Investigation on Tribology Behaviors of Oil-soluble Nano-Cu Lubricating Additive for Aluminum Alloy ZL101

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Abstract. Oil-soluble Nano-Cu lubricating additive was prepared and its tribology behaviors as lubricant additive in SJ 15W/40 heavy duty gear oil used for aluminum alloy material ZL101 were investigated on an end-face friction and wear tester apparatus. SEM and EDS techniques were used to characterize the morphology, compositions and chemical states of the worn surface. The results indicate that the oil-soluble Nano-Cu additive have excellent friction-reducing properties and 0.6wt.% addition exhibited the best friction behavior. An appropriate applied load and rotating speed can improve the tribology properties obviously. The combination of SEM-EDS analysis reveals that by addition of Cu nanoparticles, a tribo-film containing Cu nanoparticles was formed and helped improving the wear and friction properties. The results demonstrate that Cu nanoparticles are potential friction modifier when used in ZL101.

1. Introduction

Today, in order to save resource and reduce CO₂ emissions, it is necessary to improve the equipment efficiency[1]. It is an effective way to reduce friction by lower the viscosity of a lubricant. But it is likely to cause a break in oil film and result in wear and seizure. To achieve both reduction in friction and prevention of wear and seizure, various additives are added as a lubricant into the base oil including extreme pressure agent and a friction modifier[2,3].

The lubricated friction and wear properties of aluminum alloy have been largely investigated. However, as the aluminum alloy is easy to transfer to the counter metal, the surface between aluminum alloy and iron is difficult to lubricate[4]. As it contains sulfur or phosphorus atoms, the traditional friction modifier such as MoDTC and MoDTP is not environmentally friendly, it is necessary to investigate an environmentally friendly friction modifier. With the improvement of nanoscience and nanotechnology, a large number of mental and mental oxide nanoparticles have been prepared as lubricant additives to improve tribological performance[5]. Cu nanoparticles have been widely studied due to superior anti-friction and anti-wear abilities when used in steel. But the investigation of tribology behavior between aluminum alloy and steel is rarely.

In this work, Cu nanoparticles were prepared and the morphology of the synthesized target product was characterized by SEM. In order to investigated the effect of Cu nanoparticles on the tribology behaviors between aluminum alloy(ZL101) and steel, the factors which influence the friction and wear characteristics were discussed. We also use SEM-EDS analysis to investigate the friction and wear
mechanism.

2. Experimental

2.1 Materials
In this work, SJ 15W/40 heavy duty gear oil was used as the base oil, which was supplied by Shenyang Tox Chemical Co., Ltd. (Shenyang, China)

2.2 Preparation of Cu nanoparticles
The Cu nanoparticles are prepared as Zhenqi Guo mentioned[6]. Polyvinylpyrrolidone (PVP) and the cationic surfactant of cetyltrimethyl ammonium bromide (CTAB), which acted as double-capping molecules, were dissolved in anhydrous ethanol. Next, 12.5 g of CuO was added to the 100-mL solution of anhydrous ethanol. The mixed solution was placed in an ultrasonic oscillation mixer to form a polymer suspension, and 15 mL of 80% hydrazine hydrate was added as the reducing agent. After 30 min of the reaction under ultrasonic oscillation mixing, the solution became red and was cooled down to room temperature. The preparation of the Nano-Cu ethanol colloid was completed and acted as Cu nanoparticles additive. The morphology of Cu nanoparticles was shown in Fig.1. In fact, this Cu nanoparticles possess a diameter of 6–10 nm and are evenly distributed.

![Fig 1. Transmission Electron Microscope (TEM) image of Cu NPs](image1)

![Fig 2. Schematic drawing of the end-face friction and wear tester apparatus](image2)

2.3 Preparation of nano-lubrication
We select SJ 15W / 40 gasoline engine oil (SJ for short) as the reference lubricant. Then the Cu nanoparticle additive synthesized in the laboratory was added to the reference oil (abbreviated as NC). Both SJ and NC were blended with an ultrasonic bath for 15 min. The tribological properties of the samples under different applied load, rotating speed and duration time were investigated.

2.4 Tribology tests
In the current research, the wear performance of both SJ and NC are examined using an end-face friction and wear tester apparatus. Before and after each experiment, the steel upper specimen and aluminum alloy lower specimen are cleaned with acetone in an ultrasonic bath two times, each time for 15 min[7]. The schematic drawing of the end-face friction and wear tester apparatus are shown in Fig.2. As shown in Fig.2, the upper specimen is supposed stationary against the counter face of 49mm diameter disc which is made of ZL101.

3. Results and Discussion

3.1 Tribological analysis

3.1.1 Effect of Cu nanoparticle concentrations on friction coefficient.
To reveal the effect of additives under the lubrication condition, comparisons between SJ 15W/40 heavy duty gear oil with different Cu nanoparticle concentrations are shown in Table.1. All the tests are taken for 30 min at a rotating speed of 800 rpm under a load of 400N. As shown in Table.1, the friction coefficient decreases with Cu nanoparticles added to the base oil in the beginning. We can see that the 0.6wt.% Cu nanoparticle additive exhibited the best friction behavior. Research shows that the Cu nanoparticles in the lubricant can enter the friction surface and work in some form on the wear scar, which plays an anti-wear role and reduces the shear stress and friction coefficient of the worn surface. Higher concentrations of Cu nanoparticle additive did not keep improving the lubricated performances. This maybe because that the high concentration of Cu nanoparticles increases the viscosity of the oil, resulting in a decrease in lubrication performance.

