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Tribological Wear of as Cast Zn-4Al Alloy Cooled at Various Rates from the Eutectoid Transformation Temperature

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Abstract

The paper presents the results from a study on the impact of the cooling rate in the eutectoid transition on the abrasive wear of the as cast Zn-4Al alloy. The microstructure of the researched material consists of dendrites of the η solid solution and an $(\alpha+\eta)$ eutectic structure. During the eutectoid transformation at 275°C the distribution in the eutectic structure was transformed and fined. Heat treatment was carried out for this alloy, during which three cooling mediums were used, i.e. water, air and an furnace. For the research material obtained in this way, metallographic examinations were performed using the methods of light and scanning electron microscopy, as well as hardness measurements. It was found that faster cooling rate promoted the fragmentation of structural components, which translates into higher hardness of the material. This also had effects in the tribological wear of the tested alloy. As part of the tests, an abrasive wear test was carried out on a standard T-07 tester.

Keywords: Metallography, Microstructure, Heat treatment, Abrasive wear, Zinc alloys, Zn-4Al

1. Introduction

In agreement with the Zn-Al phase diagram, zinc-containing aluminum alloys can be divided into hypoeutectic, hypereutectic, and hypereutectoid. In engineering applications the most widely used are hypoeutectic alloys and are commercially known as Zamak. Zn-Al alloy coatings were developed to replace pure zinc as a sacrificial coating for steel in the automotive industry and are also used to produce low-load automotive components (small gears, gear racks, pulleys, gearboxes, etc.) [1,2]. Zinc-based alloys have found wide applications as rolling bearing materials in various machines and are often used to replace more expensive copper-based alloys in dry and lubricating conditions because of their superior mechanical and tribological properties [1-6]. Zinc-based alloys can only be effectively used at low- to medium-speed conditions because their mechanical properties and wear resistance rapidly deteriorate at operating temperatures exceeding 100 – 120°C [3,7]. Pola et al. [2] found that the temperature progress of the wear tracks versus sliding distances using a 5 N load and steel counterparts increased to 35°C.

The good tribological properties of Zn-Al alloys were attributed to the creation of aluminum and zinc oxides on bearing surfaces [6]. Panagopoulos et al. [8] found that the dependence of the wear on pH was attributed to the fact that the pH affected the corrosion products formed on the surfaces of the Zn-based alloy, which were involved in the wear mechanism. The wear rate in corrosive NaCl solution decreased at more alkaline pH values.

Component performances are also determined by the microstructure, and the mechanical properties of metal alloys largely depend on the morphological relationship between phases. These alloys are also susceptible to intergranular corrosion [9,10].

In general, wear resistance and cavitation resistance are particularly important for zinc alloys due to the their specific applications [1,11]. Thus, many authors have studied zinc-aluminum alloys to recognize and improve their tribological properties. Some alloys provide lower friction coefficients than copper alloys [2], and studies have shown that the low hardness of Zamak 3 alloy (due to the Zn-rich phase) resulted in a higher friction coefficient and wear rate than their steel counterparts under dry conditions [1,4].

Microstructure characteristics are an important factor in the wear resistance of alloys [12-15]. The abrasion resistance of alloys can be improved by increasing the hardness of an alloy, which can be accomplished by disintegrating its microstructure, including eutectics and eutectoids. Their dispersion degree is determined by controlling the cooling rate from the transformation temperature; therefore, increasing the hardness by microstructure disintegration may improve the tribological properties of Zn-4Al alloys (Zamak 3).

Over the last decade, several works have been carried out to correct the mechanical and tribological properties of Zn-Al alloys to broaden their applications. Improved mechanical properties can be obtained by the addition of copper, but this causes dimensional instability at elevated temperatures [7]. The casting temperature also affects the mechanical properties of cast zinc alloys [16], but heat treatment has been shown to have limited effectiveness [1]. Previous studies have also shown the impact of cooling rate on the microstructure and properties of Zn-4Al alloys [5,17]. Therefore, the aim of this investigation was to study the effect of cooling rate from the eutectoid reaction temperature on the tribological wear of this alloy.

