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Materials and Design 28 (2007) 1889–1897

Materials & Design

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Comparison of the wear properties of modified ZA-8 alloys and conventional bearing bronze

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Received 25 August 2005; accepted 3 April 2006
Available online 17 July 2006

Abstract

In this study, an attempt has been made to examine the wear response of some modified Zn–Al based alloys and a conventional bearing bronze (SAE 660) at the sliding speeds of 0.5 ms^{-1}, 1 ms^{-1}, 1.3 ms^{-1}, 1.7 ms^{-1} and 2 ms^{-1} using applied load of 30 N and 45 N. The standard ZA-8 alloy and modified with 1% Pb, 1% Sn and 1% Cd alloys have been subjected to a pin-on-disc wear test under dry condition. A conventional bearing bronze has also been subjected to identical tests with a view to assess the working capability of the modified Zn–Al based alloys with respect to existing ones. The results have shown that the ZA-8 alloy and modified with Pb, Sn and Cd alloys revealed higher wear resistance when compared with bearing bronze. In addition, wear resistance of ZA-8 based alloys increased with increasing sliding speed up to 1.7 ms^{-1} for 30 N and 1.3 ms^{-1} for 45 N, respectively. But it decreased with increasing sliding speed. The addition of Pb to the ZA-8 alloy increased wear resistance of the alloy for all of the sliding speeds at 30 N and 45 N, while the addition of Cd increased wear resistance of the ZA-8 at 45 N. But Sn alloying element caused worse wear resistance for ZA-8 alloy. On the other hand, the friction coefficients of ZA-8 and modified alloys are higher than that of the bearing bronze. Metallographic studies showed that the addition of Pb, Sn and Cd resulted in modifying on the microstructure of ZA-8 alloy.

Keywords: Zn–Al alloys; ZA-8; Wear resistance; Friction

1. Introduction

The main advance in zinc casting industry in recent years was the development of new zinc alloys including higher-aluminium, namely ZA-8, ZA-12 and ZA-27, known as ZA alloys to supplement the well-established Zamak alloys used in pressure die-casting [1–3]. ZA-12 and ZA-27 alloys by virtue of their excellent castability, wear resistance, and good mechanical properties have found significant industrial usage during the past couple of years. These alloys have exhibited good wear resistance under high loads and poor lubrication conditions, and have been used as replacements for bronze and brass in the bearing industry [4–7]. These alloys also compete satisfactorily with other cast alloys such as copper alloys, aluminium alloys and some cast iron. The excellent tribological properties of the cast ZA alloys are attributed to a favorable multi-phase structure produced by the formation of aluminium and zinc oxides on the bearing surfaces. Aluminium oxide is hard compound and also acts as a load-bearing phase, while zinc oxide is a much softer and has a hexagonal crystal structure which allows it to act as a lubricant under suitable conditions [8–10]. Over the last decade, many studies have been carried out to improve the mechanical and tribological properties of the zinc–aluminium alloys and to increase their application [12–18].

Pb and Sn alloying elements was generally added to the Al based alloys for decreasing wear rate of the alloys in the bearing application. However, the effect of these elements on the mechanical properties and microstructure of the Zn–Al based alloys has not been fully understood.

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doi:10.1016/j.matdes.2006.04.010

The aim of this investigation was to study the fundamental mechanism involved in room temperature dry wear and to investigate the effect of Pb, Sn and Cd on the standard ZA-8 alloy produced by gravity casting. Moreover, a conventional bearing bronze has also been subjected to identical tests to undertake a comparative study.

Table 1
Chemical composition of the experimental alloys (wt.%)

Alloys	Al	Cu	Mg	Pb	Sn	Cd	Zn
ZA-8 (Std.)	8.05	0.97	0.032	–	–	–	Balance
ZA-8 Pb	8.10	1.00	0.032	1.03	–	–	Balance
ZA-8 Sn	7.95	1.00	0.032	–	1.05	–	Balance
ZA-8 Cd	8.05	1.02	0.032	–	–	1.0	Balance
SAE 660	–	Balance	–	7.1	7.2		3

2. Experimental work

2.1. Materials preparation

The alloys were prepared by liquid metallurgy route in a permanent cast iron mould in the form of cylindrical castings (size: 16 mm in diameter, 150 mm long). An electrical furnace was used at the first stage for melting the Al in a graphite crucible under nitrogen protective atmosphere. After melting Al, the melt temperature was increased to 750 °C and then Al–Cu alloy was introduced to the melt. Subsequently, Zn was added and the melt temperature was decreased to 650 °C. After that lead, tin and cadmium elements in pure state was added separately. At final stage pure magnesium (99.99 wt.%) was added to the melt at about 620 °C with vigorous stirring under protective gas and melts were then poured into permanent cast iron mould pre-heated to about 200 °C. The raw materials were commercially pure Al (99.8 wt.%), Zn (99.95 wt.%) and Al–Cu master alloy (50 wt.% Cu). Thus, four different Zn–Al based alloys were produced. The chemical compositions of the alloys were determined by atomic absorption spectroscopy and are presented in Table 1. The chemical composition of the conventional bearing bronze, which was provided in the shape of 20 mm bar, is also shown in Table 1.

2.2. Metallography

Microstructural examination of the experimental alloys was conventionally carried out on ground and polished samples using a JEOL JSM T320 scanning electron microscopy (SEM). SEM investigation was made in the as-polished samples using a large-area backscattered electron detector to produce an image. The large atomic number differences between the Al-rich and Zn-rich phases allowed the production of medium-resolution images of good contrast in this alloy which displayed the larger scale features of the structure very well.

