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ORIGINAL PAPER

Influence of T4 Heat Treatment on Tribological Behavior of Za27 Alloy Under Lubricated Sliding Condition

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Abstract The effects of heat treatment on the microstructure, hardness, tensile properties, and tribological behavior of ZA27 alloy were examined. The alloys were prepared by conventional melting and casting route. The heat treatment of samples included the heating up to 370 °C for 3 or 5 h, quenching in water, and natural aging. Lubricated sliding wear test were conducted on as-cast and heat-treated ZA27 samples using block-on-disc machine. The friction and wear behavior of alloys were tested in contact with steel discs using combinations of three levels of load (10, 30, and 50 N) and three levels of linear sliding speeds (0.26, 0.50, and 1.00 m/s). To determine the wear mechanisms, the worn surfaces of the samples were examined by scanning electron microscopy (SEM). 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, under all combinations of sliding speeds and contact loads. The rate of improvement increased with duration of solutionizing process before quenching in water. Obtained tribological results were related to the effects of heat treatment on microstructure changes of alloy.

Keywords ZA27 alloy · Heat treatment · Tribological behavior

1 Introduction

Improvement of tribomechanical systems, from the aspect of decreasing friction and wear represents an essentially important task. The basic way of solving that task is related to development and improvement of tribological materials. There, the special importance belongs to development of alternative materials in engineering applications in order to reduce the production costs without sacrificing the functional requirements of the components [1, 2].

Zinc–aluminum alloys (ZA alloys) are occupying attention of both researchers and industries, as a promising material for tribological applications. Commercially available ZA alloys (especially ZA27) have become the alternative material, primarily for aluminum cast alloys and bearing bronzes, due to good castability and unique combination of properties [1–12]. 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) [6, 13, 14]. Interest for extending the practical application of these alloys is based on tribological, economical, and ecological reasons. These alloys are relatively cheap and can be processed efficiently with low energy consumption, without endangering the environment [6, 15–17].

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However, their broader application is limited. One of the major limitations of conventional ZA alloys, containing 8–28% Al, 1–3% Cu, and 0.05% Mg (ZA8, ZA12 and ZA27), is the deterioration of their mechanical and wear resistance properties at elevated temperatures (above 100 °C) and their dimensional instability [6, 8–21]. Due to that, recent investigations have focused attention to development of modified version of the ZA27 alloy.

The attempts have been made to partially replace copper by some high-melting element like Ni or Si and varying the quantity of aluminum up to 50% [2, 13, 22–25]. In addition, heat treatment of ZA alloys is one of the possible measures for their improvement. The following procedures of heat treatment were used: (a) artificial aging of samples at temperatures from 90 to 150 °C, mainly for optimizing the strength to specific elongation ratio [15, 21]; (b) solutionizing (usually from 320 to 400 °C) followed by artificial aging (T6 type of heat treatment) [19, 20]; (c) solutionizing with subsequent quenching and natural aging (T4 type of heat treatment) [22, 26, 27]; (d) solutionizing by rapid water quenching and aging at elevated temperatures [23]; (e) solutionizing followed by aging at elevated temperatures and water quenching [24].

Heat treatment of the conventional ZA alloys improves dimensional stability [15] and ductility [1, 20, 25]. However, the majority of the heat treatments lead to a reduction in hardness and tensile strength [19, 20, 26]. In spite of reduced hardness, the heat-treated alloys attain improved tribological properties [19, 22, 23].

The duration and temperature of solutionizing and aging play the dominant role in controlling the structural, mechanical, and tribological properties of ZA alloys [19, 20]. Accordingly, it is very important to optimize the parameters of heat treatment in order to attain good properties [19]. Therefore, purpose of this work is to determine the effects of solutionizing at temperature of 370 °C for a relatively short period of time (3 or 5 h), quenching in water and natural aging, on tribological behavior of ZA27 alloy in *lubricated sliding* contact. Tribological tests were conducted under varying test conditions from view of the sliding speed and applied contact load. The tribological response of heat-treated alloy was evaluated in regards to as-cast alloy, which was also studied under identical conditions.

2 Experimental Procedure

2.1 Alloy Preparation

The ZA27 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 a steel mold to obtain samples as 100 mm long bars with rectangular cross-section with dimensions of 30 × 20 mm^2. Some of the alloy specimens were subjected to T4 heat treatment comprising solutionizing at 370 °C for 3 h (ZA27 HT3), or 5 h (ZA27 HT5), quenching in water and natural aging at room temperature during 34 days (the aging time was kept constant for all the alloy samples). The chemical composition of the alloy (in wt%), determined by optical emission spectrometry (ARL QUANTRIS), was as follows: 28.5 Al, 2.5 Cu, 0.012 Mg, and balance Zn.

