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The influence of heat treatment on the sliding wear behavior of a ZA-27 alloy

Miroslav Babic *, Slobodan Mitrovic, Branislav Jeremic

Faculty of Mechanical Engineering, Tribology Center, 34 000 Kragujevac, S. Janjic 6, Serbia

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ABSTRACT

The effects of heat treatment, involving solutionizing at temperature of 370 °C for a relatively short period of time (3 or 5 h), followed by quenching in water, on tribological behavior of ZA-27 alloys were examined.

Dry sliding wear tests were conducted on as-cast and heat-treated ZA-27 samples using block-on-disk machine over a wide range of applied loads. To determine the wear mechanisms, the worn surfaces of the samples were examined by scanning electron microscopy (SEM). The tribological results were related to the microstructure and mechanical properties.

The heat treatment resulted in reduction in the hardness and tensile strength but increase in elongation. The heat-treated alloy samples attained improved tribological behavior over the as-cast ones, both from the aspects of friction and wear. The improved tribological behavior of the heat-treated alloys, in spite of reduced hardness, could be the result of breaking the dendrite structure, when the fraction of interdendrite regions was considerably decreased and a very fine α and η mixture was formed at the same time. The wear response of the samples has been corroborated through characteristics of worn surfaces and dominant wear mechanisms.

1. Introduction

Zinc–aluminum alloys (ZA alloys) over the past few decades are occupying attention of both researchers and industries, as a promising material for tribological applications. At this moment, commercially available ZA alloys have become the alternative material primarily for aluminum cast alloys and bearing bronzes due to good castability and unique combination of properties [1–11]. They can also be considered as competing materials for cast iron, plastics, and even for steels when being applied for operation under conditions of high mechanical loads and moderate sliding speeds (moderate operation temperatures) [12,13]. Interest for extending the practical application of these alloys is grounded by tribological, economical and ecological reasons. These alloys are relatively cheap and can be processed efficiently with low energy consumption without endangering the environment [14–17].

In the real casting conditions the ZA alloys have the typical dendritic structure, wherein the dendrite size and interdendritic spacing depend on the casting parameters. The cooling speed imposes a strong influence on the grain size during the cooling. The consequences of the dendritic structure primarily result in lower ductility, as well as in relatively high heterogeneity of mechanical properties of the cast alloy [18]. The second important problem relating to zinc–aluminum alloys refers to dimensional instability, which is caused by the presence of metastable phases [19,20].

One of the possible measures for overcoming these deficiencies is heat treatment of the castings. The following procedures of heat processing are used: (a) artificial ageing of samples at temperatures from 90 to 150 °C, mainly for optimizing the strength to specific elongation ratio [14,21]; (b) solutionizing (usually from 320 to 400 °C) followed by artificial ageing (T6 type of heat treatment) [19,20]; (c) solutionizing with subsequent quenching [22,23]; (d) solutionizing by rapid water quenching and ageing at elevated temperatures [24] and (e) solutionizing followed by ageing at elevated temperatures and water quenching [25]. Partial replacement of copper by other alloying elements (such as nickel and/or silicon) has also been found useful to reduce the problem of dimensional instability [19,24,25].

Heat treatment of the conventional zinc–aluminum alloys improves dimensional stability [14] and ductility [3,20,26,27]. However, the majority of the heat treatments lead to a reduction in hardness and tensile strength [19,20,23]. In spite of reduced hardness, the heat-treated alloys attain improved tribological properties [20,23,25]. Thermal softening problem of zinc–aluminum alloys may be reduced or overcome by addition of alloying elements such as silicon or nickel [24,25].

The duration and temperature of solutionizing and ageing play dominant role in controlling the structural, mechanical and

* Corresponding author. Tel.: +381 34 335 867; fax: +381 34 333 192.
E-mail addresses: babic@kg.ac.yu (M. Babic), boban@kg.ac.yu (S. Mitrovic), bane@kg.ac.yu (B. Jeremic).

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tribological properties of zinc–aluminum alloys [19,20]. Accordingly, it is very important to optimize the parameters of heat treatment in order to attain good properties [19].

Although the effect of heat treatment on the response of conventional and modified zinc–aluminum alloys has been studied in the past there is still a lack of information. In view of the above, in this paper an attempt has been made to analyze the influence of solutionizing at temperature of 370 °C for a relatively short period of time (3 or 5 h) and quenching in water, on microstructure, mechanical and wears behavior of ZA-27 alloy.