In addition, the distribution of alloying elements in the structure was verified by using SEM instrument with attached energy dispersive spectrometry (EDS) and X-ray map. The presence of phases in microstructure was also confirmed by means of X-ray diffraction (XRD) using a Cu Kα radiation with wavelength of 1.5406 Å.

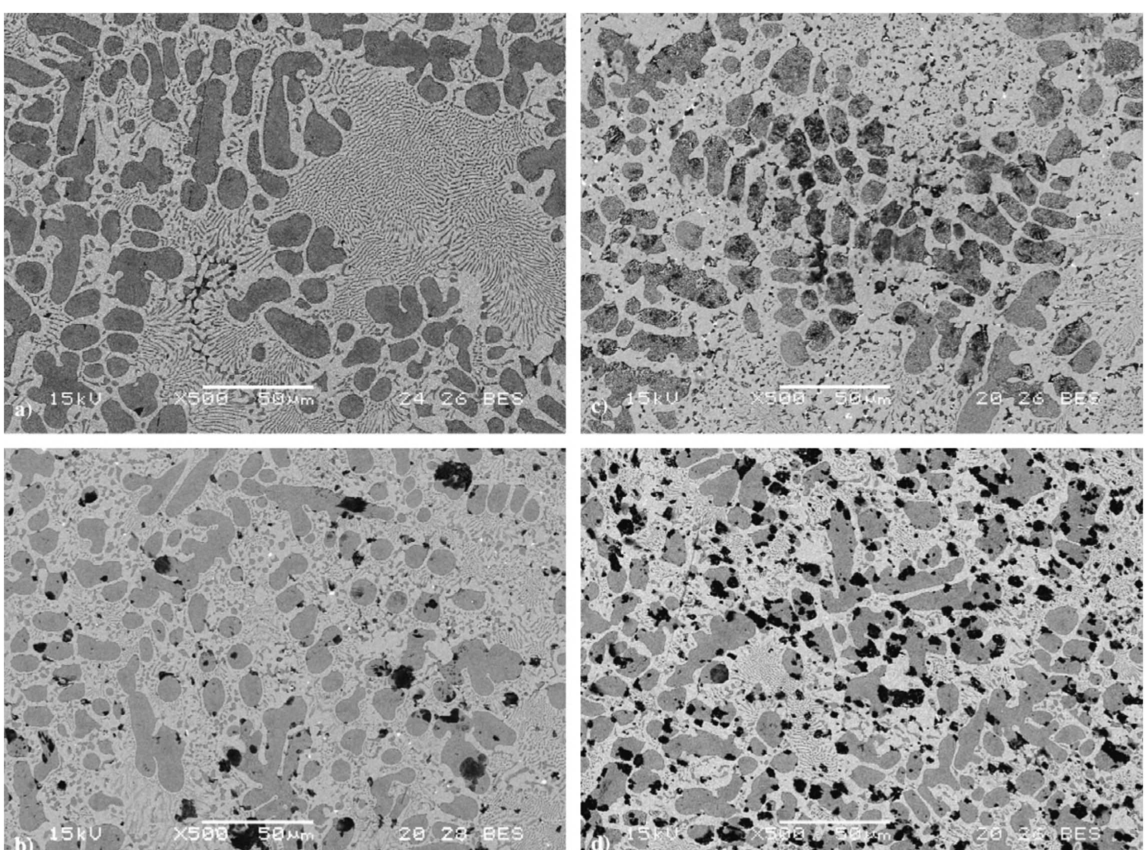

Fig. 1. The SEM micrographs of (a) Standard ZA-8, (b) ZA-8 – 1% Pb, (c) ZA-8 – 1% Sn and (d) ZA-8 – 1% Cd alloys.

2.3. Mechanical tests

Brinell hardness tests of the alloys were performed, on ground and polished samples, by using a ball diameter of 2.5 mm and applied load 62.5 kg. The load was applied for 30 s. At least 10 impressions were made to determine the mean value of the hardness at different locations to circumvent the possible effect of any alloying element segregation. Compressive tests were carried out on 8 mm in diameter, 16 mm in long specimens at the strain rate of $2.08 \times 10^{-3}\ s^{-1}$ using Dartec universal testing machine. Each test was repeated three times, and the average values were accepted as experimental result.

2.4. Wear testing

Dry sliding wear tests were performed using a pin-on-disc machine. The test materials in the form of pins of 5 mm diameter and 20 mm length