2. Materials and methods

2.1. Heat treatment and metallographic examinations

The researched material was a Zn-4Al alloy that was produced by melting and casting 99.995% Zn and 99.7% Al in a PIT10 induction furnace. The obtained material was heat treated by annealing for 2 h at 300°C and then cooled at various rates. The samples were quenched in water or cooled in open air and in a furnace, respectively.

Hardness measurements were obtained with the Vickers method. Microscopic examinations were performed with a Leica M205 C stereoscopic microscope, a Nikon Eclipse MA 200 light microscope, and a Phenom World ProX scanning electron microscope (SEM). Standard metallographic techniques were used to prepare specimens, followed by etching in 5% Nital.

2.2. Abrasive wear

Tribological studies to investigate the resistance to abrasive wear were carried out on a T-07 tester made at The Institute for Sustainable Technologies in Radom. The method was in accordance with the requirements of the GOST 23.208-79 standard. The test association consisted of a sample (plate) made from the tested material and a counter-sample (roll) with a rubber ring, rotating at a set speed *n*. The tests were carried out on four samples per series. A scheme of the method is shown in Figure 1.

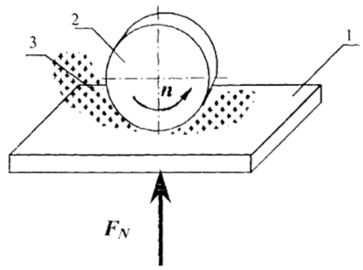


Fig. 1. Schematic representation of the abrasive wear resistance test: 1 – sample, 2 – rubber roll, 3 – abrasive

During the test, a material sample (1) was pressed with a defined force of (F_N) to a rubber disc (2) with a diameter d = 50 mm rotating at a constant speed (n). Between the rotating disc and the fixed sample, gravity was used to supply a loose abrasive (3), electrocorundum F90. The test relies on the fact that in the presence of a loose abrasive, sample abrasion of the tested materials and a reference sample occurs while maintaining operating conditions, i.e. rotational speed n = 600 rpm/min and F_N loads, according to the above standard. A sample of the tested material during the test is pressed with a force of F_N = 44.4 N. The reference sample was made of C45 normalized steel of approx. 200 HB hardness.

Then, the weight wear ratio of the reference sample and the weight wear ratio of the tested materials were determined. The weight wear of Z_{wb} specimen (weight difference before and after the tests) was measured after a defined friction time (determined by the number of rotations of the rubber roller), depending on the material hardness. In this experiment, the Z_{wb} parameter occurring after number N_b = 150 rpm of the rubber roller revolutions adopted for the tested materials with a hardness lower than 400 HV. Based on the weight wear measurements, the abrasive wear resistance index K_b (relative wear resistance) was calculated from the following equation:

$$K_b = \frac{Z_{ww}\rho_b N_b}{Z_{wb}\rho_w N_w}$$

where: Z_{ww} – weight wear of the reference specimen (C45 steel), Z_{wb} – weight wear of the test material, ρ_w – density of the reference specimen, ρ_b – density of the test specimen, N_w – number of revolutions of the reference specimen friction path, N_b - number of revolutions of the tested specimen friction path. The density of Zn-4Al was 6.60 g/cm^3.

3. Results and discussion

3.1. Metallographic examinations

Figure 2 shows the microstructures of the heat-treated samples, which was typical of the as cast hypoeutectic Zn-Al alloys and mainly consisted of primary η-Zn phase dendrites surrounded by lamellar ($\alpha+\eta$) eutectic structures. The Al-rich solid solution (α) phase showed good ductility and load-bearing capability, while the Zn-rich solid solution (η) phase provided solid lubrication by coating the coupling surfaces during sliding wear [18]. The microstructure contained fine structure elements because the γ phase was changed into ($\alpha+\eta$) eutectoid at 275^{o}C as described in [17]. At higher magnification (Fig. 3), the microstructure examination revealed that the eutectoid consisted of α phase and η phase platelets. During heat treatment, only the morphology of the constituents inside the lamellar eutectic structure was affected due to eutectoid transformation. Despite this eutectoid decomposition, the character of the interdendritic eutectic structure was unaffected because it did not undergo solid-state transformation.

