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Correlation between friction-induced microstructural evolution, strain hardening in subsurface and tribological properties of AZ31 magnesium alloy

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Dry sliding tests were performed on as-cast AZ31 magnesium alloy using a pin-on-disc configuration. Coefficients of friction and wear rates were measured within a load range of 5–360 N and a sliding velocity range of 0.1–4.0 m/s. Morphologies, compositions and hardness of worn surfaces were characterized by scanning electron microscope (SEM), energy dispersive X-ray spectrometer (EDS) and hardness tester. Microstructural evolution, strain hardening and dynamic crystallization (DRX) generated in subsurfaces of AZ31 alloy during sliding were found to correlate with the tribological properties obtained. The subsurface microstructures beneath the contact surface were subjected to large plastic strains, and experienced strain hardening, DRX and melting as a result. The roles of surface hardening and thermal softening on the mild to severe wear transition were investigated in detail. It was shown that the transition occurred when the surface layer softened with DRX. Surface oxidation and strain hardening played an important role in maintaining the mild wear, and thermal softening originating from DRX in subsurface and surface melting were responsible for the severe wear. A transition load model, which can be used predict the critical load for transition from mild to severe wear, has been developed using the method of DRX kinetics. A map has been constructed for presenting microstructural evolution and hardness change in surface layer based on the calculated mild to severe wear transition loads and critical loads for surface melting.

1. Introduction

In recent decades, magnesium alloys have become more attractive for use in aviation, aerospace and automotive industries due to a combination of low density, high specific strength, and good casting and deforming properties [1–3]. Numerous investigations have been carried out on tackling two serious impediments against widespread application of Mg alloys, i.e. poor corrosion resistance and low strength at elevated temperatures. For example, the use of casting Mg alloys is currently limited to shell components but not for engine components due to the low strength at elevated temperatures. Magnesium alloys would normally not be an attractive choice for wear components such as bearings, sliding seals or gears. However, significant improvements have been made in mechanical properties such as stiffness, creep resistance and elevated-temperature strength by additions of alloying elements and incorporating ceramic particulates or fiber reinforcements, etc., magnesium alloys as well composites may be a potential substitute for Al alloys in certain tribological applications such as automotive brakes, pistons and cylinder bores [4–6]. Furthermore, sliding wear is also an important factor to be considered in processing Mg alloys by extrusion, rolling, forging, etc., from the point of view of understanding the deformation of microstructure at the work-tool interface and the associated heat generation.

It has been recognized that under the condition of sliding with loading, large plastic strain will be developed; the corresponding subsurface microstructure will be changed accordingly due to local deformation [7,8]. Despite the increasing interest in wear of magnesium alloys, most of work has concentrated on the effects of environmental temperature and additions of alloying elements such as rare earth elements Ce, La and Si on wear behavior of magnesium alloys [9–11]. Only few papers have reported on the details of friction-induced microstructural evolution, hardness change in subsurface, and their response to the friction and wear characteristics, such as subsurface plastic deformation, strain

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hardening, dynamic recrystallization (DRX) associated with frictional heating, and their effect on transition from mild to severe wear. Chen and Alpas [12] investigated the dry sliding wear of AZ91 alloy against a steel counterface using a pin on disc apparatus under various normal loads and sliding velocities, and found that the transition from mild to severe wear was controlled by a critical surface temperature criterion, rather than a load or sliding velocity criterion, and the onset of the severe wear occurred when the surface temperature reached 74 ± 15 °C. The surface temperature was measured using a chromel–alumel type thermocouple probe inserted inside the specimen. However, the physical meaning of the measured critical surface temperature of 74 ± 15 °C was not determined, and the deviation from real surface temperature was not evaluated. They also established a sliding wear map for AZ91, in which the mild wear regime included two sub-wear regimes, namely an oxidation wear regime and a delamination wear regime; the severe wear regime encompassed a severe plastic deformation wear regime and a melting wear regime. Zafari et al. [13] also studied the wear behavior of AZ91 alloy at a temperature range of 25–200 °C. They showed that a transition from mild to severe wear occurred as the temperature reached 140 °C, 180 °C and 400 °C at 40 N, 20 N and 5 N, respectively. Das et al. [14] investigated the microstructural evolution under the contact surface during sliding wear of AZ31 alloy at high temperature mostly at 400 °C. It was identified that the oxidation controlled wear at lower temperature changed to the high temperature plastic deformation controlled wear at $T > 300$ °C, DRX occurred at the contact surface where high strains (~200–300%) were generated, the subsurface material also experienced grain growth, and grain boundary sliding at the edges of the wear tracks. Habibnejad-Korayem et al. [6] studied the tribological behavior of AZ31 Mg-based composite enforced with 2 wt% Al_2O_3 nano-particles and found that the work-hardening capability was increased in subsurface layer at the sliding velocities of 0.5 m/s and 1.5 m/s, and the main mechanism improving wear behavior of the nano-composite was due to the interaction of dislocation and nano-particles. Arora et al. [15] carried out a comparative study of the wear behavior of AZ42 alloy under as-cast as well as friction stir processed (FSPed) conditions and found that a significant decrease in the wear rate of FSPed AZ42 alloy may be attributed to the microstructure refinement resulting in enhanced hardness and ductility along with higher work hardening capability.