2.2 Microstructural Characterization and Measurement of Mechanical Properties

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.

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 prepared tensile samples had 4-mm gauge diameter and 20-mm gauge length. Tensile tests were conducted at ambient temperature (23 °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.

2.3 Sliding Wear Tests

The specimens were tested using a block-on-disc sliding wear testing machine with the contact pair geometry in accordance with ASTM G 77-83. A schematic configuration of the test machine is shown in Fig. 1. The test block was loaded against the rotating steel disc. This provides a nominal line contact Hertzian geometry for the contact pair.

The test blocks (6.35 × 15.75 × 10.16 mm^3) were prepared from the as-cast and heat-treated ZA alloys. Their contact surfaces were polished to a roughness level of $R_a = 0.2$ μm. The counter face (disc with 35-mm diameter and 6.35-mm thickness) was fabricated using the case-hardened 30CrNiMo8 steel with hardness of 55 HRC. The roughness of the ground contact surfaces was $R_a = 0.3$ μm.

The tribological pairs were tested under lubricated conditions using combinations of three levels of load (10, 30, and 50 N) and three levels of linear sliding speeds (0.26, 0.50, and 1.00 m/s). Selection of the applied loads

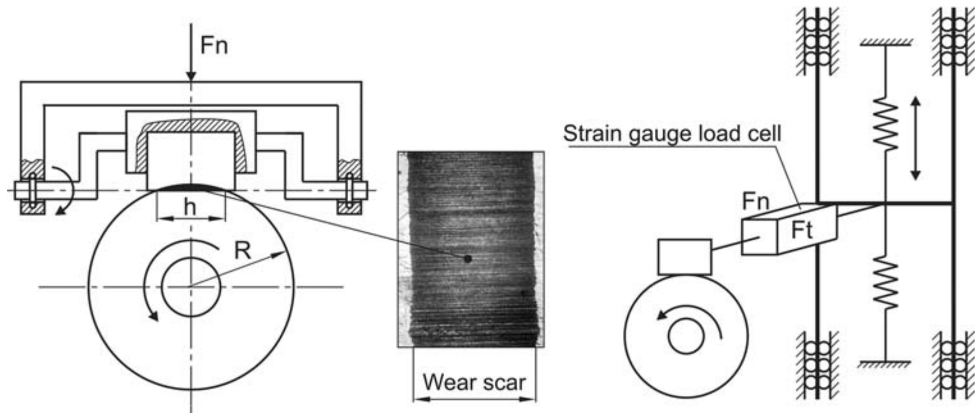

Fig. 1 Schematic diagram of the block-on-disc wear test machine

and sliding speeds was done in order to cover, by their combination at the given contact geometry, the regimes of the boundary and mixed lubrication. Those are the regimes in which mainly operate the bearings that are made of the ZA alloys. The duration of tests was 30 min (the sliding distance was 468 m). Tests were conducted with five repetitions.

The tests were performed at room temperature. The lubricant used for the lubricated tests was ISO grade VG 46 hydraulic oil, a multipurpose lubricant, recommended for industrial use in plain and antifriction bearings, electric motor bearings, machine tools, chains, and gear boxes, as well as in high-pressure hydraulic systems. During the lubricated tests, the discs were continuously immersed up to 3 mm of depth in 30 mL of lubricant.

For continuous monitoring of the friction process and measurement of the friction parameters, the tribometer was equipped with the corresponding measuring system supported by a PC. The measurement system functioning is done through: (a) generating of the voltage signals for the normal loading force F_n and the friction force F_t by the corresponding strain gauge load cells; (b) AD signals conversions with the selected sampling rate (used was 20 Hz); and (c) acquisition of time series data. The data acquisition was supported by the specialized software LABTECH Notebook, version 7.0. Within the input function, the software enables opening of several channels for data input, that represent the results of certain mathematical operations between the other channels data. This possibility was used for generating the time series of the friction coefficient data, by calculating the ratio F_t/F_n.

The wear behavior of block was monitored in terms of the wear scar width. Using the wear scar width and geometry of the contact pair (Fig. 1), the wear volume was calculated (in accordance with ASTM G77-83). The 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.

