subsequent submerged friction stir processing. For this aim, Cu-37 wt.% Zn alloy was initially heat treated to produce a double phase structure. Then, the double phase plate was friction stir processed in underwater media at room temperature. The microstructure and mechanical properties of the samples were analyzed using optical microscopy and tensile test. During heat treatment, the large α grains containing annealing twins converted to a double phase structure with β grains on the α grain boundaries. Heat treatment caused an increase in ultimate tensile strength from 240 MPa to 275 MPa, and a reduction in elongation from 67 to 49%. After friction stir processing, the ultimate tensile strength and elongation were obtained as 380 MPa and 48%, respectively. This desirable mechanical property was achieved due to the formation of a novel composite structure containing parallel ultra-fine grained β layers between dynamically recrystallized α layers.

1. Introduction

Friction stir welding (FSW), firstly developed for welding aluminum alloys in 1991, has been used to join different metals and alloys [1]. In this method, the base metals (BMs) are clamped by a fixture on a milling machine. A rotational tool enters into the interface of BMs, moves alongside the joining line [2]. In this process, the BMs do not experience fusion and solidification. Therefore, most of the common disadvantages of fusion welding processes are eliminated by FSW such as oxidation, distortions, gas porosities, shrinkages, solidification cracks, and so on [3]. The mechanism which causes the formation of a solid state joint by FSW is severe plastic deformation (SPD). The FSW tool has a pin and a shoulder part. The pin provides the plastic deformation of material, where the main role of the shoulder is generating the heat by friction between itself and BM's surface [4]. Therefore, it is a thermomechanical process since both the high temperature and materials flow coexists during FSW [5].

Friction stir processing (FSP) has been developed based on principles of FSW to surface modification of metals and alloys or to produce metal matrix composites (MMCs) [6]. In the case of surface modification, the material undergoes different restoration mechanisms due to generation of both the heat and deformation induced

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by the rotational FSP tool [7]. Hence, fine and equiaxed grains containing substructures are usually formed during FSP, which enhances the physical and mechanical properties [8-10]. In the case of MMC's production, the secondary hard phases should be inserted into the material by severe plastic deformation during FSP based on the methods explained in literature [11, 12]. The most difficulty of MMC's production by FSP is the agglomeration of the secondary phases, which destroys the final mechanical properties [13]. In this regard, formation of composite structures in metals and alloys by FSP with uniform distribution of secondary phases has been changed to a challenging topic in recent years [14-17].

Brasses, i.e. CuZn alloys, are one the materials subjected to surface modification by researchers using FSP due to its advantages compared to fusion processes [18]. During fusion processing of CuZn alloys, the Zn can evaporate, the surface color can be changed, the oxides can be formed, etc. However, FSP as a solid state process overcomes these difficulties [19, 20]. Dinaharan et al. [21] used FSP to incorporate fly ash particles into the surface of the double phase brass alloy. They have reported that no Zn evaporation was observed during FSP and fly ash particles caused lower values of friction coefficient. Meena et al. [22] have employed Taguchi method to optimize the FSP parameters during the processing of the 60/40 brass alloy. They confirmed that using a rotational speed of 1000 rpm, a traverse speed of 20 mm/min, and two number of passes results in optimum performance. Moaref et al. [23] have investigated the microstructure and wear properties of the underwater FSPed copper and brass alloy. They reported that under water FSP can improve the hardness and tribological properties of the copper and brass. Huang et al. [24] used FSP to modify the microstructure and mechanical properties of a cold-sprayed CuZn coating. They indicated that the combination of cold spray and FSP causes formation of fine grains, which improves the mechanical properties such as tensile strength from 87.2 MPa to 257.5 MPa. They also reported that FSP changes the grain morphology of the coating from elongated to equiaxed due to occurrence of dynamic recrystallization. In addition, they reported that after FSP β" phase was distributed uniformly among the equiaxed grains of α phase. Heidarzadeh et al. [25] have investigated the FSP of CuZn matrix composites reinforced with alumina particles. They reported that Zn oxide particles can be formed during FSP at high heat input conditions due to chemical reaction between evaporated Zn and present air between alumina particles. Moreover, Heidarzadeh et al. [16] have studied the effect of different FSP parameters on the final microstructure and mechanical properties of brass/alumina composites. They indicated that using a tool rotational speed of 710 rpm results in desirable incorporation of alumina particles into the brass matrix. In addition, using three passes, FSP lead to synergic increase in strength and ductility of brass/alumina surface metal matrix composites. In another study, Xu et al. [26] employed large load and low FSP speed condition to modify the microstructure and properties of a 70/30 brass alloy. Their results revealed that fine grains with an average size of 0.5 μm containing large amount of high angle boundaries result in strength-ductility trade-off.

