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*Turkish Journal of Electromechanics & Energy*
ISSN: 2547-975X

# Lubricated friction and wear properties of Zn-15Al-(1-5)Cu Alloys

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Received: 9 August 2016; Revised: 21 September 2016; Accepted: 30 September 2016; Published: 1 December 2016
Turk J Electrom Energ Vol.: 1 No: 2 Page: 1-7 (2016)
SLOI: http://www.sloi.org/
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**ABSTRACT In this study, lubricated friction and wear properties of Zn-15Al-(1-5)Cu alloys were investigated using a block-on-disc type test machine. Friction and wear tests were carried out at an oil flow rate of 1 $cm^3 h^{-1}$, a sliding speed of 2 $m s^{-1}$ and a contact pressure of 6 MPa for a sliding distance of 108 km. The variations in the friction coefficient, working temperature and wear volume of the alloys with sliding distance and copper content were monitored. The friction coefficient and the working temperature of the alloys became almost constant after the sliding distance of approximately 20 km, following an initial decrease. The wear volume of the alloys increased with increasing sliding distance and became almost constant after a sliding distance of 60 km. Zn-15Al-3Cu alloy exhibited the lowest friction coefficient, working temperature and wear volume among the alloys investigated. These observations are discussed in terms of the microstructural and mechanical properties of the alloys.**

**Keyword:** Zn-15Al-Cu alloys; Lubricated friction and wear; Friction coefficient and wear volume; Wear surface

**Cite this article:** A.P. Hekimoğlu, T. Savaşkan, Lubricated friction and wear properties of Zn-15Al-(1-5)Cu Alloys, Turkish Journal of Electromechanics & Energy 1(2) 1-7 (2016)

## 1. INTRODUCTION

Zinc-based commercial alloys named as Zamak series were first developed in the 1920s and used successfully in some industrial applications [1-3]. Alzen alloys containing 30% Al (Alzen 305) and 50% Al (Alzen 501) were developed for bearing applications during World War II [3, 4]. Further research and development studies on the zinc-based alloys resulted in the development of ZA-8, ZA-12, and ZA-27 alloys containing 8, 12, and 27 % aluminium, respectively [1, 3, 4]. These studies showed that zinc alloys have a number of advantages over traditional bearing alloys including bronzes, brasses and cast irons [1-7]. The most important advantages of these alloys can be stated as high specific strength, good castability, easy machinability, low production energy and cost, excellent tribological and mechanical properties, good surface finishing and quality, superior embeddability and damping properties, and lower friction coefficient [1-7]. Lower friction coefficient, higher hardness and high strength provide energy saving and longevity in engineering applications. Studies on the structure and properties of zinc-based alloys have been continued to improve their mechanical and tribological properties for some engineering applications [5, 8-9].

According to binary Al-Zn phase diagram [10-12] zinc-based alloys can be classified as eutectic (Zn-5Al), eutectoid (Zn-22Al) and monotectoid (Zn-40Al) alloys. Monotectoid Zn–Al alloys have been shown to be harder, stronger and more wear resistant than either eutectoid or eutectic ones [13]. However, hypereutectoid and eutectic Zn–Al based alloys have comparatively higher ductility, damping capacity and better castability [13]. Research works carried out on these alloys have been focused on the near eutectoid and monotectoid compositions and resulted in development of Zn-25Al-3Cu, Zn-27Al-2Cu, Zn-40Al-2Cu and Zn-40Al-3Cu alloys [8, 13-16]. However, the studies on the microstructure and properties of these alloys have been continued.

The studies on the zinc-based alloys have shown that the alloying elements including aluminium, copper and silicon have strong effects on their mechanical and tribological properties [10-19]. These effects have been attirubuted to the the changes in their microstructures [13-21]. It has been observed that the addition of copper more than 2-3 % results in the formation of a metastable intermetallic phase called ε ($CuZn_4$) in the microstructure of the zinc-based alloys [14, 17-19]. This phase (ε) improves the load bearing capacity of these alloys by increasing their hardness, but decreases their strength and ductility [5, 6, 14, 17-19]. Furthermore, it (ε) causes a considerable amount of dimensional instability in these alloys [5, 6, 14, 17-19]. Therefore, the copper content should be taken as an important parameter in designing the zinc-based alloys for engineering applications.