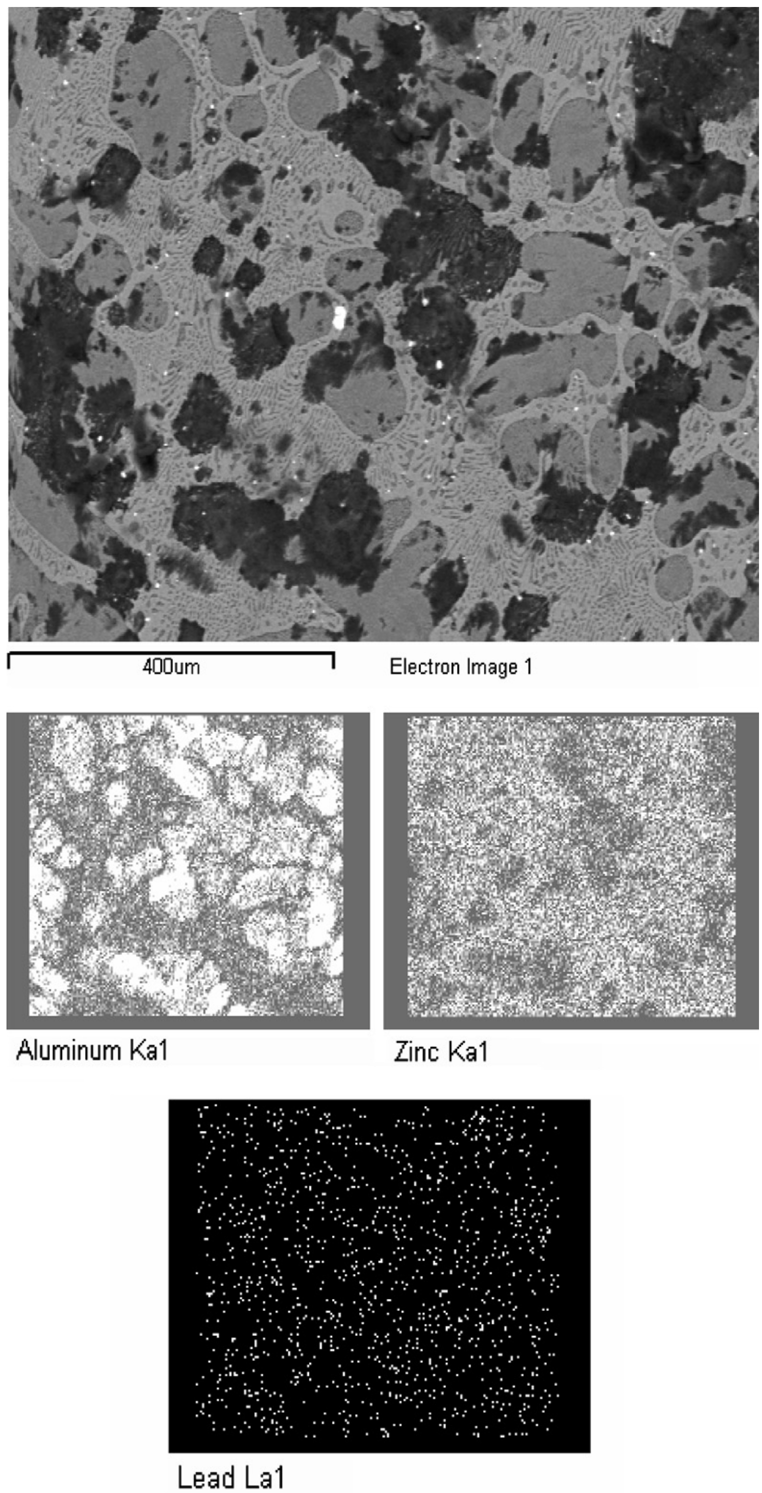

Fig. 2. X-ray map of the ZA-8 alloy containing 1% Pb.

were made to slide against a rotating heat treated DIN 8620 steel disc of hardness 65 HRC and diameter 100 mm. Wear tests were carried out at five different sliding speeds of $0.5\ ms^{-1}$, $1.0\ ms^{-1}$, $1.3\ ms^{-1}$, $1.7\ ms^{-1}$ and $2.0\ ms^{-1}$. Two loads, namely 30 N and 45 N, corresponding to nominal stress levels of 1.53 MPa and 2.3 MPa were used for each test on the samples. The frictional force was determined using a load cell and the coefficient of friction was calculated by dividing the frictional force by the normal load. The specific wear rate of the pins is defined as the weight loss per unit sliding distance. An electronic balance having an accuracy level of 0.001 mg was used to measure the weight loss. The pins were ultrasonically cleaned and dried prior to each weight measurement. The wear tests were carried out for a total sliding distance of about 7.2 km. The relative humidity was measured but not controlled and was in the range of $60 \pm 5\%$ during these tests.