2. Experimental procedure

2.1. Alloy preparation

ZA-27 alloy (28.5% Al, 2.5% Cu, 0.012% Mg and balance Zn) alloy was processed by the liquid metallurgy route. The purity of aluminum was 99.90%, zinc 99.99% and copper 99.5%. Alloy was melted in a graphite crucible in an electric resistance furnace. The melt was overheated to 680 °C and cast into steel mold in a form of 30 × 20 mm cross-section and 100 mm long bar castings for investigation. Some of the alloy specimens were subjected to heat treatment by solutionizing at 370 °C for 3 h (marked by ZA-27 HT3), or 5 h (marked by ZA-27 HT5). After the solutionizing, the specimens were quenched in water at ambient temperature.

2.2. Measurement of mechanical properties and microstructural characterization

Bulk hardness of all samples was measured using a Brinell hardness tester with a 2.5 mm diameter steel ball indenter and under a load of 625 N. The load application time was 60 s.

The tensile samples prepared had 4 mm gauge diameter and 20 mm gauge length. Tensile tests were conducted at ambient temperature (24 °C) at a strain rate of 1.3×10^{-3}/s using a universal testing machine. Reported data correspond to an average of five measurements.

Microstructural characterization of the alloys was carried out using optical microscopy on samples similar to those used for wear testing. The specimens were polished according to standard metallographic practice and etched. Diluted nitric acid (5 vol%) in water was used as the etchant.

2.3. Sliding wear tests

The specimens were tested using a block-on-disk sliding wear testing machine with the contact pair geometry in accordance with ASTM G 77. A schematic configuration of the test machine is shown in Fig. 1. The test block was loaded against the rotating steel disk. This provides a nominal line contact Hertzian geometry for the contact pair. Computer support to experiment was provided by application of the Burr-Brown PCI 20000 data acquisition system integrated into the PC and general-purpose *LABTECH NOTEBOOK* software package.

The test blocks (6.35 mm width) were prepared from the as-cast and heat-treated zinc–aluminum alloys. Their contact surfaces were polished to a roughness level of $R_a = 0.2$ μm. The counterface (disk with 35 mm diameter and 6.35 mm thickness) was fabricated using 30CrNiMo8 steel (according to DIN) having hardness 55 HRC. The roughness of the ground contact surfaces was $R_a = 0.3$ μm. The tribotests were carried out in dry conditions at applied loads of 15, 30, 50 and 100 N and a linear sliding speed of 0.26 m/s. The duration of each test was 600 s (the sliding distance was 156 m).

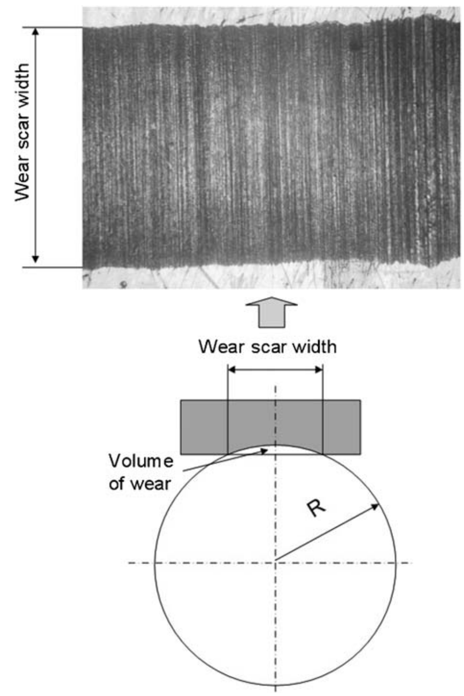

Fig. 1. The contact pair geometry.

The wear behavior of block was monitored in terms of the wear scar width. Using the wear scar width and geometry of contact pair (Fig. 1) the wear volume and wear rate (expressed in mm^3/h) were calculated.

SEM ("Philips XL30") was used to examine the worn surfaces of the tested wear blocks. The friction coefficient was obtained automatically during the tests by means of the data acquisition software. Tests were conducted with five repetitions.