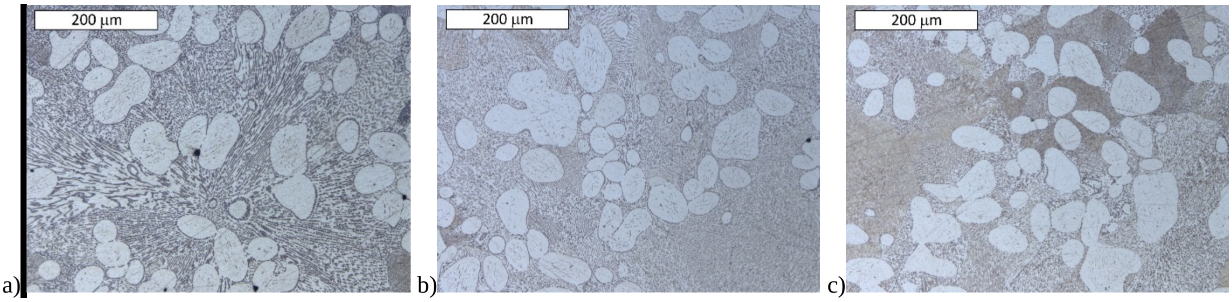


Fig. 2. Microstructure of the heat-treated Zn-4Al alloy: (a) furnace-cooled, (b) air-cooled, and (c) water-quenched. The (α+η) eutectic structure was not changed by the eutectoid decomposition. Etched state. Light Microscopy

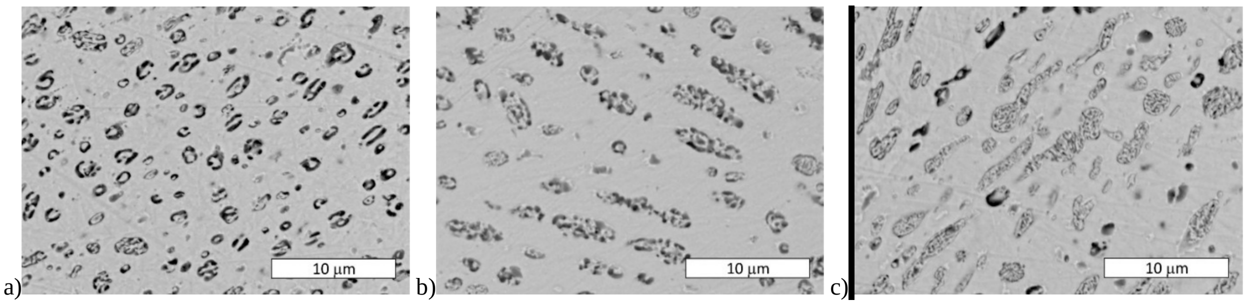


Fig. 3. Microstructure of the heat-treated Zn-4Al alloy: (a) furnace-cooled, (b) air-cooled, and (c) water-quenched. Morphology of the constituents inside the lamellar eutectic structure was affected due to eutectoid transformation. Etched state. SEM

3.2. Hardness measurements

The Brinell hardness measurement and their standard deviations are shown in Figure 4 and indicate that the cooling rate affected the hardness of heat-treated samples. The hardness increased to 66±3 HBW 2.5/62.5 for the water-quenched sample, while the material that was furnace-cooled displayed a hardness of 53±2 HBW 2.5/62.5. The hardness of the air-cooled material was 61±3 HBW 2.5/62.5. These differences occurred because a faster cooling rate below the eutectoid (275^{o}C) promoted the creation of finer ($\alpha+\eta$) eutectoid microstructures from the γ solid solution, which rendered into a higher hardness. The improved hardness due to the increased cooling rate and microstructure evolution has been observed by other Authors [5], while other studies have shown that cooling from a temperature below the eutectoid transformation does not affect the hardness [17].