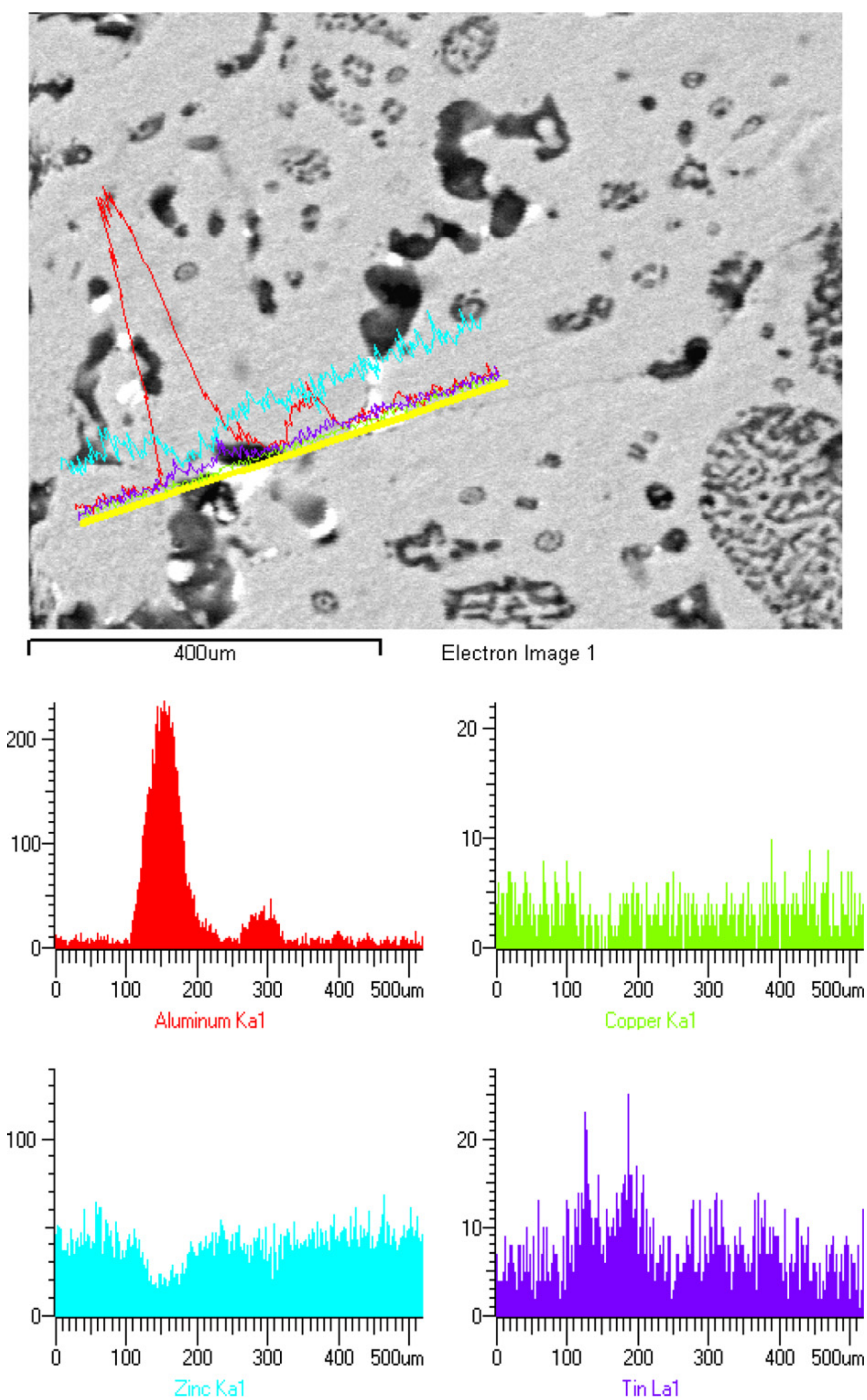

Fig. 3. The EDS line analysis in the microstructure of modified ZA-8 alloy with 1% Sn.

3. Results and discussion

3.1. Microstructure and characterization

Fig. 1a–d represent the microstructure of standard ZA-8, ZA-8 – 1% Pb, ZA-8 – 1% Sn and ZA-8 – 1% Cd alloys, respectively. The as-cast structure of standard alloy was heterogeneous and consisted of numerous relatively well developed primary β dendrites in a lamellar eutectic ($\alpha + \eta$) matrix (Fig. 1a). The β phase, which is unstable below 275 °C, had decomposed to form zinc-rich η and aluminium-rich α equilibrium phases in accordance with eutectoid reaction in Zn–Al binary phase diagram. The addition of 1% Pb to the ZA-8 alloy changed as-cast microstructure