3 Results

3.1 Microstructure and Mechanical Properties

Microstructures of the alloys in as-cast and heat-treated conditions are presented in Fig. 2. The as-cast alloy (Fig. 2a, b) exhibited dendritic structure comprising primary α dendrites surrounded by $\alpha + \eta$ eutectoid and residual η 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).

With heat treatment, the micro-composition of ZA27 alloy became more homogeneous and the microstructure was refined (Fig. 2c, d). In the microstructure of ZA27 alloy, which was solutionized for 3 h at 370 °C and then quenched (Fig. 2c), one can distinct the residual dendrite cores and very fine $\alpha + \eta$ mixture, which occupies the largest portion of the structure. After 5 h of solutionizing, with consecutive quenching in water, the dissolution of the dendritic structure has occurred. Moreover, the uniformity of distribution increased and size of various micro constituents decreased with the duration of solutionizing (Fig. 2d).

Mechanical properties of the ZA27 alloy samples, in as-cast and heat-treated conditions, are presented in Table 1. Heat treatment of the alloy caused a moderate 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 Tribological Behavior

Based on wear scar width measurements, during the sliding process, the wear curves were plotted. That was illustrated

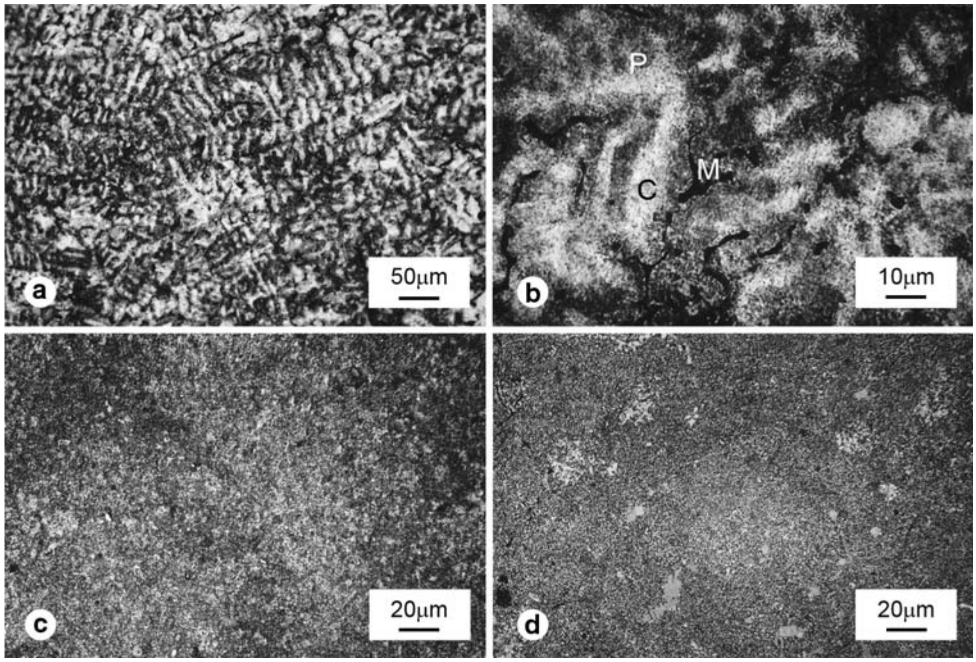

Fig. 2 Microstructure of the alloy: **a** and **b** ZA27 as-cast, **c** ZA27 HT3, **d** ZA27 HT5 (C—α dendrite core, P—$\alpha + \eta$ dendrites' periphery, M—η interdendritic phase)

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

on the example of wear curves obtained for ZA27 HT5 in all the combinations of applied loads and sliding speeds (Fig. 3). By analyzing the shape of those curves, one can conclude that the identical nature of the wear process development corresponded to all the tested materials, in all the contact conditions. Wear behavior of tested alloys was characterized by the clearly expressed period of initial intensive wear (run-in) during the first minutes of sliding, after which the steady-state period follows. The steady-state wear is moderate and can be, with the high correlation coefficient, expressed as linear.