In our recent studies, combination of non-equilibrium heat treatment and FSP has been proved to be an effective method to produce different microstructures in CuZn alloys [27]. For example, it has been concluded that β transforms to α phase during FSP causing a nanocomposite structure and corresponding improved mechanical properties [27]. In this study, the production possibility of laminar composite structure in CuZn alloys has been disclosed using submerged FSP after non-equilibrium heat treatment. The novelty of this work is the use of a cooling media to control the phase transformation during FSP of a non-equilibrium double phase brass.

2. Experimental Procedure

The BM used in this study was Cu-37 wt.% Zn single phase plate with dimensions of 100 mm $^{length}\times$ 50 mm $^{width}\times$ 2 mm ^{thick}. Non-equilibrium heat treatment was conducted to produce double phase brass plate, which is explained in the author's previous works in detail [27, 28]. The double phase plate was produced by non-equilibrium heat treatment of BM in a way that the single-phase brass plate was heated at 810°C for 1 hour, and then quenched in water, which resulted in the formation of non-equilibrium secondary disordered β phase. Then, a tool, made of H13 steel composed of pin and shoulder, was employed for FSP. The shoulder's diameter was 12 mm, and diameter and the length of the tool pin were 3 mm and 1.7 mm, respectively. Underwater single pass FSP was conducted at a traverse speed of 100 mm/min and a rotational speed of 400 rpm at room temperature. The microstructure of the processed sample was investigated using optical microscopy (OM, Olympus 100, Japan). For this aim, metallographic samples were cut from the cross section of the processed material perpendicular to FSP line, then it was polished and etched using Picral etchant with a solution of 20 ml nitric acid and 10 ml acetic acid. To evaluate the mechanical properties, the tensile samples with a gauge size of 12 mm were tested at a strain rate of 1 mm/min using a tensile test machine (INSTRON, 5500R, England).

3. Results and Discussion

The OM images of the BM after heat treatment are shown in Fig. 1 at different magnifications. From Fig. 1, double phase BM was composed of large α grains and finer β phase at α grain boundaries. The transition zone between BM and center of the processed zone, i.e. stir zone (SZ), is illustrated in Fig. 2, which is prepared by combining several OM images in advancing side of the sample. Fig. 2 shows that the macrostructure of the sample was composed of distinct zones including BM, thermomechanically affected zone (TMAZ), and SZ. The higher magnification of the TMAZs at advancing and retreating sides are illustrated in Fig. 3. From Fig.3, α and β phase grains both are elongated due to the shear deformation induced by rotational tool during FSP. In addition, partial dynamic recrystallization (DRX) has occurred in α and β elongated grains indicated by white and black arrows in Fig. 3, respectively. Fig. 4 illustrates the OM images of the SZ at different magnifications, which indicates the formation of a laminar composite