### Table 1. Effect of Cu nanoparticle concentrations on friction properties

| W(Cu nanoparticles)/% | 0  | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 |
|-----------------------|----|-----|-----|-----|-----|-----|
| Friction coefficient  | 0.126 | 0.102 | 0.073 | 0.041 | 0.044 | 0.050 |

3.1.2 Effect of applied loads, rotating speeds, and duration time on wear and friction properties.

Fig.3,4,5 display the variation of the wear loss and friction coefficient of SJ and NC(with a mass percentage of 0.6%) with different applied loads(Fig.3), rotating speeds(Fig.4), and duration time(Fig.5). Fig.3 show the effect of applied loads on friction and abrasion properties of materials respectively. Furthermore, Fig.3(a) and Fig.3(b) show a similar trend. As shown in Fig.3, the wear loss and friction coefficient decrease with increasing loads at lower loads. When the applied load increases to a certain value, the friction coefficient increases with the load increases. This may because under high load, the oil film is likely to break, resulting in an increase in the friction coefficient. According to Fig.3, we can also conclude that the wear loss and friction coefficient of the system significantly reduced under the NC lubrication. This phenomenon becomes more pronounced with the load increases. When the applied load is 500N, the wear loss reduced by 25% and the friction coefficient reduced by 71% compared with SJ.

Fig.4 shows the effect of rotating speed on friction and wear properties of ZL101. As we can see in Fig.4 (a), the wear loss of NC and SJ gradually decrease when the rotate speed increase from 300 to 1500 rpm. Then the value increase when the rotate speed increase from 1500 to 1800 rpm. The result indicate that moderate rotate speed can also help improving the abrasion properties of ZL101. As for friction coefficient, the value of SJ reduced rapidly at low rotate speed and then reduced gradually. Furthermore, the friction coefficient of NC fluctuated and remained at a low level. In a word, Nano-Cu additive can effectively improve abrasion and friction properties of ZL101.

Analysis of the outcomes of Fig.5 show that duration time have least influence on the wear loss and friction coefficient of ZL101. According to Fig.5, the friction coefficient of SJ and NC are stable with the increase of duration time. The wear loss also shows a similar trend. With the increase of duration time, the wear loss of SJ and NC increased and the growth rate slowed down. As we can see in Fig.5 (a), the wear loss of NC no longer increase when the time is up to 2.5h. This indicate that Cu nanoparticles’ addition have successfully avoid abrasion between Steel and ZL101 at this time.

![Fig 3. Wear loss weight (a) and friction coefficient (b) as functions of increasing normal load (800 rpm, 30 min).](image-url)
3.2 SEM and EDS analysis
To recognize the effect of Cu nanoparticles’ addition on the tribology performance, the worn out disc surfaces are examined through SEM and the micro structures are presented in Fig.6. The graph shows the surface morphology of the lower test aluminum alloy disc with a load of 500 N under two types of lubrication systems, enlarged by 35 and 1000 times respectively. As we can see from the graph, the wore surface of NC lubrications are relatively clean and smoothly. The wore surface of SJ lubrications possess an increased roughness, which is nonuniform and discontinuous. This is in agreement with the result obtained from the tribological analysis.

Although the NC lubrications demonstrate a better friction and wear performance, we should notice that some area of the wore surface of NC lubrications is also nonuniform when it enlarged by 1000 times. So we add an EDS analysis of wore disc surface lubricated with NC which is shown in Fig.7. As we can see in Fig.7, the smooth area(b) possess a high content of copper while the roughness area(a) possess a high content of iron. The phenomenon demonstrate that the smooth area should have experienced light wear. This is probably because when the temperature and applied load reach a certain level during the friction process, the Cu nanoparticles on the surface decomposes and desorbs, and the exposed highly active Nano-Cu directly touch the surface of the friction metal. A series of physical and chemical actions such as deposition, filling, and melting film formation have occurred, which increased the contact area between steel and ZL101. As a result, a boundary lubrication film with good anti-friction and lubricating properties formed, which effectively improves the wear and friction properties. As for the roughness area, this is probably due to the uneven distribution of copper in the oil during the friction process. The phenomenon also demonstrate that Cu nanoparticles are
potential friction modifier when used in ZL101.

![SEM morphologies of the worn surfaces of SJ and SJ containing 0.6 wt% Cu nanoparticles](image1)

(a) SJ lubrications (35, 1000)

(b) NC lubrications (35, 1000)

Fig 6. SEM morphologies of the worn surfaces of SJ and SJ containing 0.6 wt% Cu nanoparticles

![EDS analysis of wore disc surface of NC](image2)

Fig 7. EDS analysis of wore disc surface of NC

**4. Conclusion**
In the present work, Cu nanoparticles were prepared and introduced into SJ 15W/40 heavy duty gear oil as a lubricant additive. Following conclusions can be drawn:

(1) The oil-soluble Nano-Cu additive have excellent friction-reducing properties and 0.6wt.% Cu nanoparticle addition exhibited the best tribological behavior.

(2) An appropriate applied load and rotating speed can improve the wear and friction properties obviously and duration time has the least influence. When the applied load is 500N, the wear loss of NC reduced by 25% and the friction coefficient reduced by 71% compared with SJ.

(3) The cobination of SEM-EDS analysis demonstrate that by addition of Cu nanoparticles, a boundary lubrication film with good anti-friction and lubricating properties formed and improve the tribology properties.

(4) Cu nanoparticles are expected to improve the energy efficiency and can be taken as a potential friction modifier when used in aluminum alloy ZL101.

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