Extensive research carried out recently on the high-zinc containing alloys resulted in the development of new Zn-15Al-based alloys for tribological applications [13, 14, 19]. The effect of copper content on the mechanical and dry wear properties of these alloys have been determined [13, 19, 20]. However, there is no information available about the effects of copper content on the lubricated friction and wear properties of these alloys. Therefore, the aim of this work is to investigate the effects of copper additions on the lubricated friction and wear properties of Zn-15Al alloy and determine the the most suitable alloy composition for tribological applications.

## 2. EXPERIMENTAL PROCEDURE

Five (Zn-15Al-Cu) alloys were prepared by permanent mold casting using high purity aluminum (99.70 wt.%), zinc (99.90 wt.%) and copper (99.90 wt.%). The alloys were melted in an electric furnace and poured into a steel mold at temperatures of between 650 and 700 °C. The chemical composition analysis of the tested alloys was carried out by atomic absorption method. Their densities were determined by Archimedes' method. Metallographic investigations were performed with standard techniques and the samples etched in 1-4 % Nital. Microstructures of the alloys were examined using both optical and scanning electron microscopy (SEM).

The hardness of the alloys was measured using the Rockwell hardness F scale. Tensile tests were performed with the alloy samples having the diameter and gauge length of 8 × 40 mm at a strain rate of $6.25\times10^{-3}\ s^{-1}$. At least three measurements were taken to determine the hardness and tensile strength of the alloys.

Lubricated friction and wear properties of the experimental alloys were investigated using a block-on-disc type test machine. The schematic illustration of this test machine is shown in Fig. 1. The details of the friction-wear test machine and test sample were given elsewhere [20]. Friction and wear properties of the alloys were studied at a constant pressure of 6 MPa, a sliding speed of 2 m $s^{-1}$, oil flow rate of 1 $cm^3\ h^{-1}$, and a sliding distance of 108 km for each samples. The tests were performed at room temperature (23 ± 2 °C) in air with a relative humidity of 70 ± 5%. The temperature of the wear sample was monitored by inserting a copper–nickel thermocouple in a hole at a distance of 1.5 mm from the contacting surface. Each wear sample was ultrasonically cleaned and weighed before the tests using an electronic balance with an accuracy of 0.01 mg. The disc surface was cleaned with organic solvents to remove surface contaminants before each test. The samples cleaned in solvents and weighed to determine the mass loss after each test. Since the wear volume is a more meaningful parameter than the mass loss of the sliding bearings, the measured values of mass loss for the samples were converted into volume loss using the measured density of the alloys. The surface features and the subsurface microstructures of the wear samples were studied using SEM.