3. Results

3.1. Mechanical properties

Mechanical properties of the ZA-27 alloy samples in as-cast and heat-treated conditions are presented in Table 1. Heat treatment of alloy caused decreasing of the tensile strength and hardness. Moreover, the heat-treated samples attained increased elongation as compared to that of the as-cast alloy. With regard to the solutionizing duration, it could be observed that it contributed to the tensile strength decrease and the elongation increase, while hardness became practically constant at longer solutionizing duration.

3.2. Microstructural characteristics

Microstructures of the alloys in as-cast and heat-treated conditions are presented in Fig. 2. The as-cast alloy (Fig. 2a and b) exhibited dendritic structure comprising primary α dendrites surrounded by $\alpha+\eta$ eutectoid, residual η phase and ε phase in the interdendritic regions. A magnified view of microstructure in Fig. 2b clearly shows these phases (marked by C—α dendrite core, P—$\alpha+\eta$ dendrites' periphery, M—η interdendritic phase, arrow—ε phase).

With heat treatment, micro-composition of ZA-27 alloy became more homogeneous; the microstructure was refined (Fig. 2c and d). In the microstructure of ZA-27 alloy, which was solutionized for 3 h at 370 °C and then quenched (Fig. 2c), one can

Table 1
Mechanical properties of the alloys.

Alloys	Heat treatment	Tensile strength (MPa)	Elongation (%)	Hardness (HB)
ZA-27	As-cast	318	2.4	138
ZA-27 HT3	Solutionizing at 370 °C for 3 h and quenching in water	301	5.2	121
ZA-27 HT5	Solutionizing at 370 °C for 5 h and quenching in water	283	6.4	121

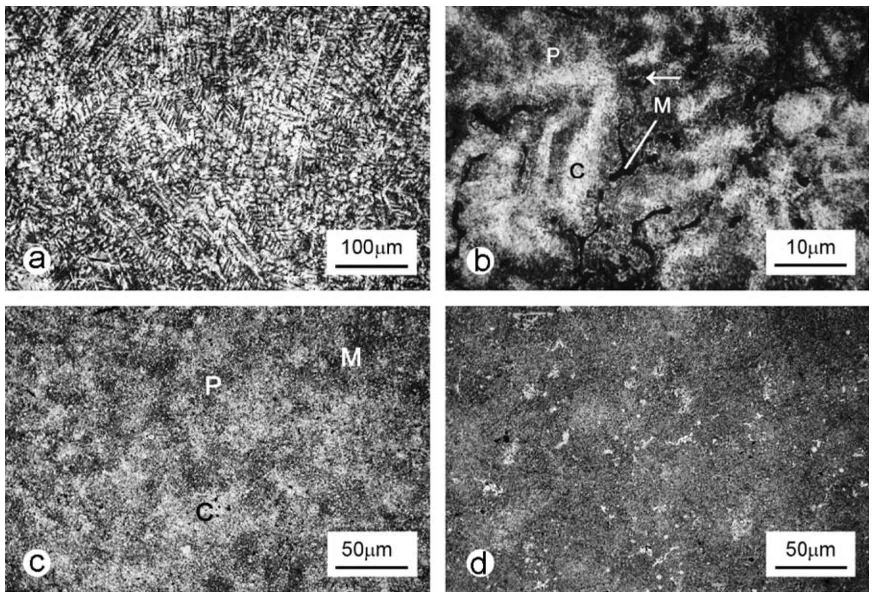

Fig. 2. Microstructure of the ZA-27 alloy in as-cast condition (a and b), and after heat treatment: (c) ZA-27 HT3 and (d) ZA-27 HT5 (C—α dendrite core, P—α+η dendrites' periphery, M—η phase, arrow—ε phase).

clearly distinct the micro constituents that are result of the thermal treatment, i.e., the residual dendrite cores, residual "islands" of the interdendritic phase η and very fine α+η mixture, which occupies the largest portion of the structure. After 5 h of solutionizing with consecutive quenching in water, it seems that the complete dissolution of the dendritic structure has occurred. The coagulation of the interdendritic η phase was noticeable, while the dendritic cores could not be noticed any more. Moreover, the uniformity of distribution increased and size of various micro constituents decreased with the duration of solutionizing.