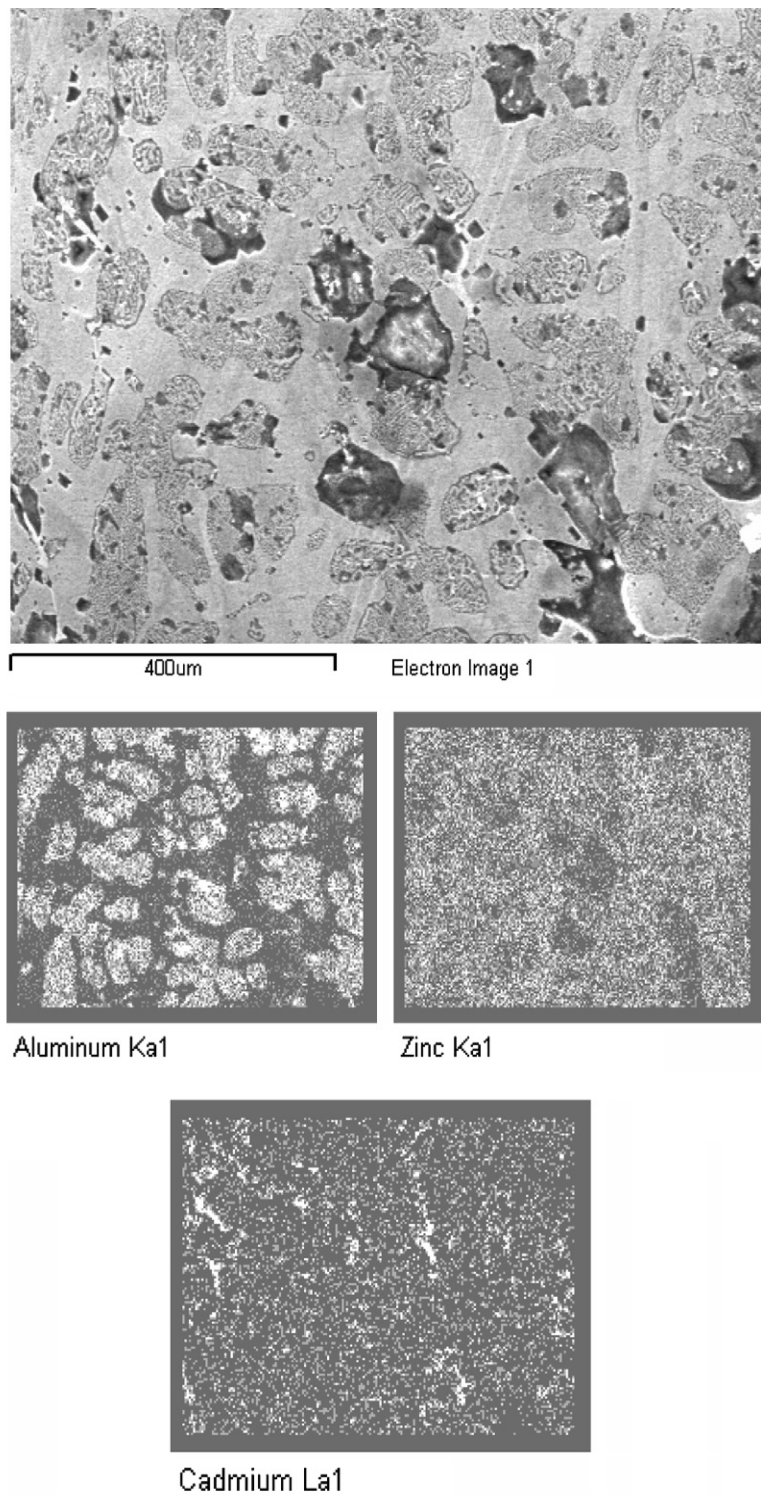

Fig. 4. X-ray map of the microstructure of ZA-8 alloy containing 1% Cd.

and caused coarse and degenerated eutectic. The lead-reach phase was in the form of white spherical or nearly spherical particles which were uniformly distributed in the matrix. Also the porosity was observed in the structure of alloy containing 1% Pb (Fig. 1b).

As it can be seen from Fig. 1c, ZA-8 alloy containing 1% Sn showed primer β dendrites surrounded by degenerate and coarse eutectic structure. The tin-reach phase in the form of white small particles was observed in the eutectic area. The addition of the tin to the ZA-8 alloy caused a little porosity in the microstructure. Fig. 1d represents the as-cast microstructure of ZA-8 – 1% Cd alloy. The addition of Cd was not changed significantly base structure of the ZA-8 alloy and it only decreased fraction of the eutectic and also caused porosity.

In order to examine the phases in the microstructure of modified alloys, EDS analysis and X-ray map was carried out on the modified alloys with Pb, Sn and Cd. Fig. 2 shows the X-ray map of the ZA-8 alloy containing 1% Pb. As can be seen from Fig. 2, Pb alloying element was uniformly distributed both in the β dendrite and eutectic structure. In general, Zinc was in the interdendrite area while Al was in the β dendrite.

The EDS line analysis in the microstructure of modified ZA-8 alloy with 1% Sn represented the Sn alloying element was in the form of white nearly spherical phase in the interdendrite region (Fig. 3). The X-ray maps of the microstructure of ZA-8 alloy containing 1% Cd alloying element are also presented in Fig. 4. From here, it can be seen that the Cd-rich phase accumulated in the near of the β dendrite.

In order to identify these phases in the microstructure, X-ray diffraction using Cu Kα radiation was performed on the ZA-8 alloy and modified alloys (Fig. 5). Fig. 5a represents the diffraction diagram of the standard ZA-8 alloy. The diffraction diagram shows peaks corresponding to those of the Zn-rich and Al-rich phases of the binary Zn–Al system. The diffraction diagram of the modified alloy with Pb shows peaks corresponding to those of the Zn-rich and Al-rich phases of the binary Zn–Al system and different peaks at 2θ position of 31.5°, 52.6°, 62.4° and 65.8° which did not correspond to any equilibrium phase of this system (Fig. 5b). These peaks were identified to belong to pure Pb element. The diffraction diagram of the modified

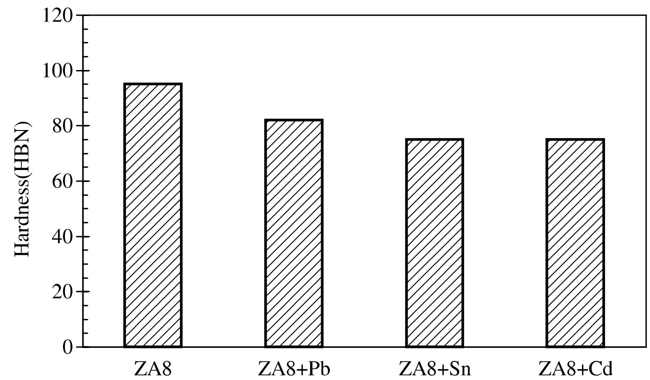

Fig. 6. Hardness of the investigated alloys.

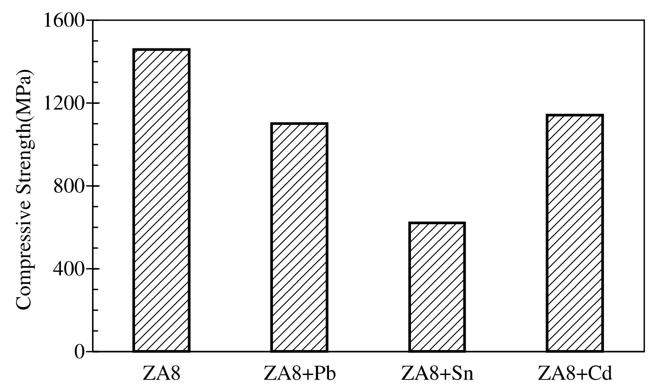

Fig. 7. Compressive strength of the investigated alloys.

