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Correlation of Mechanical and Tribological Properties of Zn-40Al-2Cu-2Si Alloy

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ABSTRACT

An attempt was made to correlate mechanical (hardness and ultimate tensile strength) and tribological properties (friction coefficient, working temperature, wear volume and average surface roughness) of Zn-40Al-2Cu-2Si alloy which was prepared by permanent mold casting. The tribological properties of the alloy were determined using a block-on-cylinder type wear test machine. The relationships between the mechanical and tribological properties of the alloy determined by linear regression analysis were observed to be expressed by linear or straight-line equations. The correlation coefficients of these relationships were found to be between 0.94 and 0.99. These linear equations indicate that the friction coefficient and the wear volume of this alloy can be calculated in terms of either its hardness or tensile strength under the given working conditions. These linear relationships also showed that as the hardness and the tensile strength of the alloy increase the friction coefficient, working temperature, and wear volume of it decrease but its average surface roughness increases. These observations were explained in terms of the microstructure and mechanical properties of the alloy, adhesion theory of friction and the Archard wear law. The equations obtained by this correlation can also be used for the selection of Zn-40Al-based alloys for bearing applications.

Keywords: Zn-based bearing alloys, Hardness, Tensile strength, Friction, Wear volume, Surface roughness

Zn-40Al-2Cu-2Si Alaşımının Mekanik ve Tribolojik Özelliklerinin Korelasyonu

ÖZ

Kokil kalıba döküm yöntemiyle üretilen Zn-40Al-2Cu-2Si alaşımının mekanik özellikleri (sertlik ve çekme dayanımı) ile tribolojik özellikleri (sürtünme katsayısı, çalışma sıcaklığı, hacim kaybı ve ortalama yüzey pürüzlülüğü) arasındaki ilişkiler araştırıldı. Alaşımın tribolojik özellikleri blok-silindir tipi bir aşınma deney düzeneği yardımıyla incelendi. Bu özellikler ile sertlik ve çekme dayanımı değerleri arasında lineer regresyon analizi ile belirlenen ilişkilerin lineer veya doğrusal denklemler ile ifade edilebileceği gözlendi. Bu analizler sonucunda elde edilen doğrusal ilişkiler için korelasyon katsayılarının 0,94 ile 0,99 arasında yer aldığı görüldü. Belirlenen denklemler Zn-40Al-2Cu-2Si alaşımının belirli koşullardaki sürtünme katsayısı ve hacim kaybı değerlerinin bu alaşımın sertlik ve çekme dayanımına göre hesaplanabileceğini ifade etmektedir. Söz konusu denklemler alaşımın sertlik ve çekme dayanımı arttıkça sürtünme katsayısı, çalışma sıcaklığı ve hacim kaybının azaldığını, ortalama yüzey pürüzlülüğünün ise arttığını göstermektedir. Bu gözlemler alaşımın metalografik yapısı, mekanik özellikleri, adheziv sürtünme teorisi ve Archard aşınma kanununa dayandırılarak tartışıldı. Zn-40Al-2Cu-2Si alaşımının mekanik ve tribolojik özellikleri arasındaki ilişkileri ortaya koyan ampirik denklemlerin Zn-40Al esaslı yatak alaşımlarının seçiminde kullanılabileceği sonucuna varıldı.

Anahtar Kelimeler: Zn-esaslı alaşımlar, Sertlik, Çekme dayanımı, Sürtünme, Aşınma, Yüzey pürüzlülüğü

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1. Introduction

Zn-40Al-2Cu-2Si alloy has been developed after intensive and extensive research on Zn-Al based bearing alloys (Jovanoviç et al., 2007; Lyon, 1986; Michalik 2014; Pola et al., 2020; Savaşkan and Bican, 2005). Further studies have shown that it has superior mechanical and tribological properties compared to other Zn-Al based alloys and traditional bearing materials (Hekimoglu and Savaskan, 2018; Prasad, 2000; Savaskan and Azaklı, 2008). It was also shown that the mechanical and tribological properties of this alloy can be further improved by application of some heat treatments including T6 and isothermal transformation (Michalik, 2018; Savaşkan and Hekimoğlu, 2015; Savaşkan et al., 2021; Savaşkan et al., in press). The microstructure, mechanical and tribological properties of this alloy have been studied and discussed in detail (Savaşkan et al., 2021; Savaşkan et al., 2022; Savaşkan et al., in press), but no study has been conducted on the correlation of its mechanical and tribological properties. Therefore, the aim of this work is to determine the relationships between the mechanical and lubricated wear properties of this alloy using the data reported in the recently published papers of the authors of this paper (Savaşkan et al., 2021; Savaşkan et al., 2022; Savaşkan et al. in press).