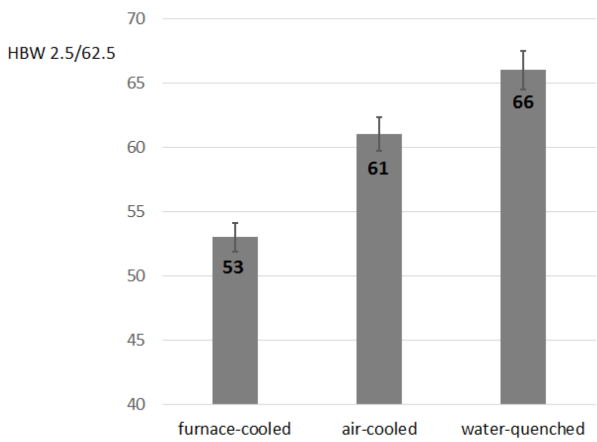


Fig. 4. Brinell hardness values obtained for heat-treated samples using various cooling rates

3.3. Wear testing

The samples were investigated under heat-treated conditions, and the results showed that a higher cooling rate during eutectoid decomposition reduced the alloy's wear resistance (Fig. 5, 6). The abrasive wear resistance index K_b was decreased for water-cooled and air-cooled to average values of 0.125 and 0.128, respectively. The mass decrement was compared to the hardness materials. The materials tested under abrasive conditions usually has a strong correlation with hardness. It is expected that the greatest weight loss should be achieved by the samples with the lowest hardness. Although a faster cooling rate improved the alloy hardness, it considerably increased the wear volume loss, suggesting that the hardness was not the only parameter that governed the wear behavior of the Zn-4Al alloy. Savaskan noted a similar tendency for a Zn-40Al alloy in Ref. [18]. The obtained results make it interesting to study the role of the microstructure in determining wear resistance. These relationships may lead to a better insight into the wear mechanisms.

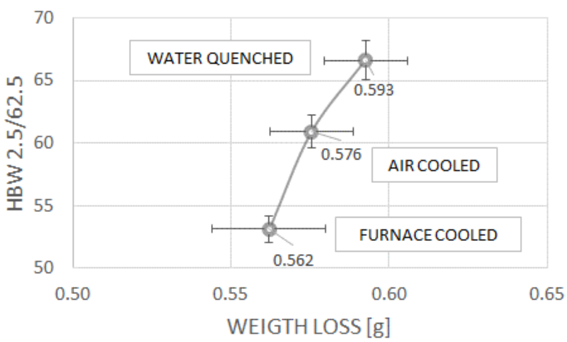


Fig. 5. Weight loss data for Zn-4Al specimens

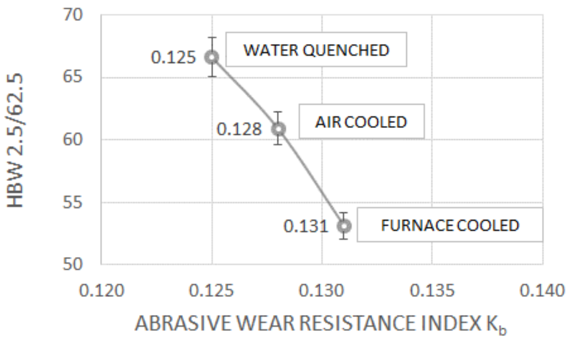


Fig. 6. Abrasive wear resistance index K_b data for Zn-4Al specimens

3.4. Microscopic examinations

The wear tracks were observed using SEM imaging techniques (Fig. 7) to understand the wear mechanism. Abrasive wear damage was expected due to higher hardness of the counterpart than that the tested samples [2]. Figure 7 shows the SEM image of the air-cooled sample as a representative, which shows that the tracks are typical of abrasive wear and exhibit grooves from the ploughing action of the electrocorundum particles. The wear debris was removed from the surface, and no smearing was observed on the wear surfaces, which instead had continuous scratches affiliated with the direction of sliding and extensive gouging in all samples.

The wear tracks were analyzed by SEM cross-sectional images to provide a more complete understanding of the wear mechanism. Features of the worn surfaces are shown in Figures 8 to 12. Despite the lack of clear smearing, microstructural changes caused by plastic deformation were observed in the worn regions. Figure 8 shows a transverse section of the wear surface taken parallel to the sliding direction. The subsurface region was plastically deformed and contains flow lines oriented in the direction of sliding. The original alloy microstructure was observed far from the contact area. Plastic deformation in the surface zone was observed in local areas of the η solid solution and also manifested as the formation of single twins (Fig. 9).