The present paper presents the results of an experimental study of correlation between the friction-induced microstructure evolution, hardness change and transition from mild to severe wear for AZ31 alloy. By comparison of difference in subsurface microstructure and surface hardness between mild and severe wear regimes, a critical surface temperature criterion has been established, i.e. DRX temperature controls the transition from mild to severe wear. The mild to severe wear transition loads at different sliding velocities are evaluated using the DRX kinetics approach.

2. Experimental details

2.1. Characterization of as-received alloy

The material tested was a commercial AZ31 magnesium alloy ingot with the nominal chemical composition of Mg–3.0Al–1.0Zn–0.2Mn (in mass %). The hardness of the alloy was measured as 51.1 ± 2.3 on Vickers scale using a load of 1.0 N. The microstructure of as-cast AZ31 ingot is shown in Fig. 1. The average grain size of α-Mg phase was 157.7 ± 52.1 μm, and two types of intermetallic phases were identified as Al_8Mn_5 and $Mg_{17}Al_{12}$ by EDS analysis. Al_8Mn_5 intermetallic particles appeared in rod and sphere shapes, β-$Mg_{17}Al_{12}$ phase particles were mainly spherical, and both types of particles precipitated within the grains and on boundaries of α-Mg solid solution grains. Das et al. [14] have also reported these two types of intermetallic phases in a wrought AZ31 alloy.

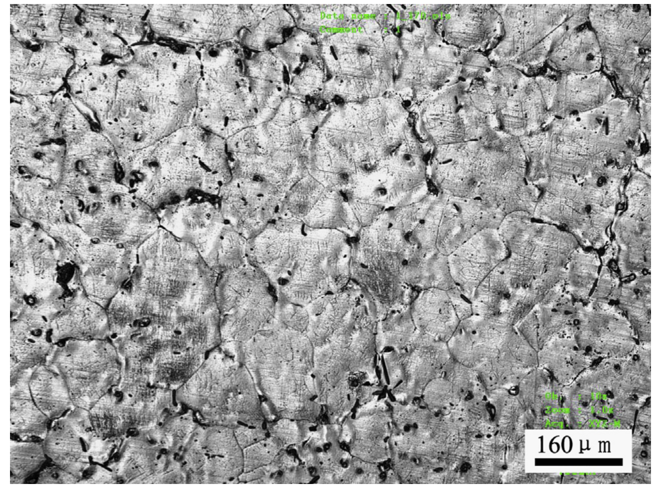

Fig. 1. Microstructure of AZ31 alloy.

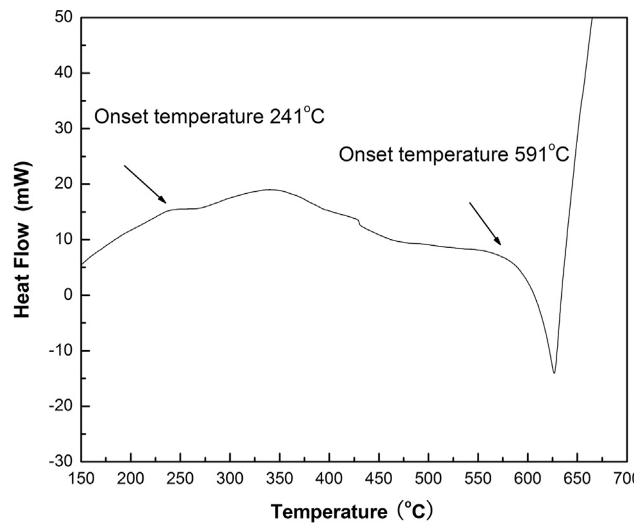

Fig. 2. DTA thermogram of AZ31 alloy.

To measure the thermal stability of constituent phases in AZ31 alloy, thermal transformations in the as-cast AZ31 alloy were examined using differential thermal analysis (DTA). DTA thermogram for AZ31 alloy revealed that an endothermic peak appeared with an onset temperature of 241 °C, corresponding to the dissolution of β-$Mg_{17}Al_{12}$ precipitate phase, the other endothermic peak appeared with an onset temperature of 591 °C, corresponding to the melting of α-Mg phase, as shown in Fig. 2. With reference to the Mg–Al binary phase diagram, the two onset temperatures agree well with those on the solvus and solidus lines on the Mg–Al phase diagram.

2.2. Friction and wear tests

Friction and wear tests were conducted with a pin-on-disc tribometer. All friction and wear tests were carried out under dry sliding condition at a room temperature of 25 °C. The pins, 6 mm diameter × 13 mm length, were machined out from AZ31 alloy ingot, polished, thoroughly degreased by acetone and dried before the commencement of each wear test. The discs, 70 mm in