2. Material and Methods

The data used in this study were taken from the recently published papers of the authors (Savaşkan et al., 2021; Savaşkan et al., 2022; Savaşkan et al., in press;). As described in these papers Zn-40Al-2Cu-2Si alloy was produced by permanent mold casting (Savaşkan et al., 2021; Savaşkan et al., 2022; Savaşkan et al., in press). It was subjected to several different heat treatments including homogenizing, quench-aging (T6 and T7) and isothermal transformation to improve its mechanical and tribological properties. Homogenization treatment was conducted by either air or furnace cooling after solutionizing. Isothermal transformation was performed at four different temperatures (100 ºC, 150 ºC, 200 ºC and 250 ºC). Brinell hardness measurements were conducted using a 2.5 mm diameter ball as an indenter under a load of 62.5 kgf. Tensile tests were performed using the specimens with the dimensions of Ø10 mm × 50 mm at a deformation rate of 5×10^{-3} s^{-1}. Tribological tests were conducted at an oil supply rate of 1 $cm^3\times h^{-1}$, a pressure of 14 MPa and a sliding velocity of 2 m/s for a sliding distance of 102 km in a block-on-cylinder type experimental setup. In this setup, the block is the wear test sample, and cylinder simulates the engine crankshaft. The level of the contact pressure was selected to simulate the working conditions of the diesel engine crankshaft bearings. The details of these tests and examinations were reported in the previously published papers (Savaşkan et al., 2021; Savaşkan et al., in press; Savaşkan et al., 2022).

3. Results

The microstructure of Zn-40Al-2Cu-2Si alloy was observed to be composed of aluminum-rich α dendrites, eutectoid mixture of α + η phases, and silicon and copper-rich fine ε ($CuZn_4$) particles (Savaşkan et al., 2021; Savaşkan et al., 2022; Savaşkan et al., in press). Microstructures obtained after different heat treatments of the alloy were also reported in a recently published papers (Savaşkan et al., 2021; Savaşkan et al., 2022; Savaşkan et al., in press). The influences of heat treatments on the hardness (*H*), ultimate tensile strength (*TS*), friction coefficient (*FC*), temperature (*T*), wear volume (*WV*) and average surface roughness (*ASR*) values of the alloy are shown in the bar chart of Figure 1 and 2 (Savaşkan et al., 2021; Savaşkan et al., 2022, Savaşkan et al., in press).

Solutionizing followed by air-cooling (H1) and quench-aging (T6) caused an increment in the hardness and tensile strength of the alloy while solution treatment followed by furnace-cooling (H2) and quench-aging (T7) treatments caused a decrement in these values, as shown in Figure 1. This figure also shows that as the isothermal transformation temperature increases, the *H* and *TS* of the alloy decrease. H1 and T6 heat treatments caused a decrease in *FC*, *T*, and *WV* of the alloy but H2 and T7 heat treatments increased these values, Figure 2. Besides, the FC, *T*, and *WV* of the alloy increased but the *ASR* of it decreased with increasing isothermal transformation temperature.