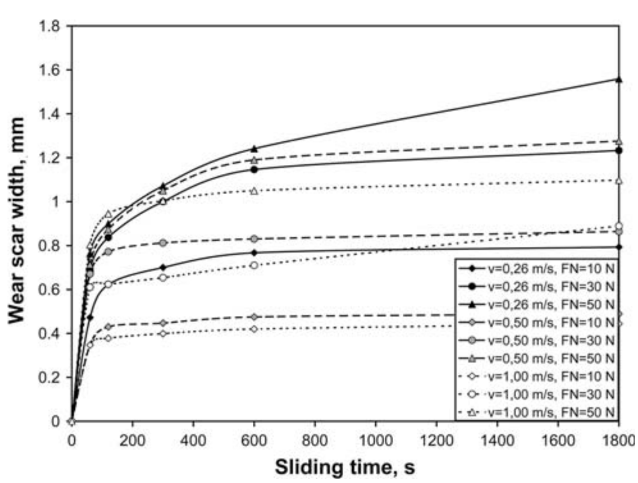

Fig. 3 Wear curves of ZA27 HT5 alloy at different specific loads and sliding speeds

The character of friction coefficient variation during sliding is illustrated in Fig. 4. This is a graphical representation of the results obtained for ZA27 HT5 alloy with three levels of applied loads and two levels of sliding speed. From the diagram, one can clearly notice the run-in period, during which the intensive decrease of the friction coefficient occurs. During the steady-state period, the level of the friction coefficient is being stabilized. Such a dependence of the friction coefficient is in accordance with the described wear behavior of tested alloys.

Generally, it can be concluded that the conducted tests are characterized by the low level of the friction coefficient. This is the consequence of presence of the large quantity of oil in the contact zone and of the contact geometry.

Diagrams in Fig. 5 show the dependence of the steady-state friction coefficient on the sliding speed, for various normal forces. The nature of that dependence, in all the tested alloys, manifests as decrease of the friction

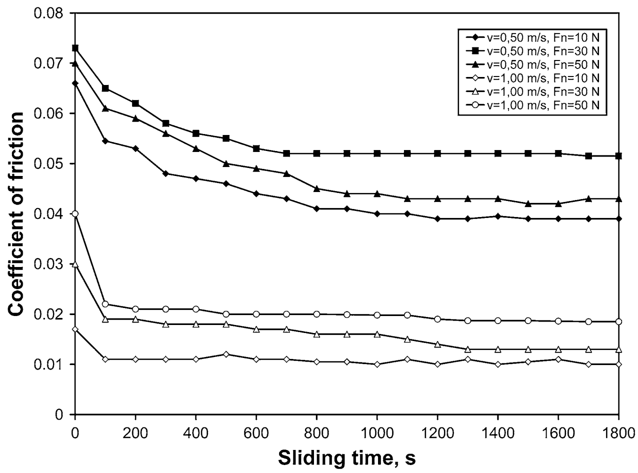

Fig. 4 Friction coefficient variation of ZA27 HT5 alloy during sliding time at different specific loads and sliding speeds

coefficient with increase of the sliding speed. The degree of change is especially prominent in the region of lower values of speeds. Also, in all the tested alloys, the friction coefficient increases with increase of the normal force. The degree of increase is somewhat larger in the region of the lower normal loads (from 10 to 30 N).

In all the tested alloys, the friction coefficient decreases with increase of the v/F_n ratio. The graphical representation of the friction coefficient dependence on speed-to-load ratio, v/F_n, for the tested alloys is presented by the Stribeck curve in Fig. 6. The graphs cover the boundary and the mixed lubrication regime. It confirms shape of the curves, as well as the obtained range of the friction coefficient (from 0.09 to 0.1). At the start of run, the lubricated system operates under boundary lubrication condition. However, as the sliding distance increases the thickness of the oil increases, giving rise to less metal-to-metal contact by producing mixed lubrication condition.

Based on the values of the wear scar width, the average values of the wear loss were calculated, expressed in mm^3. Diagrams in Fig. 7 present the dependence of the wear volume loss on the sliding speed for various normal forces. It can be seen that in all the alloys the wear volume decreases with increase of the sliding speed and decrease of the contact load. This is in accordance with the described lubrication conditions. The influence of the speed variation on wear is less expressed at lower sliding speeds.

The obtained results show existence of the significant differences in the friction behavior of the tested alloys. An example of those differences during friction is presented in Fig. 8 for the case of friction at the applied load of 30 N and sliding speed of 0.5 m/s. It can be seen that the highest friction coefficient, during the whole friction process, corresponds to the as-cast alloys.

