Wear 318 (2014) 177–187

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Fretting wear of Mg–Li–Al based alloys

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ARTICLE INFO

Article history:
Received 20 February 2014
Received in revised form
19 May 2014
Accepted 10 June 2014
Available online 21 June 2014

Keywords:
Fretting
Non-ferrous metals
Profilometry
Wear testing
Friction log and hysteresis

ABSTRACT

The fretting wear behavior of newly developed Mg–Li–Al based alloys LAT971 and LATZ9531 is investigated by using reciprocating fretting wear testing under dry condition with varying number of cycles ($10–10^4$), normal load (1–10 N), oscillation frequency (1–9 Hz), and displacement amplitude (80–200 μm). The worn surface is characterized by scanning electron microscopy to reveal wear mechanisms governing under each condition. Overall, results show that LATZ9531 elicits consistent performance, lower coefficient of friction (~0.50) than conventional AZ31 (~0.69) and LAT971 (0.60). But, under the condition of high normal load (of 10 N), LAT971 shows least wear volume loss (~0.05 mm^3) as well as lower coefficient of friction (~0.26) compared to that of LATZ9531 or conventional AZ31. In addition to central cracking in LATZ9531, mainly adhesive and delamination wear mechanism are noticed. Under frequency variation LAT971 shows enhanced performance especially at high frequency (~9 Hz). However, with increase in slip amplitude (~200 μm), the major wear mechanism is observed to be abrasive and oxidative wear, wherein LATZ9531 shows least wear volume. Friction hysteresis of increasing slip amplitude shows increase in energy consumption during fretting wear, and its shape confirms that in spite of change in stroke lengths, fretting is occurring in the gross slip regime.

1. Introduction

High specific strength and modulus of magnesium based alloy enable its usage as a strong structural material especially in the field of automobile and aviation. But, limited slip systems present in magnesium owing to its hexagonal crystal structure introduce difficulty in its processing. Therefore, lithium addition develops body centered cubic phase that eases the formability during hot rolling of Mg–Li–Al based alloys. In previous publications of our group, the activity of non-basal $(1\ 0\ \bar{1}\ 0)$ plane confirmed absence of texture in thermo-mechanically processed LAT971 and LATZ9531 alloys [1–3]. Further, strain hardening arising due to heavy alloying (of Li, Al, Sn and Zn, exceeding 25 vol%) is quantified through serrated yielding (and resulting dislocation density) during nanoindentation [4]. But, the processed parts must be joined to result a component of usable size for aerospace and automobile applications. Along those lines, arc welding of Mg-based alloys may not be a feasible option because of its combustible nature. Thus, riveting or bolting of joints is one of the reasonable solutions. But mechanical fastening does result in micrometer-length scale relative motion (due to clearance) between the surfaces. The damage resulting due to micrometer length scale relative motion (i.e. *fretting*) cannot be neglected, and is a serious safety concern.

Fretting induced damages are frequently encountered in accessories and/ or components (like bearings, gears, spines, clutches etc.) subjected to quasi static loading rounder condition of small amplitude (in order of a few micrometer) oscillating movement [5], between two contacting surfaces. Fretting may lead to increase in vibration/damping, or catastrophic failure of the component under service, therefore, assessment of fretting induced wear is essential for predicting safe service life of components subjected to engineering applications [6]. Fretting induced damages can be broadly classified as fretting wear (associated with material removal and formation of oxide debris due to tribo-oxidation) and fretting fatigue (involving crack nucleation, propagation and even total failure of the component) [7]. Mechanism of fretting is very intricate involving various mechanisms like adhesive, abrasive, oxidative and fatigue induced wear [8].

Several studies have been carried out to understand the wear behavior of Mg alloys [9–13]. One of the most common alloys that have been studied are AZ based alloys. Zafari et al. studied the fretting experiments, from room temperature to elevated temperature (25 °C to 250 °C), for AZ91 and related alloys [13], where superior wear behavior of AZ91 alloys at elevated temperature was observed under normal load of 20 N. An et al. [9] have studied the

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http://dx.doi.org/10.1016/j.wear.2014.06.012
0043-1648/

dry sliding wear behavior of Mg–Zn–Y alloy and compared it with AZ91 using pin-on-disc method, similar to that used by Zafari et al. [13], but their experiments were carried out at much higher load ranges (20 N to 380 N). They found the Mg–Zn–Y alloy has lower coefficient of friction and lower wear rate compared to that of AZ91 at room temperature. The wear-mechanism for these alloys in both the studies were found to be varying between abrasion, oxidation, delamination, along with thermal softening. Wear behavior of AZ91D alloy conducted at low sliding speeds elicited that abrasive wear is dominant for very slow sliding speed, while delamination is dominant at relatively high sliding speed and oxidational wear was predominant at intermediate speed [10]. All these study underline the strong dependence of wear mechanism in magnesium alloys on various parameters like load, amplitude, frequency, etc.