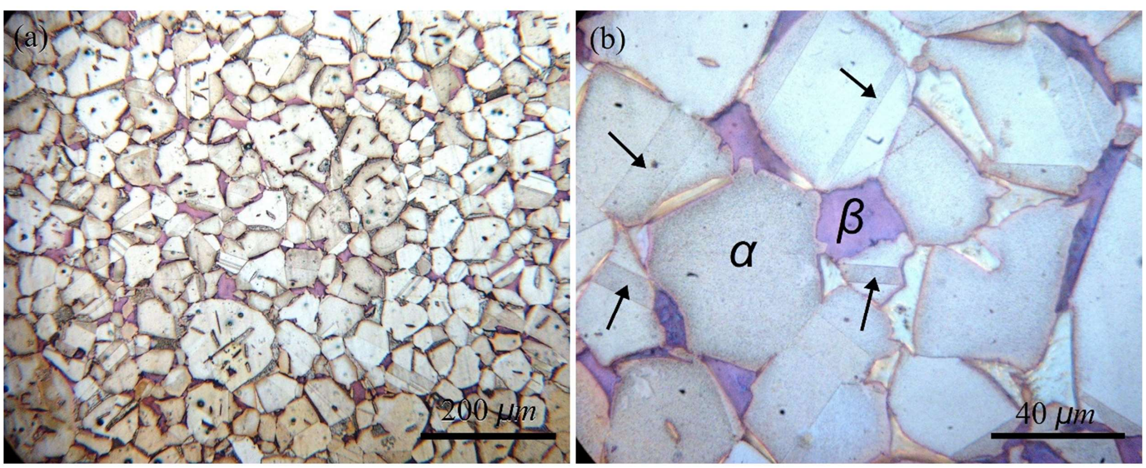

Fig. 1. OM images of the BM after non-equilibrium heat treatment at different magnifications: (a) low magnification and (b) high magnification. The arrows refer to the annealing twin in α grains.

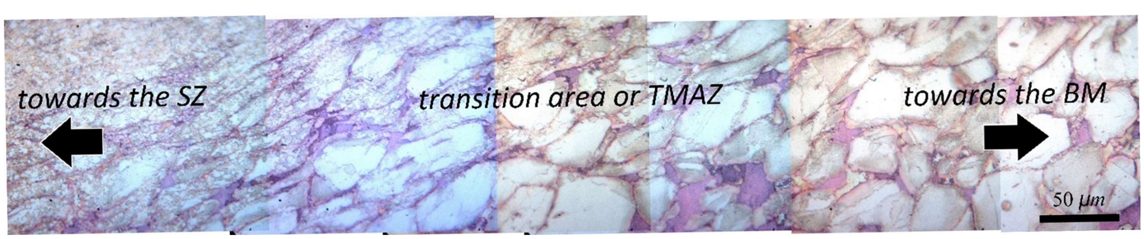

Fig. 2. Combined OM image of the transition area in advancing side of the friction stir processed sample form BM to SZ.

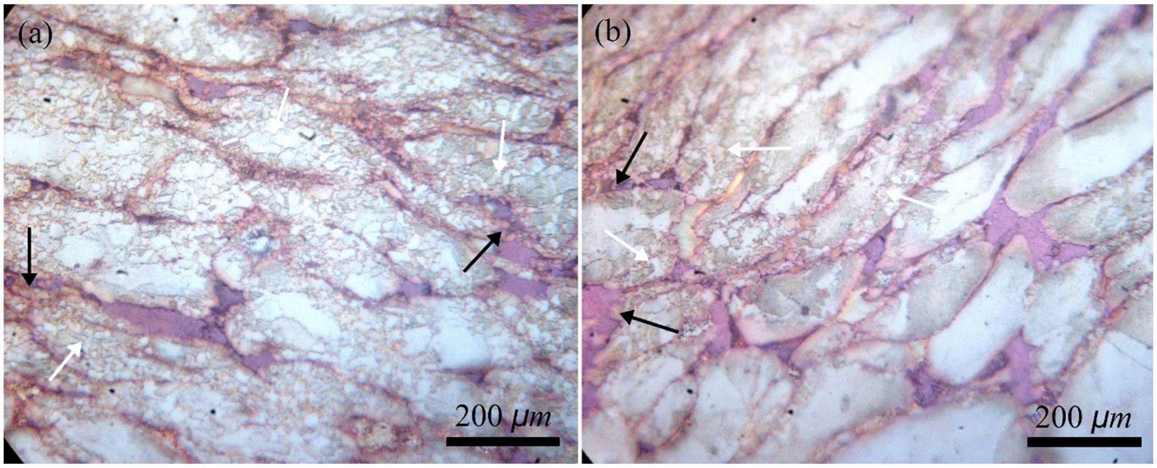

Fig. 3. OM images of the TMAZs at different sides of the sample: (a) retreating side and (b) advancing side.

