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Microstructure–wear behavior correlation on a directionally solidified Al–In monotectic alloy

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ABSTRACT

Al–In monotectic alloys are potential alternatives for application in the manufacture of wear-resistant automotive components, such as cylinder liners and journal bearings. The comprehension regarding the development of distinct microstructures of monotectic alloys and their interrelation with wear behavior are challenges of prime importance. The present study aims to contribute to a better understanding of the relationship between the scale of the minority phase of the monotectic microstructure and the corresponding wear behavior. Transient directional solidification experiments were carried out with an Al–5.5 wt% In alloy with a view to provide samples with significant differences in the microstructural scale along the casting length. The results of wear tests permitted an experimental quantitative expression correlating the wear volume (V) with both the interphase spacing between indium droplets (λ) and time of wear tests (t) to be proposed. The increase in λ is shown to improve the wear resistance. The effect of λ on V becomes more significant as the sliding distance (or time) is increased.

1. Introduction

Aluminum base immiscible monotectic alloys such as Al–Pb, Al–Bi and Al–In having the minority phase typified by fibrous and/or droplet-like shapes have significant potential for practical applications. These include self-lubricated bearings, electrical contact materials and the fabrication of porous materials [1–5]. A low modulus of elasticity (E) is one of the requirements for bearing alloys, and from these soft metals (Pb, Bi and In), which are alloyed with Al, In has the lowest E [6].

Indium when combined with aluminum forms an immiscible alloy system characterized by a monotectic reaction ($L_1 > \alpha Al+L_2$) for a composition of 17.3 wt% In at a temperature of about 910 K. The resulting microstructure is formed by an Al matrix with a dispersion of In embedded particles [7–9]. The magnitude and distribution of these particles will depend on the rate of displacement of the solid/liquid interface during solidification and the movement of such particles, which can eventually be entrapped by the growth front. Silva et al. [7] analyzed the microstructural evolution of a hypomonotectic Al–In alloy and reported that for growth rates (v) higher than 0.95 mm/s, the Al matrix had a cellular morphology with In particles of different sizes remaining in the intercellular regions. On the other hand for $v < 0.95$ mm/s the microstructure was characterized by In droplets disseminated into the Al matrix. Ozawa et al. examined the microstructure of monotectic (Al–17.3 wt% In) and hypermonotectic (Al–20 and 25 wt% In) Al–In alloys solidified in a continuous casting setup [8]. These authors reported a very homogeneous structure of In spheroids in the Al matrix, which increased with the increase in In alloying. Liu et al. [9] studied the microstructure development of an Al–In alloy of monotectic composition (Al 17.5 wt% In) during rapid solidification in a melt spinning apparatus. These authors reported that the as-solidified microstructures were characterized by a homogeneous distribution of nanometer sized In particles embedded in the Al matrix.

Recent studies pointed out the effect of the grain size and of the scale of microstructure parameters of metallic alloys, such as the cellular, dendritic and interphase spacings, on the resulting mechanical, corrosion and wear resistances [10–16]. Hall–Petch type correlations have also been recently proposed describing the dependence of microhardness on the cellular and primary dendritic arm spacings [17,18]. The effects of microstructural defects such as porosity [19] and of mechanical and heat treatments of alloys on the resulting wear behavior have been investigated in recent studies [20,21]. Despite the potential for the use of Al–In alloys in tribological applications, detailed studies on the interaction between wear and microstructure of these alloys cannot be found in the literature.

The present study aims to contribute to a better understanding of the effect of the size and distribution of the minority phase of an

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Al–In monotectic alloy, represented by the microstructural interphase spacing (λ) and the corresponding wear behavior. Transient directional solidification experiments were carried out with a view to provide a range of interphase spacings for micro-abrasive wear tests. A correlation between the wear volume and the time corresponding to the sliding distance of wear tests and λ is aimed.

2. Experimental procedure

The vertical water-cooled directional solidification (DS) apparatus used in the experiment allows unsteady-state heat flow conditions to be attained. This experimental setup has been detailed in a previous article [22].The DS experiment was carried out with an Al 5.5 wt% In alloy and samples were extracted along the casting length at different positions from the cooled bottom corresponding to the range of growth rates ($v < 0.95$ mm/s) that is conducive to microstructures formed by In droplets disseminated in the Al matrix [6]. Longitudinal and transversal samples were extracted along the casting length. The longitudinal samples were electropolished and etched with a solution of 0.5% HF in water to reveal the microstructure. Image processing systems were used to measure the diameter (d) of the In droplets and the interphase spacing (λ), which was determined by averaging the horizontal distance between the center of adjacent In particles (about 50 readings for each examined position in casting). The microstructure was also characterized by scanning electron microscopy.