Exact mechanism of fretting is design dependent, implying that the overall configuration of the system determines the various stages of fretting. However, Hurricks have done a systematic study of fretting with reference to iron and steel under normal loading conditions, and also compared various other models in order to get an in-depth understanding of the mechanism of fretting [5]. They showed that under low loading conditions, fretting damage occurs in three stages. When two metallic surfaces are brought into contact, they are originally separated by oxide layer. Initially, the oxide layer is dispersed, following which metal transfer occurs with increasing slip. Rupture of metallic junctions during oscillatory motion leads to the formation of debris. Oxidation of debris can occur initially on the surface itself, or during its formation during fretting. Formation of the debris layer can lead to reduction of coefficient of friction as the debris can 'roll' between the contacts. Steady state is achieved because mild wear persists at higher loads because of the abrasive action of the 'rolling debris' on the metal surfaces.

Waterhouse and Taylor, and Suh have suggested a delamination theory for wear that propagates through sub-surface cracks which result in detachment of plate-like particles of the substrate [14,15]. Mindlin's elastic model suggests that depending on contact loading, fretting crack are mainly observed under gross slip regime [16], whereas fretting induced wear are encountered in partial and/or gross slip regime [17].

All the above references point to the fact that a general theory describing fretting behavior is still missing and exact mechanism of fretting is highly design dependent. The mechanism of fretting changes not only with the configuration of the system, but also with the composition of the alloy. Therefore, objective of the present investigation is to assess fretting wear behavior of newly developed thermomechanically treated Mg–Li–Al based alloys (LAT971 and LATZ9531) and compare their performance against conventional AZ31B alloy.

2. Experimental procedure

Novel Mg–Li–Al based alloys Mg-9 wt%, Li-7 wt%, Al-1 wt%, Sn (LAT971) and Mg-9 wt%, Li-5 wt%, Al-3 wt%, Sn-1 wt%, Zn (LATZ9531) were processed and characterized (phase and microstructure), details of which are published earlier [1]. The tribological characterization of these alloys was performed in order to relate the comparative performances of newly developed LAT971 and LATZ9531 Mg–Li–Al-based alloys in relation to pure Mg and commercially available AZ31 alloy. Before fretting test, samples were mechanically polished and ultrasonicated in ethanol to remove surface damages, if any. To investigate the influence of fretting, tests were performed using ball on flat configuration (Reciprocating Friction and Wear MonitorTR 281 M fretting wear testing machine programmed with Winducom 2006-upgrade software). AISI E52100 steel counter-body of 6 mm ball diameter was used against fretting of Mg–Li based alloys.

Alloys were tested and evaluated for its fretting wear behavior by varying three parameters: (i) oscillation frequency, (ii) normal load, and (iii) slip amplitude, details of which are provided in Table 1. Hertzian contact diameter was calculated for the AZ31, LAT971 and LATZ9531 alloys in order to attribute the effect of loading (at 2 N, 6 N, and 10 N) on wear volume to the contact-damage arising from fretting. Friction hysteresis was also performed to ascertain the effect of slip amplitude (80 μm, 120 μm, 160 μm, and 200 μm) on energy dissipated during the fretting cycle. Variation of frequency (1 Hz, 3 Hz, 6 Hz and 9 Hz) on resulting wear volume has also been ascertained during fretting. In order to retain brevity, fretting-wear images of AZ31 sample is not shown, and only LAT971 and LATZ9531 samples are shown in greater detail. But, the corresponding fretting damage (such as wear volume, coefficient of friction, Hertzian contact diameter and friction hysteresis) of AZ31 is provided in great detail for comparison with LAT971 and LATZ9531. Further, fretting wear mechanism was arrived at using friction log plot (variation of tangential force (F_t), displacement amplitude (D), and number of cycles (N) amongst one another).

After fretting wear, samples were cleaned by ultrasonication in ethanol to remove the oxide debris that forms due to fretting. Wear volume loss due to fretting wear was evaluated using laser surface profilometer (Mahr, Perthometer, PGK 120). A total area of 2 × 2 mm around the wear-scar was scanned with a total of 51 lines with distance of 40 μm between the lines. After which, area of each line over the wear scar was measured and integrated to acquire the wear volume.

Samples were put under scanning electron microscope (SEM, FEI Quanta 200) for observing wear scars under back-scattered electron imaging mode. Further, energy dispersive spectroscopy (INCA Penta FETx3, Oxford Instruments, UK) was utilized to observe the tribolayer that formed during fretting.

3. Results

3.1. Effect of oscillation frequency on tribological behavior

Wear scars of LAT971 and LATZ9531 elicit increase in the scar size with increase in oscillation frequency (Fig. 1). Such a linear increment in wear scar size with increasing frequency is also reported by Bryggman et al. [18]. SEM images shows that wear track for LAT971 (Fig. 1a and b) is smoother, and marginally longer (~400 μm) that of LATZ9531 (~350 μm, Fig. 1c and d) irrespective

Table 1
Test parameters of for performing dry fretting wear at parameters of normal load (L), frequency of oscillation (f), and slip amplitude (A), and number of cycles (N).

S. No.	Variation in	Magnitude of varied parameter
1.	Oscillation frequency (f)	1 Hz, 3 Hz, 6 Hz and 9 Hz (at $L=5$ N, $A=100$ μm, $N=10^3$ cycles)
2.	Normal load (L)	2 N, 6 N and 10 N (at $f=5$ Hz, $A=100$ μm, $N=10^3$ cycles)
3.	Slip amplitude (A)	80 μm, 120 μm, 160 μm and 200 μm (at $L=5$ N, $f=5$ Hz, $N=10^3$ cycles)