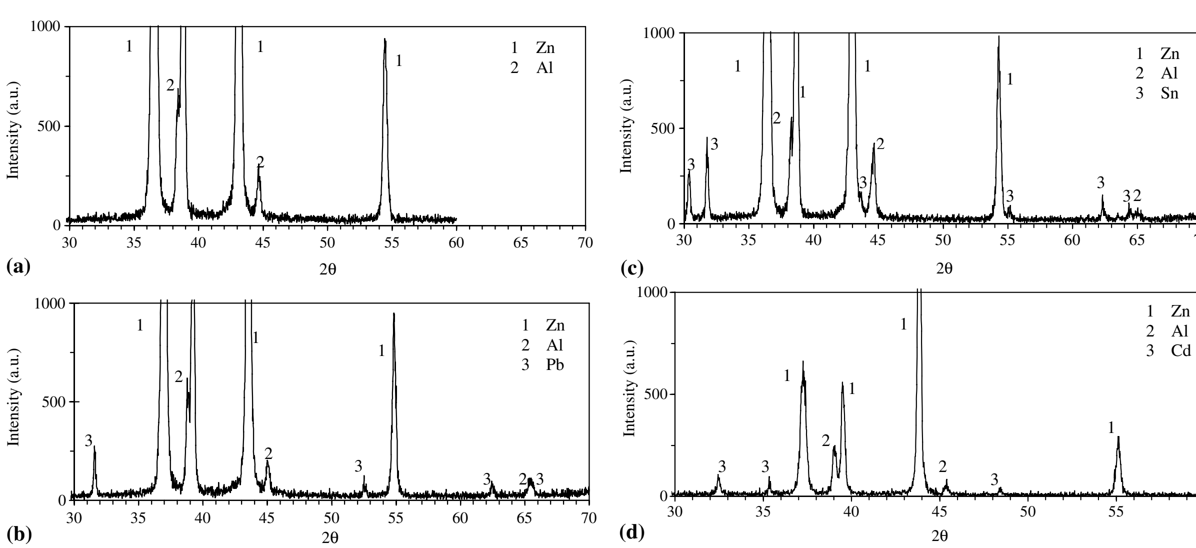

Fig. 5. XRD patterns of (a) ZA-8 alloy, (b) ZA-8 – 1% Pb, (c) ZA-8 – 1% Sn and (d) ZA-8 – 1% Cd alloys.

alloys with Sn and Cd are presented in Fig. 5c and d, respectively. The diffraction diagrams of these elements were different small peaks which did not correspond to any equilibrium phase of Zn–Al system. These peaks were belonged to pure Sn and pure Cd elements.

The above result indicated that the addition of modifying elements to the standard ZA-8 alloy changed based structure of the alloy, and they caused degenerate microstructure and decreased volume fraction of the $\alpha + \eta$ eutectic matrix. Each element was in the form of pure state. However, in these modified alloys, the microstructures usually possess a great amount of casting defects; especially porosity resulted from gravity casting.

3.2. Mechanical properties

The hardness of the investigated alloys are 95, 82, 75 and 75 HBN for standard ZA-8, ZA-8 – 1% Pb, ZA-8 – 1% Sn and ZA-8 – 1% Cd alloys, respectively (Fig. 6). Generally, hardness decreases with addition of modified alloying elements due to the change in the microstructure and porosity. Fig. 7 shows the compressive strength of the ZA-8 alloy and modified alloys. The compressive strength of the ZA-8 alloy is approximately 1455 MPa. The addition of Pb, Sn and Cd to the ZA-8 alloy was significantly decreased this property.

The wear loss data for ZA-8 based alloys and commercial SAE 660 bronze are listed in Table 2. The wear rate of the ZA-8 and modified alloys as a function of sliding speed are presented graphically in Figs. 8 and 9 for 30 N and 45 N applied load. As can be seen from Table 2 and Fig. 8a, the addition of Pb alloying element to the ZA-8 alloy decreased wear rate at all sliding speed while Cd only decreased wear rate of the alloy at high sliding speed for 30 N (Fig. 8a). Modified alloy with Sn showed higher wear rate than that of the standard alloy at all sliding speed for 30 N and 45 N (Fig. 8a and b). For 45 N applied load, modified alloys with Pb and Cd indicated significantly lower wear rate than that of the ZA-8 alloy between the sliding speed of 1 ms^{-1} and 2 ms^{-1}. At 0.5 ms^{-1} sliding speed, these elements are not considerably effect the wear rate of ZA-8 alloy (Fig. 8b).

Altering the sliding speed and applied loads revealed different wear regimes for the ZA-8 and modified alloys. For example, in Fig. 8a the variation of wear rate with sliding speed for 30 N applied load is presented. As can be seen