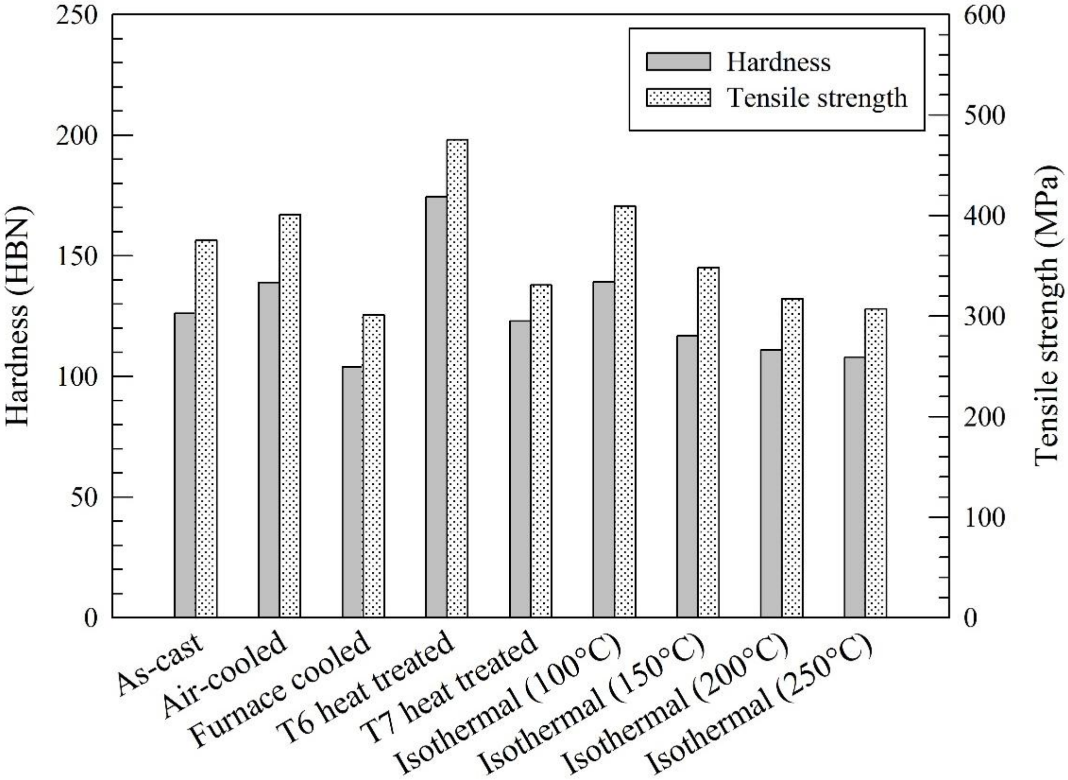

Figure 1. The bar chart showing the hardness and tensile strength of the alloy samples (Savaşkan et al., 2021; Savaşkan et al., 2022; Savaşkan et al., in press)

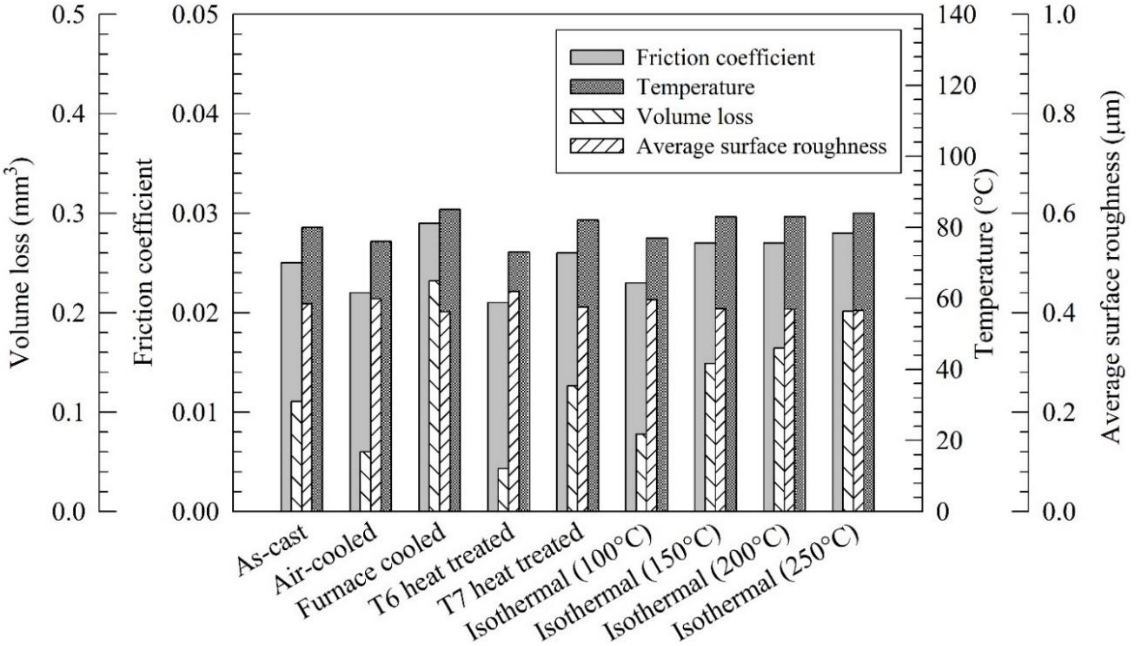

Figure 2. The friction coefficient, temperature, wear volume and average surface roughness values of the alloy samples (Savaşkan et al., 2021; Savaşkan et al., 2022; Savaşkan et al., in press)