3.3. Tribological behavior

The character of friction coefficient variation during sliding is illustrated in Fig. 3. This is a graphical representation of the results obtained for as-cast ZA-27 alloy with applied loads of 15 and 100 N. Two lower loads of 15 and 30 N result in very "quiet" friction coefficient signals for all the alloys, which shows very sustainable sliding friction. Higher load, especially 100 N, corresponds to amplification of the signal dynamics. It means worsening of the contact conditions and generation of the large quantity of the wear debris. In accordance with nature of dry sliding, it is clear that the friction coefficient increases with sliding. This increase depends on loading and the type of alloy.

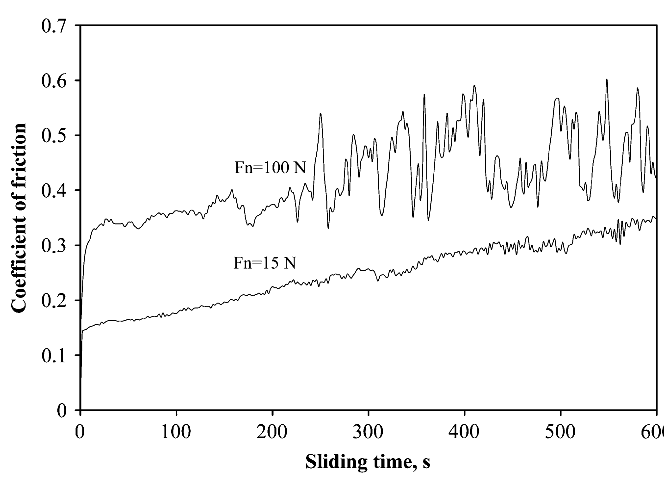

Fig. 3. Friction coefficient variation during sliding time (ZA-27 as-cast alloy with applied loads of 15 and 100 N).

The obtained results show existence of the significant differences in the friction behavior of the tested alloys. An example of those differences is presented in Fig. 4 for the case of friction at the lowest contact load of 15 N. It can be seen that the highest friction coefficient, during the whole friction process, corresponds to the as-cast alloy. The lower level of friction coefficient was obtained for heat-treated alloys. In the first two thirds of the friction process, the friction coefficients of heat-treated alloys are approximately equalized. During the last period of sliding the friction coefficient of alloy solutionized for 3 h shows higher rate of increasing with duration of sliding.

The average values of the friction coefficient for all four levels of normal force are shown in Fig. 5. In accordance with the nature of dry friction, the increase of the friction coefficient corresponds to the increase of the normal load. The increasing rate is especially evident for the load change from 15 to 30 N. It can be noticed that for all the contact loads the friction coefficient of heat-treated

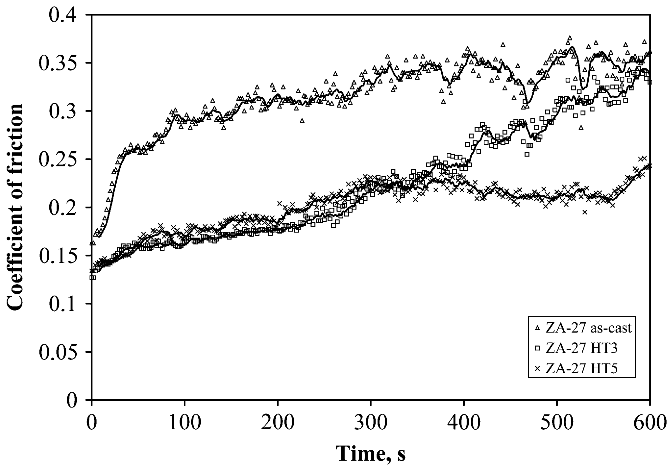

Fig. 4. Coefficient of friction vs. sliding time curves for ZA-27 alloy in as-cast and heat-treated conditions (applied load 15 N, sliding speed 0.26 m/s).