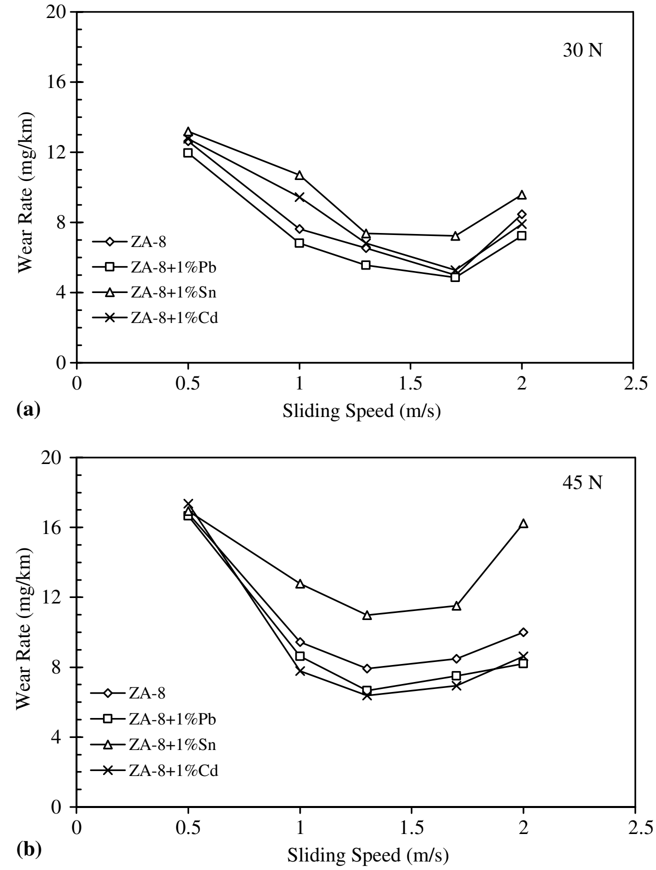

Fig. 8. The variation in wear rate of the ZA-8 and modified alloys as a function of sliding speed at applied loads: (a) 30 N and (b) 45 N.

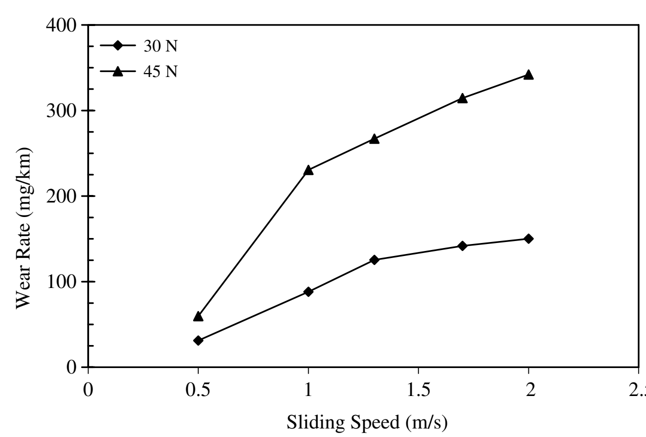

Fig. 9. The variation in wear rate of the SAE 660 bronze as a function of sliding speed.

Table 2
Wear loss data (mg) for experimental alloys

Applied load	30 N					45 N				
Sliding speed (m/s)	0.5	1	1.3	1.7	2	0.5	1	1.3	1.7	2
ZA-8	91	55	47	36	61	121	68	57	61	72
ZA-8 + 1% Pb	86	49	40	35	52	120	62	48	54	59
ZA-8 + 1% Sn	95	77	53	52	69	122	92	79	83	117
ZA-8 + 1% Cd	92	68	49	38	57	125	56	46	50	62
Bronze	224	635	903	1021	1081	430	1660	1923	2264	2463

from the figure, an increase of sliding speed resulted in a relatively decreased wear rate. In general, when sliding speed was continuously increased, lower values of wear rates were obtained up to 1.7 ms^{-1} inclusive. Further increase of sliding speed caused increasing wear rate of the alloy. Similar results were obtained for 45 N applied load, but decreasing of wear rate continued up to 1.3 ms^{-1}, between 1.7 ms^{-1} and 2.0 ms^{-1} wear rate increased.

The wear rates of conventional bearing alloy (SAE 660 bronze) as a function sliding speed are presented in Fig. 9 for 30 N and 45 N applied loads. The wear rate of bronze alloy is very high compared with ZA-8 based alloys at all sliding speed. For a sliding speed of 0.5 ms^{-1} and an applied load of 30 N the wear rate of the standard ZA-8 alloy is 12.64 mg/km and 11.8 mg/km for ZA8 – 1% Pb alloy. At this load and sliding speed a 31.11 mg/km wear rate is obtained for the bronze. At 45 N applied load, this difference between ZA-8 based alloys and bronze dramatically increases. Moreover, increasing sliding speed resulted in a increased difference between wear rate of the bronze alloy and ZA-8 based alloys, because increasing sliding speed increased wear rate of the bronze alloy for 30 N and 45 N. At sliding speed of 2 ms^{-1}, the wear rates of the bronze alloy are 150.14 mg/km and 342.1 mg/km for 30 N and 45 N while those of the ZA8 – 1% Pb are 7.22 mg/km and 8.2 mg/km, respectively.

The friction coefficient values of the ZA-8 based alloys and bronze alloy are summarized in Table 3. The variations of the friction coefficient with sliding speed are presented graphically in Fig. 10 for 30 N and 45 N. As can be seen in Table 3 and Fig. 10, the addition of modifying element to the ZA-8 alloy resulted in a decreased friction coefficient at 30 N and 45 N applied loads. In general, the bronze alloy showed lower friction coefficient than those of the ZA-8 based alloys (Fig. 10a and b). However, ZA8 – 1% Sn alloy revealed lowest friction coefficient values in the investigated alloys between the sliding speed of 1.7 $ms^{-1}$and 2 ms^{-1} for 45 N applied load (Fig. 10b).

