Effects of Lubrication and Temperature on the Tribological Behavior of a Magnesium Alloy under Contact Sliding

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Abstract. This paper aims to experimentally investigate the effects of lubrication and temperature on the tribology behavior of a magnesium alloy, AZ31B, sliding against 86CrMoV7. The effects of lubricant additives, including oil film improver and extreme pressure (phosphorous donors), on the friction coefficient and surface morphology in the sliding zone were studied. It was found that the relatively lower surface hardness of the material significantly affects the wear of the materials in the sliding zone. The lubricant with oil film improver and extreme pressure can reduce friction. Temperature rise brings about lower friction due to the lubricant additives.

1. Introduction
In the automotive industry, magnesium alloys have been widely used to reduce the vehicle weight because of its characteristics of lightweight and high specific strength. However, the fabrication of magnesium alloy components faces critical challenges due to the limited ductility of the materials at room temperature. As such, the forming process of magnesium alloy products are usually carried out at an elevated temperature, e.g., in a warm rolling condition, which can improve the material’s ductility [1-4]. Additionally, the friction within a contact pair involving a magnesium alloy usually leads to poor surface quality [5] and material adhesion [6]. Particularly, the adhesion at the contact interface has been a major problem in a forming process at an elevate temperature and usually occurs due to insufficient lubrication. Thus, it is necessary to develop proper lubricant to reduce the interface friction and hence to improve the surface finish of magnesium alloys.

This paper aims to experimentally investigate the effects of lubrication and temperature on the tribological behavior including the influence of oil film improver and extreme pressure, on the friction coefficient and surface morphology at the sliding zone.

2. Experimental configuration
To measure the interface friction of magnesium alloy AZ31B sliding against 86CrMoV7, a CETR UMT 100 tribometer with a heating chamber and liquid container was used, as shown in Fig. 1. The disc sample with a thickness of 5mm was fixed inside the liquid container while the pin was fixed by the pin holder. Before the tribology test, the surface hardness of AZ31B was measured by indentation on Struers DuraScan. The surface morphology of the contact pair was measured by the 3D optical surface stylus, Zygo NewView 700 Scanning White Light Interferometer. The diameter of pin is 2 mm while the contact radius for the sliding test is 24mm, as shown in Fig. 2
To study the effects of lubricant and its additives on the tribological behaviour and surface morphology, four different types of lubricant were prepared [7], as listed in Table 1. The effects of two typical lubricant additives, i.e., oil film improver, extreme pressure (phosphorous donors), used in the production on the friction were investigated.

| Samples | Base oil (Sunflower oil) | Oil film improver | Extreme pressure (phosphorous donors) |
|---------|--------------------------|-------------------|---------------------------------------|
| #1      | 100%                     | 0%                | 0%                                    |
| #2      | 90%                      | 10%               | 0%                                    |
| #3      | 90%                      | 5%                | 5%                                    |
| #4      | 90%                      | 0%                | 10%                                   |

3. Experimental procedures
The tests were carried out under the same contact sliding conditions. The sliding speed and normal load were fixed at 5 mm/s and 5 N, respectively. The temperature range in the tests varied from 25 °C to 101 °C. Each test ran for 20 minutes and repeated for three times. During a test, the instant friction coefficient of a contact pair was plotted against the running time. The above procedures were repeated for each type of the lubricant listed in Table 1. At the end of the tests for each lubricant, the surface morphology of the disc was measured.
4. Results and discussion
4.1 Hardness
Before the test, the surface hardness of AZ31B was measured. A mapping method was used to measure the surface hardness of a rectangular area in the surface of AZ31B, as shown in Fig. 3. The obtained surface hardness was about 50 HV, as shown in Fig. 4. For each sliding test, the hardness of the sample was measured again after the elevated temperature of samples completely decreased to the room temperature. It was found that the hardness was not changed on the non-sliding zone (see Fig. 4) because the measured hardness with the error bar was almost in the same magnitude. However, the surface hardness increased significantly inside the sliding-zone at a lower temperature, e.g., 25 °C. Yet, it decreased rapidly as the temperature increased from 25 °C to 200 °C, as shown in Fig. 4. This reveals that the sliding zone of AZ31B may undergo work hardening process due to the contact pressure for a lower temperature. With an increase in the temperature, the mechanical hardening decreases gradually and can be ignored for a higher temperature, e.g., 200°C. This is critical for understanding the tribology behaviour of AZ31B under the condition of elevated temperature.