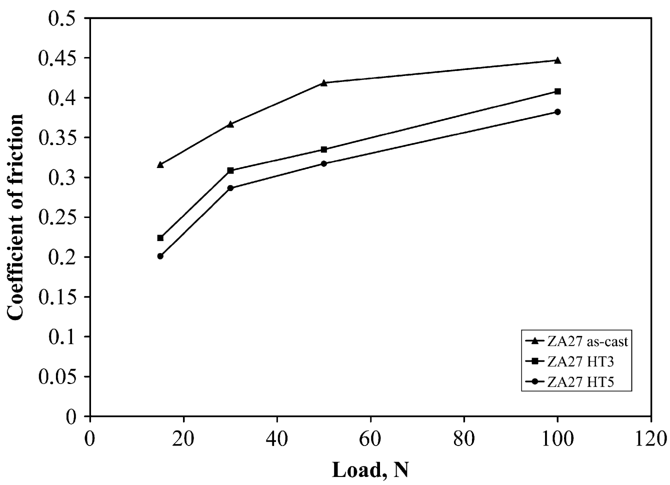

Fig. 5. Coefficient of friction vs. applied load for ZA-27 alloy in as-cast and heat-treated conditions.

alloys is significantly reduced as compared to that of the as-cast one. The reduction rate is the highest for load of 15 N. The differences in the frictional behavior of heat-treated alloys relative to as-cast alloy decreases with the increase of load. The alloy solutionized for 5 h and quenched attained the lowest level of the friction coefficient for all tested loads.

The comparative wear rate of the tested alloys as a function of the normal load is presented in Fig. 6. One can notice that for all the test alloys, the intensity of wear increases with the increase of the normal force. However, the gradient of that increase is not the same for all the alloys. The fastest increase corresponds to the cast alloy without the subsequent heat treatment. At the same time, for alloys that were heat-treated the gradient of change is significantly lower and approximately equal for both types of heat treatment.

The presented dependencies of the wear rate on the normal load clearly show that in the whole range of load, the wear rate of heat-treated alloys is significantly lower as compared to that of the as-cast one. This difference in their wear behavior is amplified in the area of higher loads, due to the mentioned higher influence of the normal load increase on the wear rate increase for the as-cast alloy. The lowest wear rate corresponds to the alloy annealed for 5 h, quenched in water.

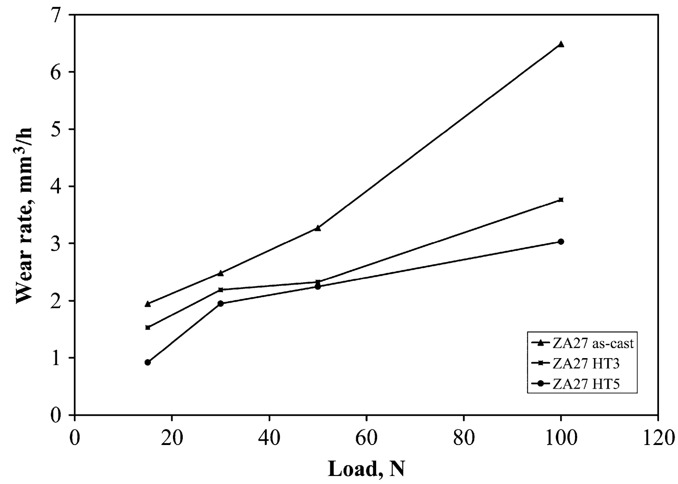

Fig. 6. Wear rate vs. applied load for ZA-27 alloy in as-cast and heat-treated conditions.

The worn surfaces of the samples are shown in Fig. 7. The worn surfaces of the heat-treated samples were noticed to be smoother than those of the as-cast one (Fig. 7c and d vs. Fig. 7b). Generally, the parallel ploughing grooves and scratches can be seen over all the surfaces in the direction of sliding (Fig. 7, marked by A). These grooves and scratches resulted from the ploughing action of asperities on the counter disk of significantly higher hardness. Simultaneously with this two-body abrasive wear, the three-body abrasive wear takes place, due to the abrasive action of the hard wear debris emanating from fragmented and oxidized asperities of alloy and abraded surface of steel disk [25]. Such hard debris gets entrapped in between the contacting surfaces and behaves as a cutting tool causing abrasion [20,25].

Besides abrasive wear mechanism, existence of the material smeared onto the sliding surface (clearly visible in Fig. 7a and b, marked by B) shows presence of the adhesive wear. This material had been detached from the alloy surface by adhesion to the steel surface [28]. During sliding, some of transferred material was lost, but some re-embedded and was smeared over the alloy sample surface.