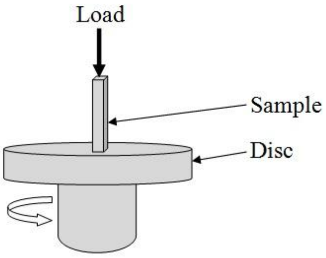


Fig. 1. Schematic illusturation of the wear test machine

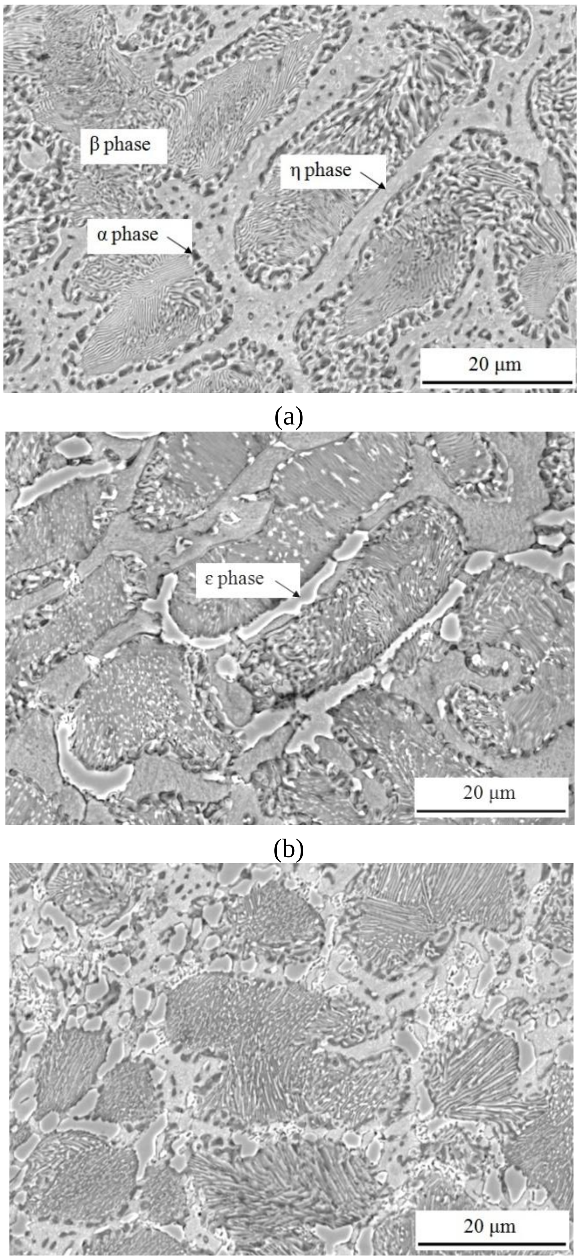
## 3. RESULTS

The chemical compositions of the experimental alloys are given in Table 1. The micrographs showing the microstructures of the Zn-15Al-Cu alloys are given in Figs. 2a-c. The microstructures of the alloys containing less then 2% copper consisted of partially decomposed proeutectic β dendrites, and α and η phases as seen in Fig. 2a. It was observed that when the copper content exceeds 2-3%, copper rich ε phase forms in the interdendritic regions and the volume fraction of this phase increases with increasing copper content, Fig. 2b and c.

Table 1. Chemical composition of the experimental alloys

| Alloy | Chemical composition (wt. %) | | |
|---|---|---|---|
| | Zn | Al | Cu |
| Zn-15Al-1Cu | 84.2 | 14.9 | 0.9 |
| Zn-15Al-2Cu | 82.9 | 15.0 | 2.1 |
| Zn-15Al-3Cu | 81.9 | 15.2 | 2.9 |
| Zn-15Al-4Cu | 81.3 | 14.8 | 3.9 |
| Zn-15Al-5Cu | 80.4 | 14.8 | 4.8 |

The curves showing the changes in the tensile strength, hardness, yield strength, and elongation to fracture of the Zn-15Al-Cu alloys with copper content are given in Figure 3. The hardness, tensile strength, and yield strength of the alloys increased with increasing copper content, but above 3% Cu the yield and tensile strength decreased. Elongation to fracture of the alloys decreased with increasing copper content, Figure 3.



(a)

(b)

(c)

Fig. 2. SEM micrographs of the microstructure of (a) Zn-15Al-1Cu, (b) Zn-15Al-3Cu and (c) Zn-15Al-5Cu alloys

The changes in friction coefficient, working temperature, and wear volume of the alloys as a function of sliding distance and copper content are shown in Figs. 4, 5 and 6, respectively. The friction coefficient of the experimental alloys reached steady states after showing a sharp decrease with sliding distance, Fig. 4a and b. However, the working temperature of the alloys reached steady states after showing a sharp increase and a decrease as seen in Fig. 5a, and b. The wear volume of the alloys increased with increasing sliding distance and reached almost a constant value after the 60 km, Fig. 6. The friction coefficient, working temperature and wear volume of the alloys decreased with increasing copper content, but above 2-3% Cu the trend reversed, Fig. 7.