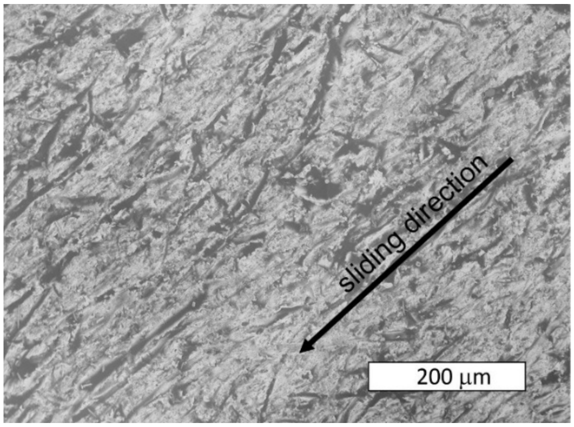


Fig. 1. SEM image showing the surface in the center of the wear track

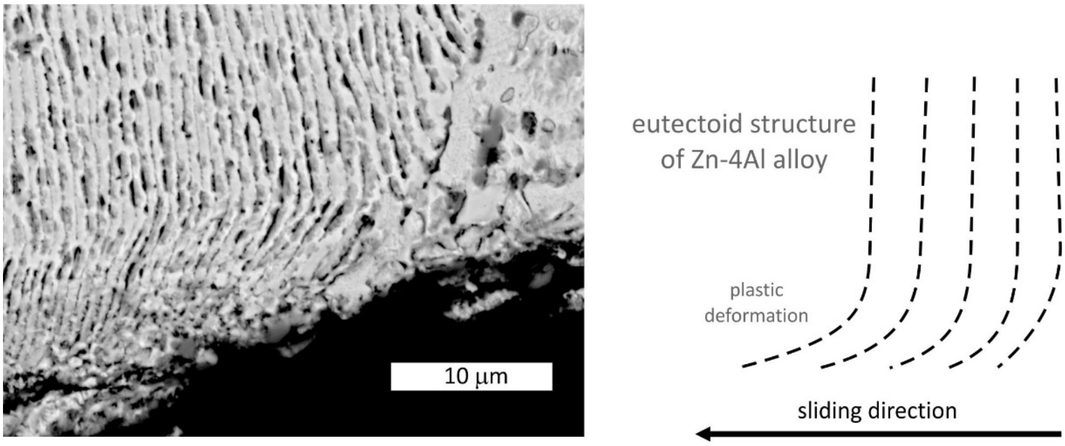


Fig.8. SEM image and scheme of plastic deformation in the surface of Zn-4Al alloy wear tracks

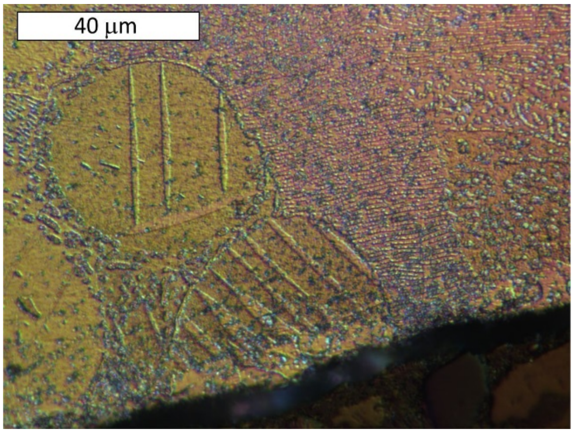
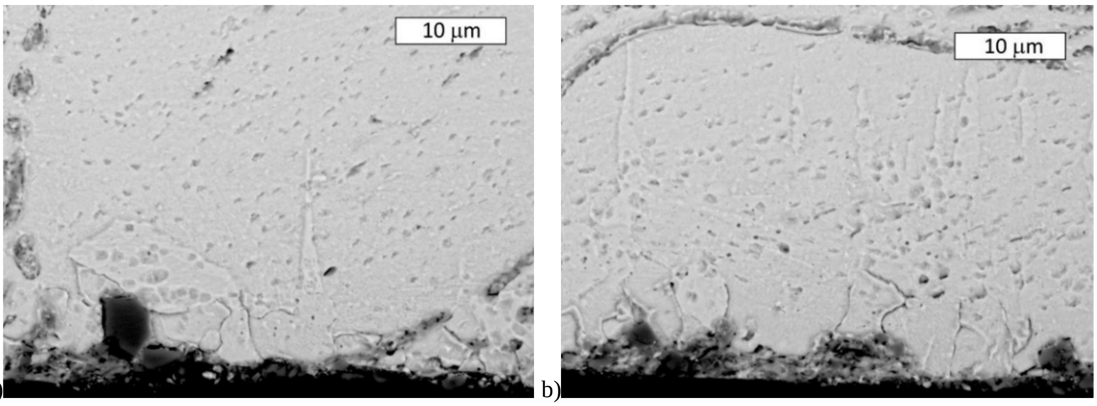