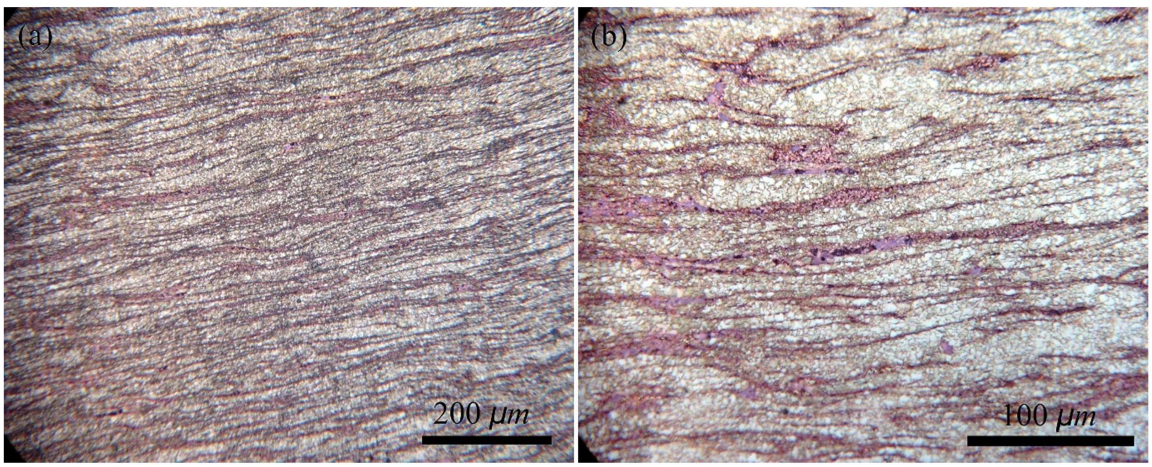

Fig. 4. OM images of the SZ at different magnifications: (a) low magnification and (b) high magnification.

structure in this area composed of parallel thick α and thin β layers. The higher magnified OM image of the SZ is shown in Fig. 5, which confirms the formation of ultrafine-grained (UFG) β layer between DRX grains of α layers as indicated by black arrows. From Figs. 1-3, there is a sharp gradient the cross-section microstructure of the samples, which indicates the existence of a sharp gradient in strain, strain rate, and temperature during FSP from the center of the sample (SZ) to TMAZ and BM. This gradient causes different degrees of metallurgical phenomenon in different zones. For example, in TMAZ the microstructural mechanisms are not completed, but they can be finished in SZ due to the existence of enough strain and temperature.

Different DRX mechanisms can occur during FSP of metals and alloys due to heat generation and deformation induced by rotational tool, which prepares the required condition for various restoration mechanisms [5, 6, 29]. In the case of the current study, CuZn alloy undergoes discontinuous DRX (DDRX) during FSP due to its low stacking fault energy (SFE). However, continuous DRX (CDRX) can also participate to some extend in grain structure formation during FSP. Moreover, the presence of secondary phase affects the microstructural evolution during FSP by Zener pinning effect and particle stimulated nucleation (PSN) mechanisms, which are reported in the case of friction stir processed double phase brasses [27]. It is worth to note that in a previous study [27], the phase transformation of β→α resulted in formation of nanocomposite structure in the SZ. However, in the case of this study, β was not transformed to α, and it remained the same in the final microstructure of the sample (Figs. 4 and 5). Comparison between literature [6, 27] and outcome of this study confirms that