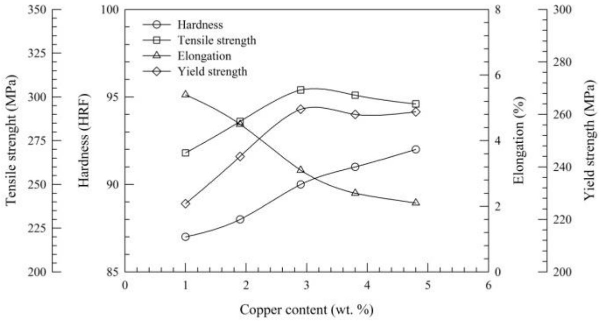
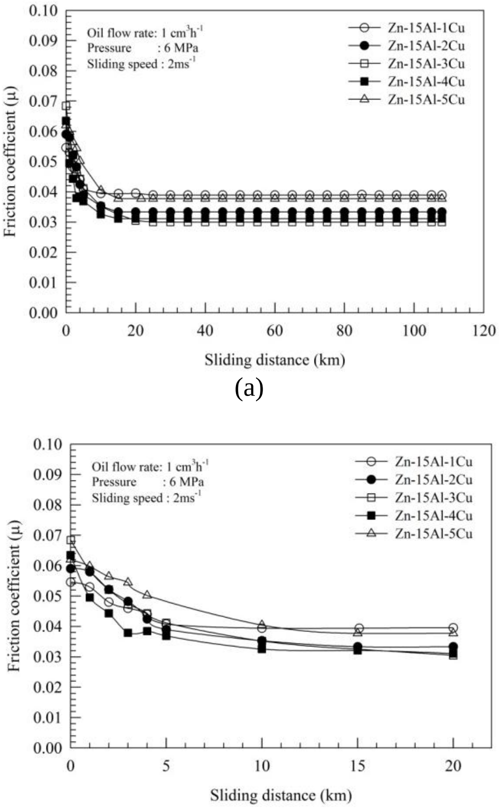


Fig. 3. The curves showing the changes in tensile strength, hardness, elongation, and yield strength of Zn-15Al-Cu alloys with their copper content

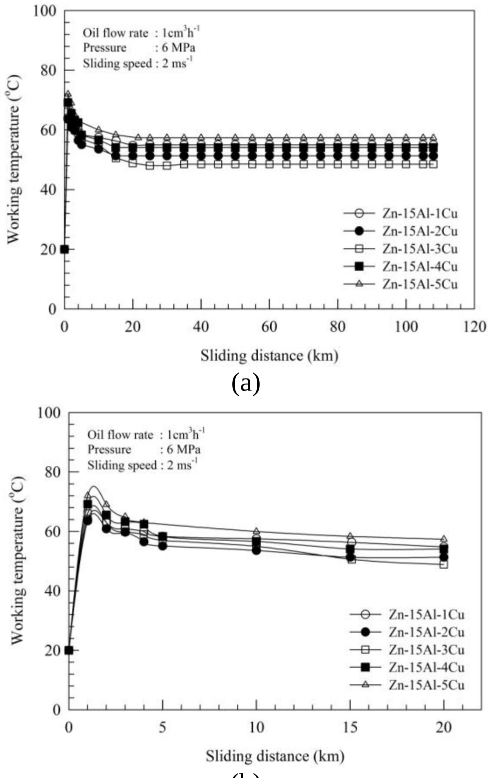
Smearing and scratches were observed to be the main surface features of the wear samples of the experimental alloys as seen in Figs. 8a-c. As the copper content increased the amount of smeared material on their wear surfaces decreased, but the number and size of the scratches increased as it can be noticed from Figure 8a and 8c.



(a)

(b)

Fig. 4. The curves showing the changes in friction coefficient of Zn-15Al-(1-5)Cu alloys for the sliding distances of (a) 108 and (b) 20 km



(a)

(b)

Fig. 5. The curves showing the changes in working temperature of Zn-15Al-(1-5)Cu alloys for the sliding distances of (a) 108 and (b) 20 km

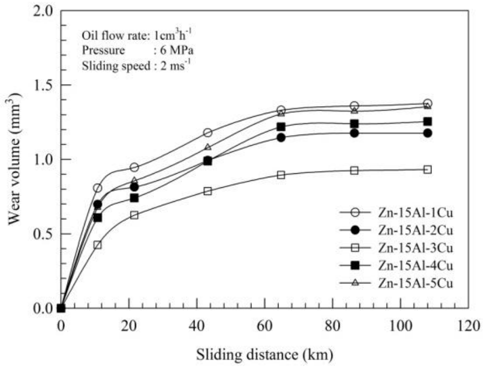


Fig. 6. The curves showing the changes in wear volume of the Zn-15Al-(1-5)Cu alloys as a function of sliding distance