Fig. 9. Single twins formed due to plastic deformation in the Zn-rich solid solution. Etched. Light Microscopy

The occurrence of microcracks and microconstituent fragmentation in the zones under the worn surfaces were observed in Figure 10. The cracking tendency was related to the Zn-rich solid solution (*η*). During microcrack extension, deformation twins also formed. The destruction of eutectic areas was initiated by the formation of cracks in the η solid solution, which led to the mechanical separation of eutectoid areas (Fig. 11,12). The scratches on the wear surface may consequently be intensified by the plowing action of the eutectoid areas pulverized and removed from the surface of the base material. In this situation, the finer microstructure facilitates their mechanical separation from the matrix, and harder eutectoid particles in the friction zone can support abrasive wear, explaining why the alloy with the finer eutectoid structure displayed the highest wear and a higher hardness.

The samples show the existence of locally irregular aluminum oxides on the wear surface (Fig. 13). Pola et al. [2] used EDX to demonstrate the formation of many discontinuous oxide areas on the surface of some Zn-Al alloys. This oxide layer protected the surface from deformation and damage, reducing the wear rate. Aluminum oxide is a hard compound that also acts as a load-bearing microconstituent, while zinc oxide has a hexagonal crystal structure and is softer that causes it to act as a lubricant under appropriate conditions [6]. The zinc and aluminum particles were detected in the wear debris in all environments [8]; however, these may be abrasive particles embedded in the surface, considering the applied research method. In this case, a lower hardness should facilitate their driving into the metallic surface of the substrate.



a) b)

Fig. 10. The presence of microcracks in the area of the η solid solution that initiated twinning deformation. Etched. SEM

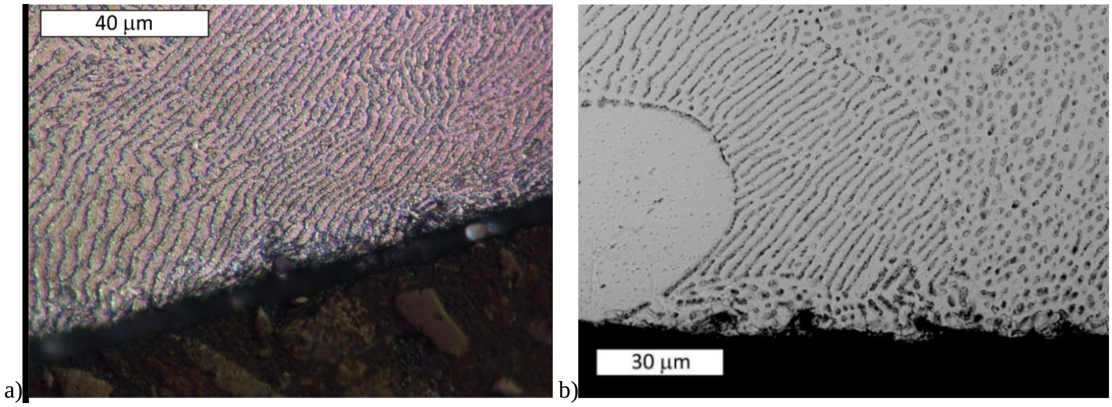


Fig. 11. Cross-section of the worn surface, showing mechanical separation of the eutectoid areas on the surface. Etched. a) Light Microscopy, b) SEM