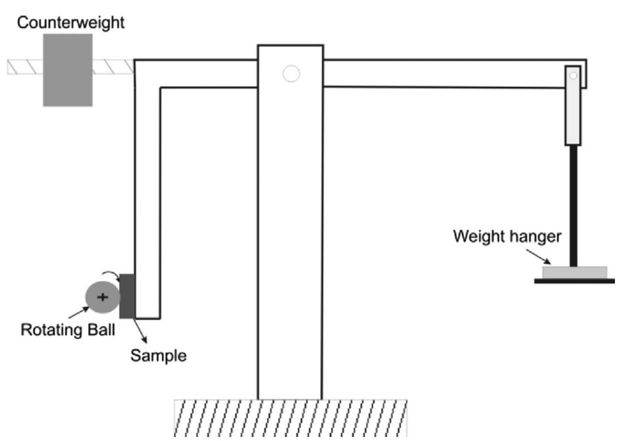

Fig. 1. Schematic diagram of the sliding wear tester.

The transverse samples were used in the micro-abrasive (ball crater) wear tests in order to analyze the effect of λ on the wear volume (V). A schematic presentation of the used wear tester is shown in Fig. 1. During the tests, a hard spherical bearing steel ball (AISI 52100, diameter of 25.4 mm and hardness of 818 HV) was rotated against the sample, producing a wear crater. The ball is driven directly by clamping the ball in a split drive shaft. The sample is pressed into the rotating ball from the side by test loads placed on the weight hanger. As the test duration (number of rotations or sliding distance) increases the size of the crater increases. The used ball sliding speed was 0.33 m s^{-1} (260 RPM) and the applied normal contact load was 0.2 N. The wear volume V was calculated as follows, where d is the crater diameter, and R the ball radius [15]:

$$V = \frac{\pi d^4}{64R} \quad (1)$$

The diameter was measured at least four times for each wear crater. The tests were carried out under dry sliding conditions to prevent any interfacial element from causing influences on the feedback of the microstructure [23,24].

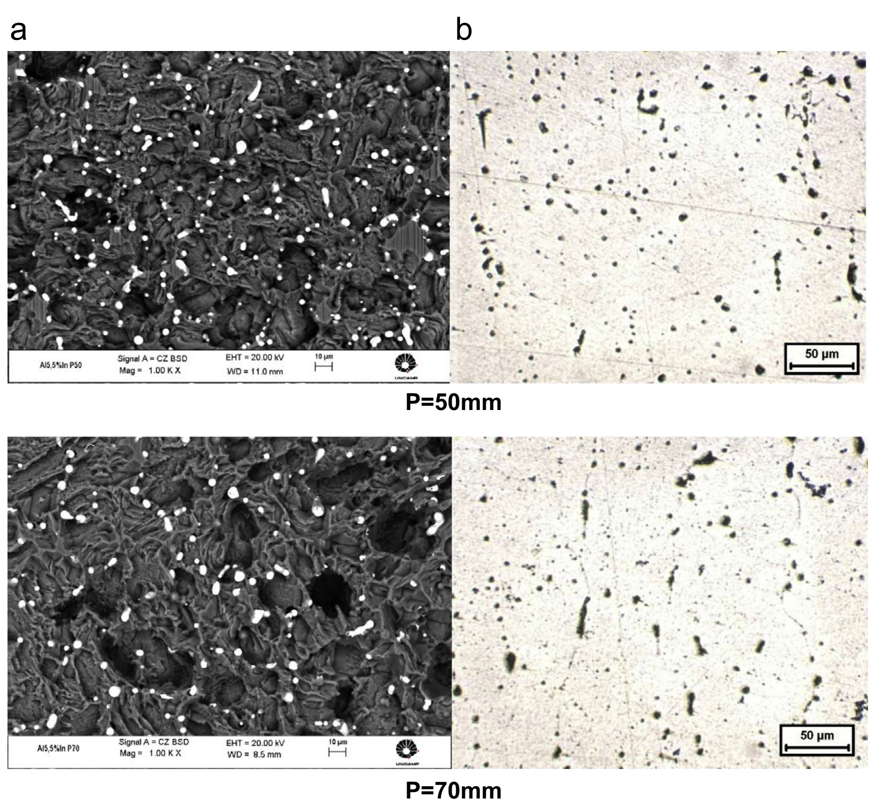

Fig. 2. Microstructures of the Al 5.5 wt% In alloy at different positions along the casting length: (a) SEM images of samples evidencing non-corroded In particles and the corroded Al matrix, and (b) optical micrographs.