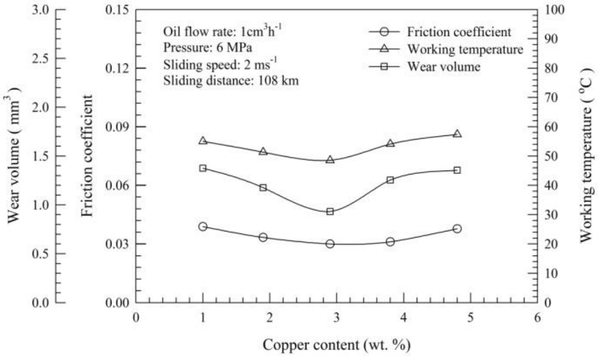
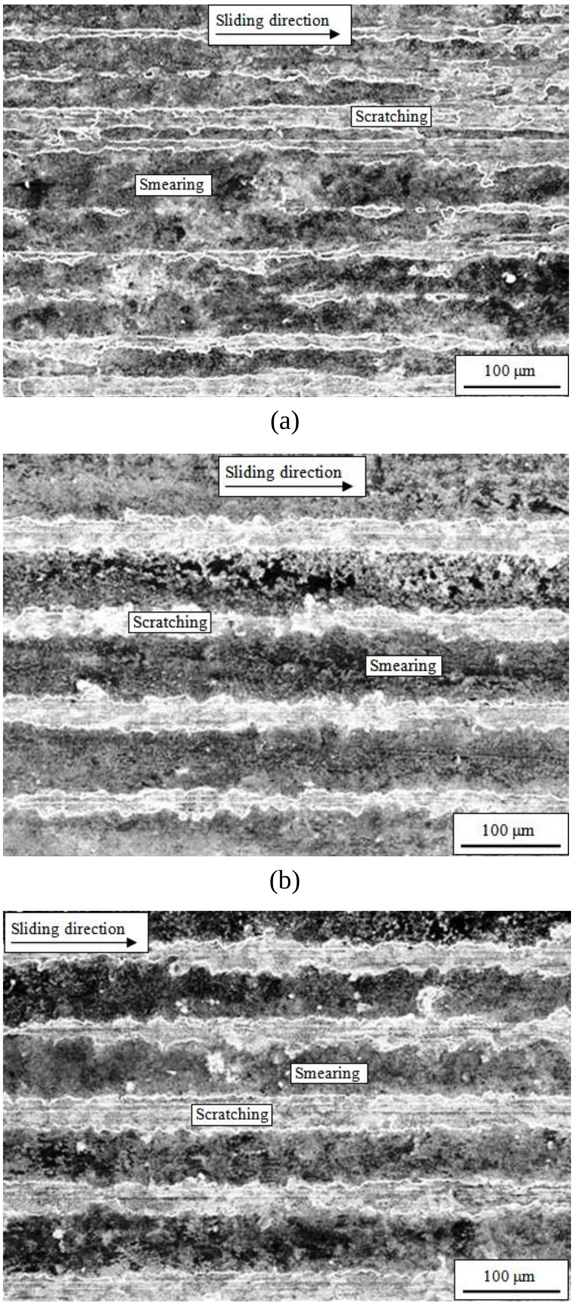


Fig. 7. The curves showing the variations in the friction coefficient, working temperature, and wear volume of the Zn-15Al-(1-5)Cu alloys with copper content



(a)

(b)

(c)

Fig. 8. SEM micrograph showing the wear surfaces of (a) Zn-15Al-1Cu, (b) Zn-15Al-3Cu and (c) Zn-15Al-5Cu alloys

## 4. DISCUSSION

The microstructure of the Zn-15Al-1Cu alloys consisted of β dendrites and α and η phases as seen Fig.2a. The ε ($CuZn_4$) phase formed in the microstructure of the alloys when their copper content exceeded 2%, and the volume fraction of this phase increased with increasing copper content as seen in Figs. 2a and b. This observation is in agreement with the results of previously published papers [20-23]. Formation of these phases can be related to the phase transformations which take place during solidification of Zn-15Al based alloys [19].

