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Microstructure evolution and microhardness of friction stir welded cast aluminum bronze

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ABSTRACT

Microstructural characteristics and mechanical properties of a friction stir welded cast aluminum bronze (Cu–9Al–1Fe), produced by a sand casting method, have been investigated at tool rotation of 850–1500 rpm and traverse speed of 50–100 mm/min. Refinement of the primary coarse cast microstructure in the base metal was seen after friction stir welding. Microstructure of the stir zone was characterized in four distinct areas of non-isometric fine grains while a significant grain growth was noticed in some of the areas. Conditions of grain growth are defined with high heat input intensity and low heat transfer capability. The grain size was observed to decrease after FSW, resulting in a greater microhardness across the welded region from about 100 HV in the base metal to about 150 HV at the center of the stir zone. The increased hardness in the stir zone may have stemmed from the locally refined grain size according to Hall–Petch relation.

1. Introduction

Aluminum bronze alloys are copper-based alloys in which the Al is added to the mixture up to 12% as the main alloying element Copper Development Association (1988), with the other major alloying elements being Ni, Fe, Mg and Si (Callcut, 2002). Aluminum bronze alloys are widely used in engineering components of marine applications due to the useful combination of good strength, wear and corrosion resistance (Ni et al., 2010), in addition to toughness and ductility (Fuller et al., 2007). However, aluminum bronzes which contain10 wt% Al, solidify in 1030 °C as a single β-phase (bcc) due to an eutectic transformation. Mishra et al. (2007) and Oh-ishi and McNelley (2005) described that during a slow cooling, the β-phase will be transformed to both a α-phase (fcc) and an intermetallic γ-phase at lower temperatures through a eutectoid reaction. Further addition of iron to this compound will raise proportion of the α-phase allowing a greater amount of Al with no more γ-phase being formed. Meanwhile, the addition of Fe will form an intermetallic κ-phase within the microstructure. Callcut (2002) and Ni et al. (2009) noted that an additional amount of Fe in the compound will improve strength, fatigue strength and wear resistance.

Fusion welding of the cast aluminum bronze is usually employed to fabricate various components which are difficult to be produced as a single casting. It is also used to repair the casting defects. However, cracks, HAZ cracks, porosity and formation of brittle phase are some defects which can occur during fusion welding of the aluminum bronze. This is corroborated by the results of Michael (2006) and Oh-ishi and McNelley (2004). They showed that the friction stir welding is the best known technique to enhance both mechanical properties and microstructure of the welding in the aluminum bronze joins.

This article focuses on the microstructure evolution and mechanical properties of a cast aluminum bronze (Cu–9Al–1Fe) during FSW in a wide ranges of tools rotation (ω) and traverse speed (ν). The purpose of this research is to determine the relationship between microhardness and microstructure of the aluminum bronze in addition to describe the microstructural changes in the welded zone.

2. Experimental

FSW technique was carried out on an as-cast aluminum bronze (UNS C 95,300) plates of 4 mm thickness. Chemical composition of this alloy is shown in Table 1. Characteristics of the used welding tools were as follows: 16 mm diameter of a concave shoulder with a jagged pin of 3.8 mm length, with the other dimensions of this equipment being summarized in Table 2. This tool design increases the contact surfaces between the pin and the plasticized

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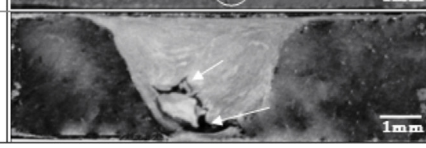
ω (rpm)	v (mm/min)	ω/v	ω²/v	Macrostructural of the joints welded (AS / Soulder / RS)	Weld defects
1500	50	30	45000		Defect-free Weld
1250	50	25	31250		Defect-free Weld
1500	100	15	22500		Cavity
1250	100	12/5	15625		Cavity & Lack of penetration
850	50	17	14450		Cavity & Lack of penetration&Crack

Fig. 1. Macrostructure of the joints welded and defects at the various ω/v and ω^2/v ratios.

Table 1
Chemical composition of aluminum bronze used in the present study.

Element	Al	Fe	Cu	Other
Percent (%)	9.1	1	Balance	0.5

material (Gadakh and Adepu, 2013), thereby increasing the heat generation and providing a much easier flow of the plasticized material.

The tool itself is made of an air quenched AISIH13 hot worked tool steel. The rates of tools rotation (ω) and traverse speed (v) applied in the FSW of specimens are listed in Table 3. Using Optical Microscopy (OM) and Image Analysis software, microstructure and grain size of the base metal (BM), HAZ, TMAZ and several areas of the stir zone (SZ) were examined. Etching was performed in a (5 g) $FeCl_3$+ (2 ml) HCl+ (95 ml) C_2H_5OH solution (Ni et al., 2010), while microhardness was evaluated along vertical and cross-sectional areas of the weldment using a micro-Vickers hardness tester with 1 kg load for 15 s.

3. Results and discussion

3.1. Macrostructure and microstructure

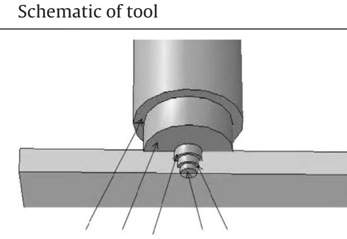
Arbegast and Hartley (1998) defined ω^2/v as a pseudo heat index, using an experimental viewpoint, and discussed the effect of it on heat input. The following proportion indicates the relation between; maximum temperature of the FSW process (T_{max}, °C), rotation rate (ω) and traverse speeds (v):

$$\frac{T_{max}}{T_{melting}} \propto \frac{\omega^2}{v}$$

It means that increasing the ω^2/v ratio leads to a higher welding temperature. Furthermore, it can be inferred that the variations of the tool rotation speed would have larger effects on the maximum temperature of process in comparison with the variations of the travel speed.

Arbegast (2008) demonstrated that the flow related defects occur at low temperature and cold FSW condition. It is postulated

Table 2
Dimensions and schematic of the used tool.

	Shoulder		Pin			Schematic of tool
	D1	D2	D3	D4	D5	
Diameter (mm)	20	16	5	3.75	2.5	