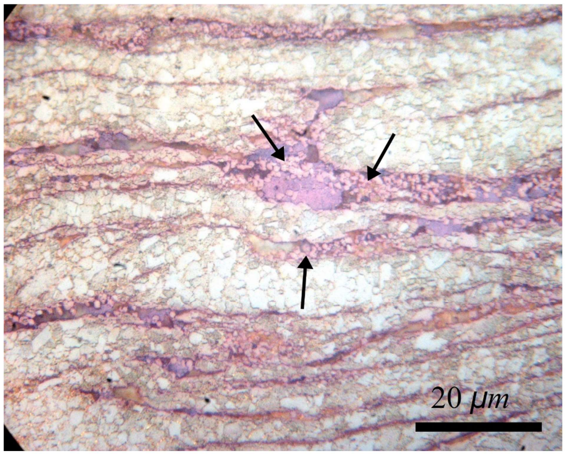

Fig. 5. OM images of the SZ at higher magnifications indicating the formation of UFG β layer between DRX grains of α phase.

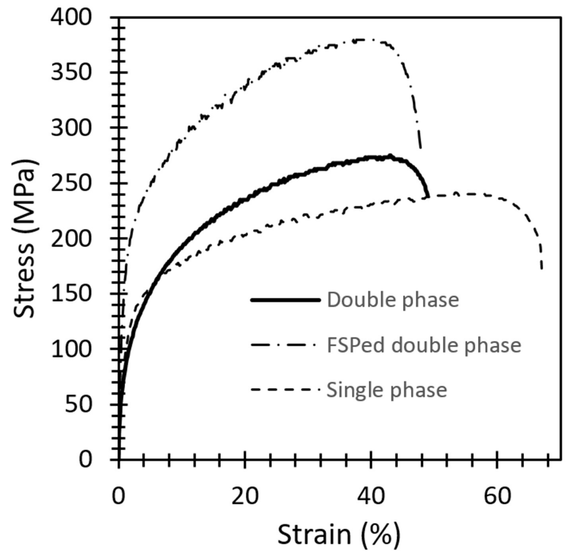

Fig. 6. Stress-strain plots for different samples before heat treatment (single phase), after heat treatment (double phase), and after FSP.

underwater media prevents β→α transformation during FSP of double phase CuZn alloy. Underwater condition reduces heat input and peak temperature during FSP, and hence it restricts the diffusive mechanisms such as β→α phase transformation.

The tensile properties and microstructural features of the BMs before and after heat treatment and FSP are summarized in Table 1. In addition, the stress-strain plots have been shown in Fig. 6. From Table 1 and Fig. 6, the non-equilibrium heat treatment increases the UTS of the material form 240 MPa to 275 MPa by producing β phases on α grain boundaries. However, it reduces the amount of tensile elongation from 67% to 49%. Surprisingly, underwater FSP enhances the UTS of the double phase sample up to 380 MPa without a considerable reduction in elongation. Production of a laminar composite structure composed of DRX α layers and UFG β layers helps to strength-ductility trade-off in CuZn alloys. Furthermore, by combining non-equilibrium heat treatment and submerged FSP the UTS of the Cu-37 wt.% Zn alloy can be increased from 240 to 380 (53.3%) besides an acceptable elongation of 48%.

Table 1. Tensile properties and microstructural features of the single phase, double phase, and FSPed double phase samples

Sample	UTS (MPa)	Elongation (%)	Microstructure
Single phase CuZn	240	67	Large α grains containing annealing twins
Double phase CuZn	275	49	Large α grains containing annealing twins + β grains on the α grain boundaries
FSPed double phase CuZn	380	48	Laminar composite structure: DRX α layers + UFG β layers

4. Conclusion

Non-equilibrium heat treatment and subsequent friction stir processing were conducted on a Cu-37 wt.% Zn brass alloy, and the following conclusions can be summarized:

1. The amount of heat input plays a main role in determining the final microstructure after FSP.

2. The submerged condition, using underwater media at room temperature, reduces the heat input and peak temperature during friction stir processing, which causes formation of laminar composite structure in the stir zone of the samples.

3. Laminar composite structure composed of dynamically recrystallized α grains and ultrafine-grained

β layers enhances the ultimate tensile strength without a considerable reduction in elongation.

4. Combination of non-equilibrium heat treatment and friction stir processing results in strength-ductility trade-off in brasses, which can be employed in other alloys with similar binary phase diagrams.

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