The hardness, tensile, and yield strength of the experimental alloys increased with increasing copper content; but above 3% Cu, the yield and tensile strength decreased. Elongation to fracture of the alloys decreased with increasing copper content (Figure 3). These observations can be attributed to the solid solution hardening and formation of the relatively hard and brittle copper-rich intermetallic ε phase in the alloys containing more than 2% Cu [17-20].

The friction coefficient of the experimental alloys decreased with increasing sliding distance and became almost constant (Fig. 4a and b). The working temperature of these alloys also became almost constant, but after showing a sharp increase and a decrease (Fig. 5a and b). These observations may be related to metal-to-metal contact due to inadequate oil film on the mating surfaces. Metal-to-metal contact gives rise to high friction force which results in high friction coefficient [22-24]. It is well known that the friction coefficient of the lubricated systems decreases with increasing oil film thickness and when the oil film thickness becomes sufficient to separate the rubbing surfaces friction coefficient levels off and becomes almost constant [22-24]. Working temperature of the alloys showed a similar trend with their friction coefficient. This can be attributed to the frictional heat caused by rubbing of the surfaces.

The wear volume of the alloys increased with increasing sliding distance and reached almost a constant value after 60 km, Fig. 6c. This can be attributed to the increase in the oil film thickness with sliding distance as was mentioned in the discussion of the friction coefficient of these alloys.

The friction coefficient, working temperature and wear volume of the alloys decreased with increasing copper content, but above 3% Cu the trend reversed, Fig. 7. These observations can be explained in terms of the microstructure and tensile strength of the alloys. It is known that as the copper content increases the hardness of the alloys increase, but their elongation to fracture decreases. Tensile strength of these alloys also increases with increasing copper content up to 3%, but above this level the trend reverses. It is also known that when the copper content of the Zn–Al–Cu alloys exceeds 2–3%, a hard and brittle ε-phase form in their microstructures and the volume fraction of this phase increases with increasing copper content [17-20]. Therefore, the changes in the tensile strength of the Zn-15Al-Cu alloys can be attributed to the solid solution strengthening and cracking tendency, respectively [17-20]. According to the adhesive wear law, the friction coefficient and wear volume of the materials decrease as their hardness and strength increase [22, 25, 26]. Therefore, the friction coefficient, working temperature and wear volume of these alloys are expected to decrease with copper content up to 3%. The increase in these parameters may be related to the formation of hard and brittle ε-phase and a reduction in the tensile strength of the alloys when their copper content exceeds 3%. This is because the tensile strength of the zinc-based alloys is more influential on their wear volume than their hardness [20]. It is also known that there is a strong relationship between the wear resistance and the tensile strength of Zn–Al–Cu alloys [17, 18, 20]. Therefore, the alloys which have the highest tensile strength are expected to show the highest wear resistance or the lowest wear volume.

Smearing and scratches were observed to be the main features of the worn surface of the alloy samples, Fig. 8a and b. Smearing takes place by back transferring of the wear debris from the disc to the sample surface; scratches occur due to the removal of hard silicon and ε particles from the wear surface of the samples and microcracks result from the brittleness of the hard surface layer as reported in previously published papers [17, 18, 20-22].

## 5. CONCLUSIONS

1. Microstructure of Zn-15Al-(1-5)Cu alloys consists of α, β and η phases. When the copper content exceeds 2%, copper rich ε phase forms in the microstructure.
2. Hardness of Zn-15Al-(1-5)Cu alloys increase with increasing copper content. Their tensile strength also increase with increasing copper content, but the trend reverses above 3% Cu .
3. Zn-15Al-3Cu alloy exihibits the lowest friction coefficient, working temperature and wear volume among Zn-15Al-(1-5)Cu alloys.
4. The friction coefficient and working temperature of Zn-15Al-(1-5)Cu alloys decrease with increasing sliding distance, but above a sliding distance of approximately 20 km they become almost constant.
5. Wear surfaces of Zn-15Al-(1-5)Cu alloys are characterized by smearing and scratches.

## Acknowledgement

This work was supported by the Karadeniz Technical University under a research contract (No. 2008.112.03.2).

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## Biographies

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