4. Discussion

H2 and T7 heat treatments caused a decrease in the hardness and tensile strength of Zn-40Al-2Cu-2Si alloy. This observation may be attributed to the removal of the residual stresses and transformation of metastable phases of the alloy during these heat treatments (Savaşkan et al., 2021; Savaşkan et al., 2022; Savaşkan et al., in press). H1 and T6 heat treatments increased the hardness and tensile strength of the alloy. This increment can be related to the precipitation hardening that occurs during aging of supersaturated solid solutions (Savaşkan et al., 2021; Savaşkan et al., 2022; Savaşkan et al., in press). The adverse effect of the isothermal transformation treatment on the hardness and tensile strength of the alloy can be attributed to the overaging of the alloy due to a long transformation time (8 hours) (Savaşkan et al., in press).

The variations of the *FC*, T, *WV* and *ASR* of Zn-40Al-2Cu-2Si alloy subjected to wear tests at an oil supply rate of 1×10^{6} m^3 h^{-1}, a contact pressure of 14 MPa and a sliding speed of 2 m s^{-1} for a sliding distance of 102 km with their hardness and ultimate tensile strength are shown in Figures 3a-d. These plots show that as the hardness (H) and the ultimate tensile strength (UTS) of this alloy increase its friction coefficient (FC), working temperature (T), and wear volume (WV) decrease but the average surface roughness (ASR) increases. The mechanical (*H* and *UTS*) and tribological properties (*FC, T, WV and ASR*) of the alloy were correlated using the results reported in the literature (Savaşkan et al., 2021; Savaşkan et al., 2022; Savaşkan et al., in press).