In addition, scanning electron micrograph shown in Fig. 7 exhibits the typical appearance of the surface fatigue damages after repeated unidirectional sliding of block over disk. The forms of surface fatigue damage are spalls (craters of different depths and shapes on contact surface marked by C), pits (marked by D) and surface cracks (marked by E). The SEM examination of the subsurface regions (below the wear surfaces) in similar study on the same alloy [20] clearly demonstrated the appearance of micro constituents flow in sliding direction and subsurface cracks. These subsurface cracks nucleated due to the stresses propagate during the sliding process. When such subsurface cracks join the wear surface, delamination of material occurs. This mechanism of wear is described by delamination theory of wear, introduced by Suh [29]. Contact surfaces of ZA-27 alloy are not subjected to fatigue failures only as a result of repeated stressing caused by moving asperities of steel disk. Hard wear debris trapped by the two moving surfaces during dry sliding could have significant role in fatigue wear particles forming [30].

4. Discussion

The obtained results show that the heat treatment of ZA-27 alloy (solutionizing at 370 °C and quenching) resulted in a reduction in the hardness and tensile strength and in an increase

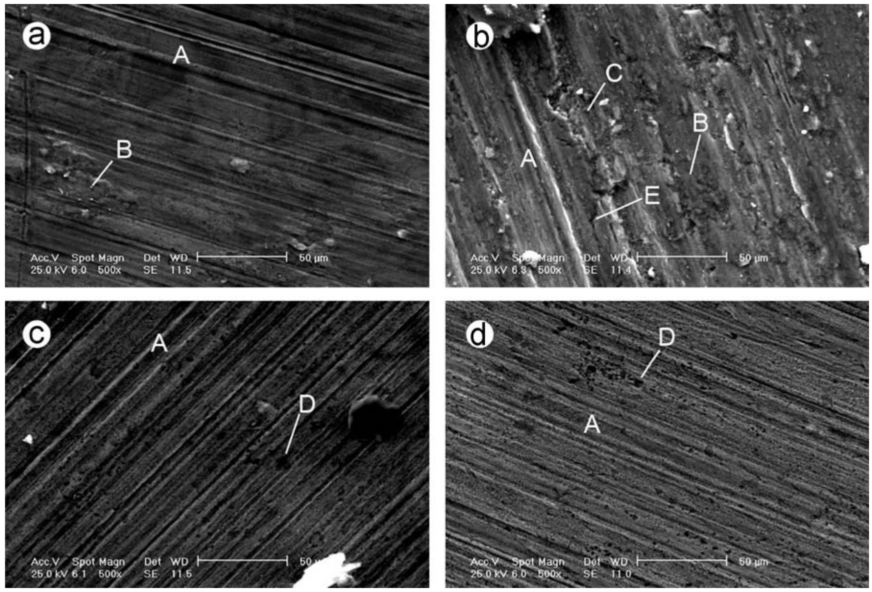

Fig. 7. Wear surfaces of the ZA-27 alloy in as as-cast conditions for applied load of 15 N (a) and 50 N (b) and after heat treatment for applied load of 50 N (c) ZA-27 HT3 and (d) ZA-27HT5 (A—ploughing grooves, B—meared material, C—spalls, D—pits, E—surface cracks).

in elongation. In spite of reduced hardness and strength the heat-treated alloy samples attained improved tribological behavior over the as-cast ones. The friction coefficient and wear rate of heat-treated alloy samples are significantly lower than that of as-cast alloy samples for all applied contact loads (Figs. 5 and 6).

In order to explain these effects of heat treatment on mechanical properties and tribological characteristics it is necessary to analyze the influence of heat treatment on microstructure of investigated alloy.

Zn–Al-based alloys basically comprise a mixture of the two solid solutions of α and η phases. The α-Al rich solid solution provides strengthening and thermal stability to alloys in view of the higher melting point of Al (than that of Zn). Also, this phase with face-centered cubic crystal structure (FCC) is characterized by good work hardening capability that contributes to wear behavior improving of the alloys [18,27]. The η-Zn rich solid solution has a hexagonal-close-packed crystal structure (*hcp*) with a higher c/a ratio than observed in ideally close packed hexagonal crystal system [17]. Thanks to that characteristic, the η micro constituent has very good smearing characteristics acting as a solid lubricant [1,17]. Effects of these micro constituents on tribological behavior of the alloy depend on their distribution and size.