The results of this investigation showed that the ZA-8 based alloys tested were more wear resistant that bronze alloy at all sliding speed for 30 N and 45 N. It is possible to explain this that microstructure and the formation of oxide films on the wear surface of alloys [7]. The ZA alloys have a multiphase structure consisting of mainly Al-rich α and Zn-rich η phases. The α phase has a fcc crystal structure and the η phase an hcp crystal structure with a larger c/a ratio than the ideal. In general, fcc crystals have excellent ductility, while the close packed planes of hcp crystals can give rise to good smearing characteristics or even allow certain materials [11]. The oxide films are formed on the surface of ZA alloys during dry sliding condition and these oxide films give to wear resistance. The aluminium oxide is a hard compound and it acts as a load bearing phase, while the zinc oxide is a much softer compound which allows it to act as a lubricant [12]. It is well known that in Al–Pb bearing alloys, lead acts as a solid lubricant. Similar results were obtained by this investigation on the modified alloys with Pb and Cd. During the sliding process, lead was supposed to flow out from its location in the microstructure and to smear on the mating surface forming a tribo-

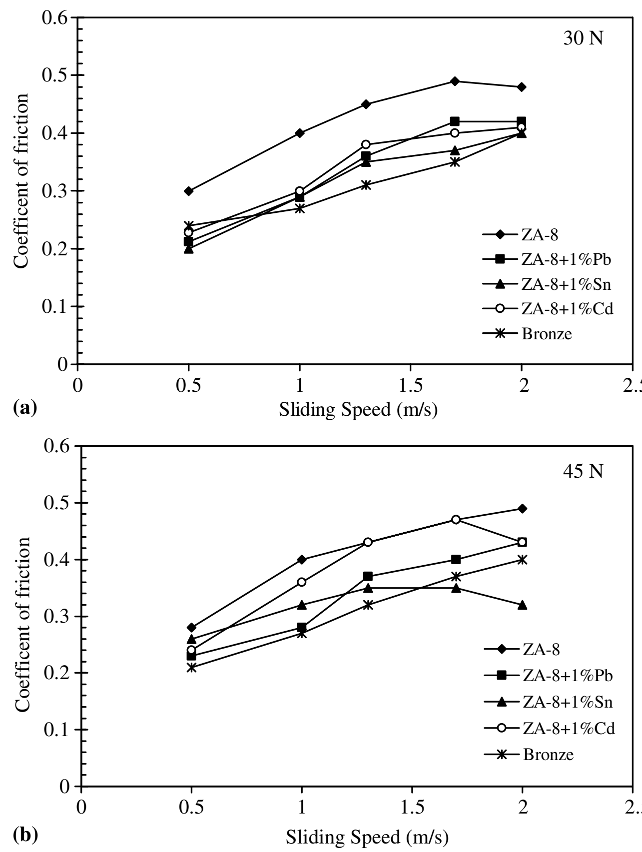

Fig. 10. The variation in coefficient friction of the investigated alloys as a function of sliding speed at applied loads: (a) 30 N and (b) 45 N.

Table 3
Coefficient of friction for experimental alloys

Applied load	30 N					45 N				
Sliding speed (m/s)	0.5	1	1.3	1.7	2	0.5	1	1.3	1.7	2
ZA-8	0.3	0.4	0.45	0.49	0.48	0.28	0.4	0.43	0.47	0.49
ZA-8 + 1% Pb	0.212	0.29	0.36	0.42	0.42	0.23	0.28	0.37	0.4	0.43
ZA-8 + 1% Sn	0.2	0.29	0.35	0.37	0.4	0.26	0.32	0.32	0.35	0.32
ZA-8 + 1% Cd	0.228	0.3	0.38	0.4	0.41	0.24	0.36	0.43	0.47	0.43
Bronze	0.24	0.27	0.31	0.35	0.4	0.21	0.27	0.32	0.37	0.4

induced lubricating film. From EDS and X-ray diffraction analysis showed that lead was in the form of pure state in the ZA-8 alloy. Pb phase, as a solid lubricant, is soft and has good ductility; a small ratio of shearing strength to fluidizing pressure of the Pb phase makes the friction obstruction decrease. As a result, the friction coefficient drops. It is possible that Pb may smear on the friction surface, fill in the worn track or form a coat of lubricating film. This can provide a good antifriction role, thus reducing the wear loss of mating axle. Similar results were obtained by addition of the Cd alloying element to the ZA-8 alloy and wear resistance of the alloy increased. However, wear resistance of modified alloy with Sn resulted in a decreased due to degeneration of base structure of ZA-8 alloy.

4. Conclusions

1. The addition of Pb, Sn and Cd elements to the standard ZA-8 alloy changed based structure of the alloy, and they caused degenerate microstructure and decreased volume fraction of the eutectic matrix. X-ray diffraction and EDS analysis revealed that each element was in the form of pure state.
2. The addition of the modifying elements decreased hardness and compressive strength of the ZA-8 alloy.
3. The ZA-8 alloy and modified alloys with Pb, Sn and Cd showed higher wear resistance when compared with SAE 660 bronze, and wear resistance of ZA alloys increased with increasing sliding speed up to 1.7 ms^{-1} for 30 N and 1.3 ms^{-1} for 45 N, respectively. But it decreased with increasing sliding speed.
4. The addition of Pb to the ZA-8 alloy increased wear resistance of the alloy for all of the sliding speeds at 30 N and 45 N, while the addition of Cd only increased wear resistance of the ZA-8 at 45 N. But Sn caused worse wear resistance for ZA-8 alloy.

Acknowledgement

The authors thank the Sakarya University for financial support in this research.

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