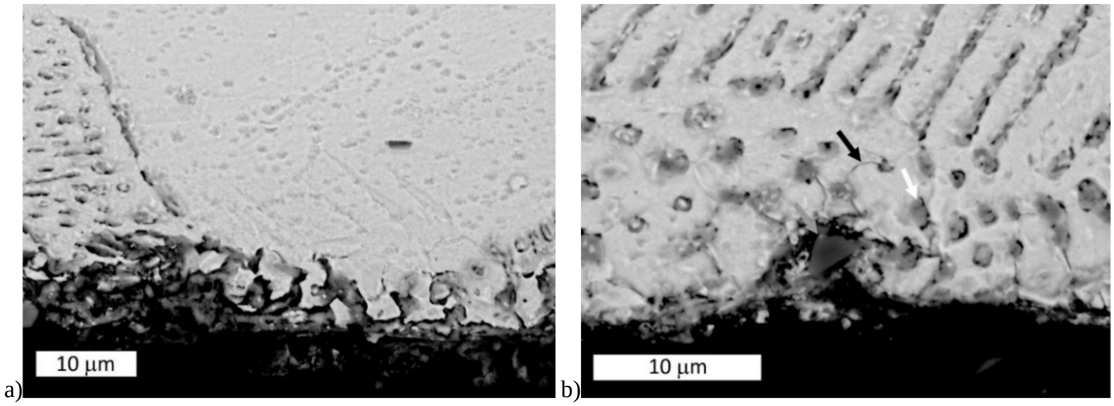


Fig. 12. a) Mechanical separation of the eutectoid region due to microcrack formation in the η phase due to friction. b) Visible microcracks in the η phase (black arrow) and loss of material coherence (white arrow). Etched. SEM

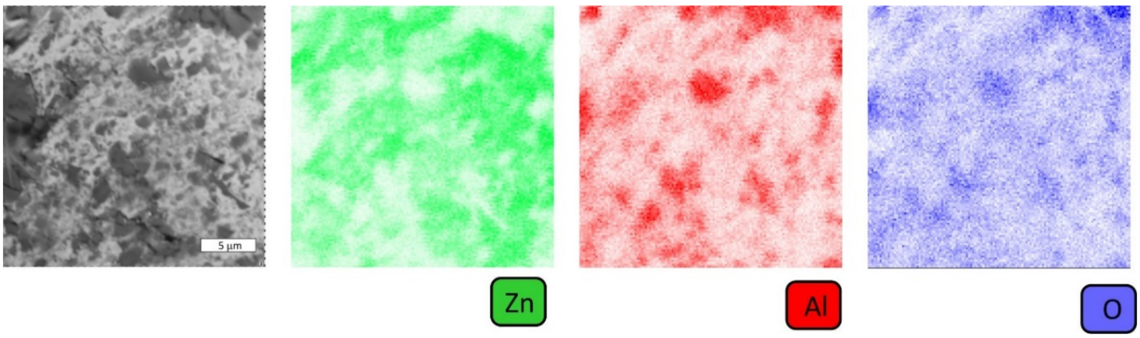


Fig. 13. Aluminum oxides observed on the wear surface. SEM/EDX

4. Conclusions

This work studied tribological wear of a Zn-4Al alloy cooled at various rates from the eutectoid reaction temperature. The conducted research has shown that the hardness was not the only parameter influencing the wear behavior of the Zn-4Al alloy used in the production of low-load automotive components. The conclusions are as follows:

1) Increased structure dispersion improved the hardness of the Zn-4Al, but it reduced the wear resistance due to the greater weight loss during abrasive wear. The water-quenched versions of the alloy showed the lowest abrasive wear resistance index K_b.
2) The SEM observations showed that the wear tracks all of the heat-treated material specimens were quite similar to each other, and scratching was the main characteristic of the worn surfaces of the Zn-4Al alloy. No smearing was

observed on the worn features of the surface zones of the samples, which instead displayed gouging and microcracks; however, surface plastic deformation was also locally observed.

3) The destruction of eutectic areas after *η* phase formation contributed to the mechanical separation of hard eutectoid regions, as confirmed by the SEM images. Hard and fine particles penetrating into the friction zone promote tribological destruction of the cooperating elements. The greater dispersion degree of these areas may promote this process, which can increase abrasive wear and may be responsible for the higher wear volume loss for the water-quenched alloy specimens.

4) In agreement with the SEM observations, many aluminum oxide debris were also detected on the wear tracks of the samples; however, they may be the abrasive particles used in this method, and additional testing must be conducted to investigate the surface oxidation.

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