The tested as-cast alloy contains primary α dendrites surrounded by eutectoid α+η mixture. Such a dendritic structure is characterized by non-uniform distribution of various micro constituents (Fig. 2a and b). Besides that, different thermal characteristics and mechanical properties of various phases cause residual stresses on a micro-scale [20]. The thermal treatment dissolved, by diffusion, the nonequilibrium dendritic structure, i.e., its major part (or completely for a longer period of solutionizing), and contributed to increased share of the two-phased α+η mixture in the final material structure. Moreover, the microstructure of alloy is refined with uniform distribution of micro constituents. This improvement of uniformity relieves the residual stresses, as also evident from decreasing of hardness and strength and increasing of elongation (Table 1) after heat treatment. Reduction in hardness and strength of the zinc–aluminum alloy after heat treatment has been suggested also by Prasad [19,20,25] to be due to the transformation of the metastable to the stable T' phase.

Just the finer and well distributed micro constituents (with prevailed two-phased α+η mixture) are helpful to reduce the friction and wear of heat-treated alloys. Self-lubricating role of η micro constituent is especially precious in conditions of dry sliding. In accordance with higher uniformity of distribution and decreased size of various micro constituents, positive tribological effects of heat treatment were slightly higher for longer time of solutionizing.

In explaining the favorable influence of the heat treatment on antifrictional properties of the zinc–aluminum based alloys, Haoran [22] has also used the experimental results of the shearing strength (s_c), and compression yield (P_m) of heat-treated alloys. These results showed that the s_c/P_m ratio of the alloy treated with TRT technique (heating up to 385 °C for 3 h, quenching into 25 °C water, ageing in room temperature more than 7 days) is smaller with respect to the as-cast alloy, which is evident from decrease of the shear force cutting off the metal binding points on the friction surface [31].

The explanation for the obtained tribological results should be also looked for in characteristics of worn surfaces and wear mechanisms. The characteristic features of the worn surfaces of tested alloys are presented in Fig. 7. The worn surfaces of heat-treated alloys (Fig. 7c and d) are relatively smooth with shallow wear grooves, resulted from mild abrasive wear. Also, no smearing was observed on the worn surfaces. In contrast, significantly, rougher worn surface with deep grooves, damages and smeared material corresponds to the as-cast alloy (Fig. 7b), which is a consequence of intensive abrasive and adhesive wear. The phenomenon of delamination also contributes to higher wear of the as-cast alloy with respect to the heat-treated one, which can be approved by the surface fatigue damages (Fig. 7b, marked by C). The prominent delamination wear of the as-cast alloy could be explained by residual stresses on a micro-scale, resulted from non-uniform distribution of various micro constituents. This wear mechanism of as-cast alloy was noted for wear tests in conditions of higher loads (Fig. 7b vs. Fig. 7a).

Characteristics of wear surfaces are in accordance with determined effects of applied load on wear response of tested alloys, shown in Fig. 6. The data plots show considerable higher slope of line corresponding to as-cast alloy compared to heat-treated alloys. Slope increase can be clearly noticed at the applied load change from 30 to 50 N, and it is especially prominent at the further increase of the applied load up to 100 N. This difference in wear degree increase with load of as-cast alloy, with respect to heat treated alloys, is a consequence of the described phenomenon of delamination as a dominant mechanism, which occurs in the area of higher applied loads.

5. Concluding remarks

The microstructure of the as-cast alloy consisted of primary α-dendrites surrounded by $\alpha+\eta$ eutectoid, residual η phase and metastable ε phase in the interdendritic regions. The dendritic structure broke during the heat treatment. Moreover, the uniformity of distribution of various microconstituents, as well as their fineness, increased with the duration of solutionizing.

Heat treatment of alloy caused decreasing of the tensile strength and hardness. Furthermore, the heat-treated samples attained increased elongation as compared to that of the as-cast alloy. The solutionizing duration contributed to the tensile strength decrease and the elongation increase.

The heat-treated alloy samples attained improved tribological behavior (reduced coefficient of friction and wear rate) over as-cast ones, for all applied loads. The improved tribological behavior of the heat-treated alloys, in spite of reduced hardness, could be attributed to finer and more uniform distributed micro constituents and reduced cracking tendency.

Dominant wear mechanisms for tested alloys were abrasion and adhesion. However, under conditions of higher applied load delamination has considerable role in wear process of as-cast alloy. Due to that, difference in wear behavior of heat-treated vs. as-cast alloy is amplified in the area of higher loads.

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