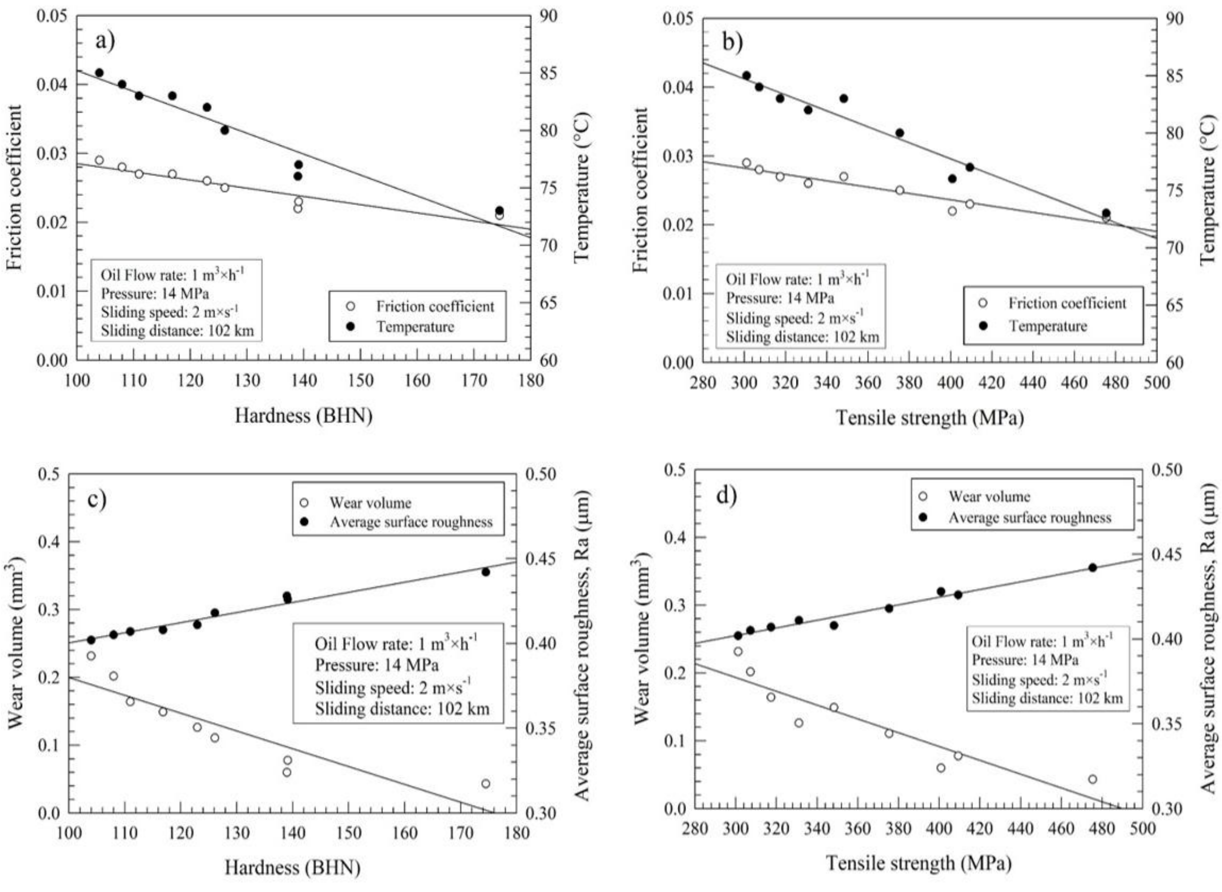

Figure 3. a) *FC* and *T* versus *H*, b) *FC* and *T* versus *UTS*, c) *WV* and *ASR* versus *H*, and d) *WV* and *ASR* versus *UTS* plots for Zn-40Al-2Cu-2Si alloy

The relationships between the mechanical values (H and UTS) and tribological properties (FC, T, WV and ASR) of Zn-40Al-2Cu-2Si alloy determined by linear regression analysis are given below:

$$FC = -0.0001 \times H\,[\text{BHN}] + 0.0405 \quad (1)$$

$$\text{FC} = -4.59\text{x}10^{-5} \times UTS\,[\text{MPa}] + 0.0420 \quad (2)$$

$$T\,[^{\circ}\text{C}] = -0.1820 \times H\,[\text{BHN}] + 103.41 \quad (3)$$

$$T\,[^{\circ}\text{C}] = -0.0697 \times UTS\,[\text{MPa}] + 105.6126 \quad (4)$$

$$WV\,[\text{mm}^3] = -0.0026 \times H\,[\text{BHN}] + 0.4621 \quad (5)$$

$$WV\,[\text{mm}^3] = -0.001 \times UTS\,[\text{MPa}] + 0.4985 \quad (6)$$

$$ASR\,[\mu\text{m}] = 0.0006 \times H\,[\text{BHN}] + 0.3407 \quad (7)$$

$$ASR\,[\mu\text{m}] = 0.0002 \times UTS\,[\text{MPa}] + 0.3341 \quad (8)$$

The correlation coefficient (R) values for these linear relationships were found to be 0.94, 0.95, 0.96, 0.98, 0.90, 0.98, 0.98, and 0.99, respectively.

These relationships can be interpreted in terms of the adhesion theory of friction and the Archard wear law (Bowden and Tabor, 1967; Halling, 1989; Hutchings, 1992). According to the adhesion theory of friction, friction coefficient of the wearing materials decreases with increasing yield strength. The Archard wear law (Bowden 1967; Halling 1989; Hutchings 1992) states that the wear volume is inversely proportional to the hardness or the yield strength of the softer of contact partners. It is also known that an increment in the tensile strength of the materials means an increase in their yield strength. Since the wear occurs due friction of the contacting surfaces a decrement in the friction force or friction coefficient results in a decrease in the wear volume. Therefore, the *FC*, *T*, and *WV* of the alloy are expected to decrease with increasing *H* and *UTS*.

5. Conclusions

The conclusions obtained from this study are given below:

1. The hardness and tensile strength of Zn-40Al-2Cu-2Si alloy can be significantly changed with the application of heat treatment.

2. As the hardness and tensile strength of Zn-40Al-2Cu-2Si alloy increase friction coefficient, working temperature, and wear volume of it decrease but its surface roughness increases.

3. The relationships between mechanical and tribological properties of Zn-40Al-2Cu-2Si alloy can be expressed by linear or simple straight-line equations as shown in the discussion section. This means that tribological properties (friction coefficient and wear volume) of this alloy can be calculated in terms of either its hardness or tensile strength under the given working conditions. The equations obtained by this correlation can also be utilized in the selection of Zn-40Al-based alloys for bearing applications.

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