![Fig. 3 Measured points](image1)

![Fig. 4 Measured surface hardness](image2)

4.2 Friction coefficient
The friction coefficient of the AZ31B/86CrMoV7 pairs under dry contact sliding are shown in Figs. 5 to 8. The friction coefficient is about 0.3 under a lower temperature, e.g., less than 46 °C. A lower friction coefficient was observed at 72 °C. However, it becomes very unstable when the temperature reaches 101 °C, e.g., a sudden increase from 0.3 to 0.5, because of the surface hardness softness caused by the elevated temperature. Overall, a relatively higher friction coefficient can be expected for the dry surface contact.

![Fig. 5 Dry friction T=25°C](image3)

![Fig. 6 Dry friction T=46°C](image4)
Figs. 9 to 12 show the lubricant and additive effects on friction, using the base oil without any additive. Compared with the results under dry sliding, a much lower and stable friction was observed in the whole temperature range tested (25 to 101 °C).

When the oil film improver was applied, friction coefficient decreases significantly, as shown in Figs. 13 to 16. Moreover, its effect becomes much more sensitive as temperature increases. For instance, the friction coefficient becomes lower than 0.1 when temperature reaches 101°C. Compared with the case using the base oil, the oil film improver can dramatically improve the lubrication performance.
With pure extreme pressure (10%), the lubricant performance does not seem to be as effective as that with the pure oil film improver at room temperature. However, the extreme pressure can effectively lead to the reduction in friction when the temperature increases, as shown in Figs. 17 to 20. It should be noted that friction becomes less stable compared with the lubricant with pure oil film improver.
When oil film improver and extreme pressure were used together, the lubricant performance was excellent, as shown in Figs. 21 to 24. The friction coefficient became less than 0.1 and an even lower friction was observed when temperature reached 101 °C (see Fig. 24). Overall, the lubricant with oil film improver and extreme pressure can significantly reduce the friction of the AZ31B/86CrMoV7 contact pair.

Generally, the lubrication results in a lower interface friction because of the asperity-lubricant interaction. The lubricant additive can further bring about a friction reduction because of a boundary layer formed by a physical absorption or a chemical reaction process. In fact, the elevated temperature can enhance the chemical reaction process, which results in a decrease in the interface friction [8].

4.3 Surface morphology
Apart from the friction coefficient of the sliding zone, the effects of lubricant and additives on the surface morphology were investigated as well. Fig. 25 shows the measured 3D surface topography of AZ31B under dry sliding. A very rough surface was observed due to the significant wear at the sliding zone.
Compared with the dry surface contact, the pure base oil can improve the surface quality inside the sliding zone, as evidenced by Fig. 26. However, pile-up appeared at the edge between the sliding and non-sliding zone. This could be caused by the material’s plastic deformation under the contact stresses. The softening of the AZ31B alloy might also occur as temperature increases. Compared with the pure based oil, the application of the oil film improver led to surface oxidation in the sliding zone, as shown in Fig. 27. Moreover, this oxidation surface layer cannot be easily removed after the test. Figs. 28 to 29 demonstrate that the extreme pressure can form a solid lubricant layer on the non-sliding zone. Fig. 30 shows the optical images of the AZ31B surfaces. A shining surface appeared when the lubricant with oil film improver was used, while a dark surface was observed when using of the extreme pressure. Further investigations are necessary to explore the underlying mechanisms.
5. Conclusions
This paper has investigated the tribological behaviour of AZ31B sliding against 86CrMoV7 under a range of elevated temperatures. The effect of lubricant with/without additives has also been studied. The result has led to the following conclusions:

(1) The surface hardness of AZ31B was about 50 HV before contact sliding but increased significantly inside the sliding zone for a lower temperature due to the work hardening process. However, the effects of work hardening can be ignored as the temperature increases. The relatively low surface hardness of the AZ31B makes the wear significant, shown by, e.g., the pile-ups at the edge between the sliding and non-sliding zone.

(2) The lubricant with oil film improver and extreme pressure can reduce friction because of a boundary layer formed by a physical absorption or a chemical reaction process. Temperature increase makes the friction smaller due to the effect of lubricant additives.

(3) Compared with the pure base oil, both the oil film improver and extreme pressure can form an oxidation layer on an AZ31B surface. However, the former leads to a layer within only the contact zone while the latter also results in a layer outside the contact zone. The optical images of the AZ31B surfaces demonstrate that the lubricant with oil film improver leads to a shiny surface but the extreme pressure results in a dark surface. Further study is essential for a deeper understanding of the mechanisms.

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