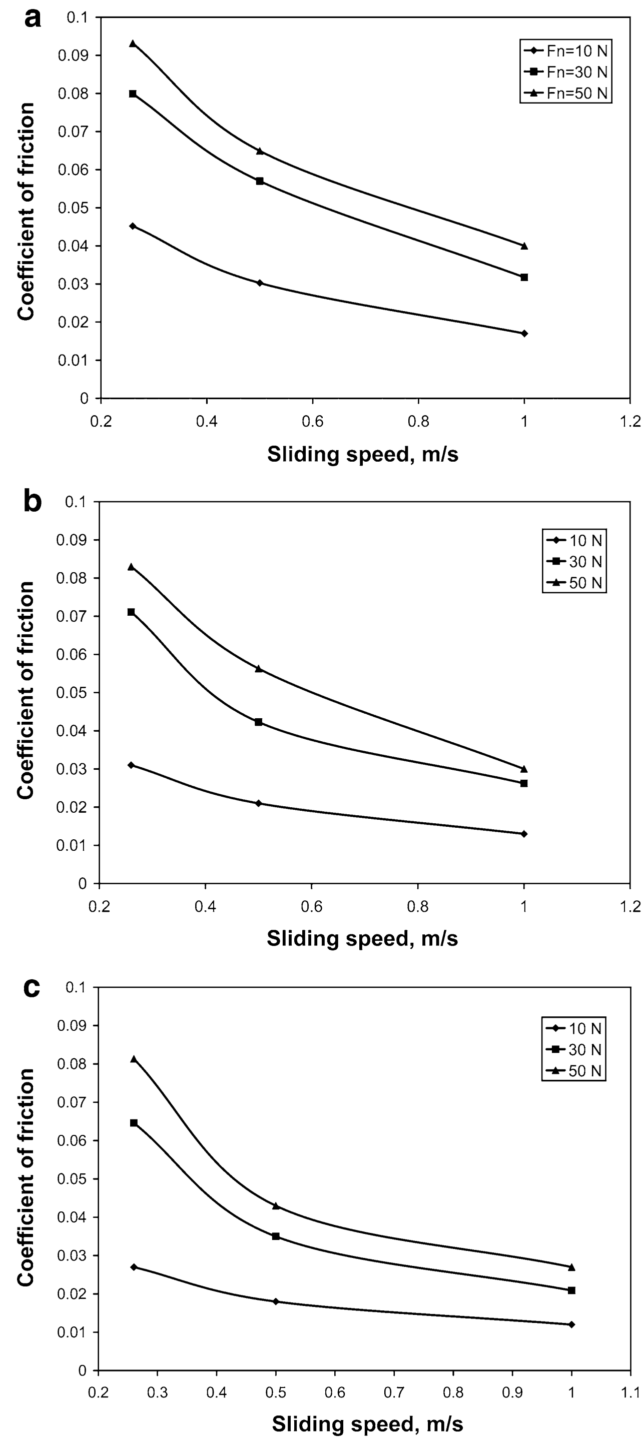

Fig. 5 Friction coefficient versus sliding speed for different applied loads: **a** ZA27 as-cast alloy, **b** ZA27 HT3 alloy, **c** ZA27 HT5 alloy

The average values of the friction coefficient for all the three levels of normal force and sliding speed are shown in Fig. 9. It can be noticed that for all the contact loads and sliding speeds the friction coefficient of heat-treated alloys is significantly reduced as compared to that of the as-cast one. Reduction rate is higher in area of lower applied loads.

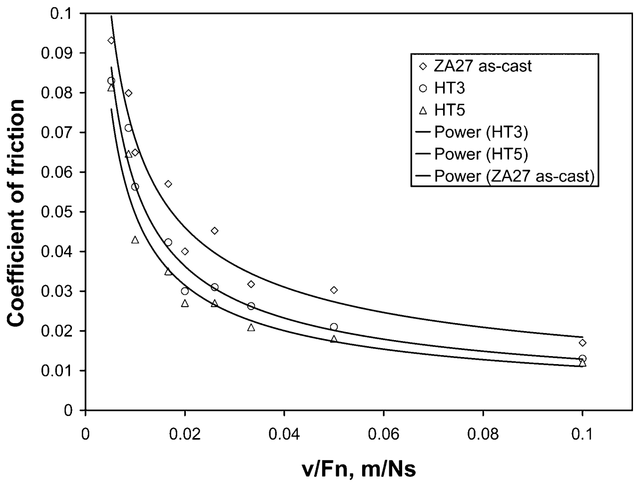

Fig. 6 Friction coefficient of tested alloys versus speed-to-load ratio

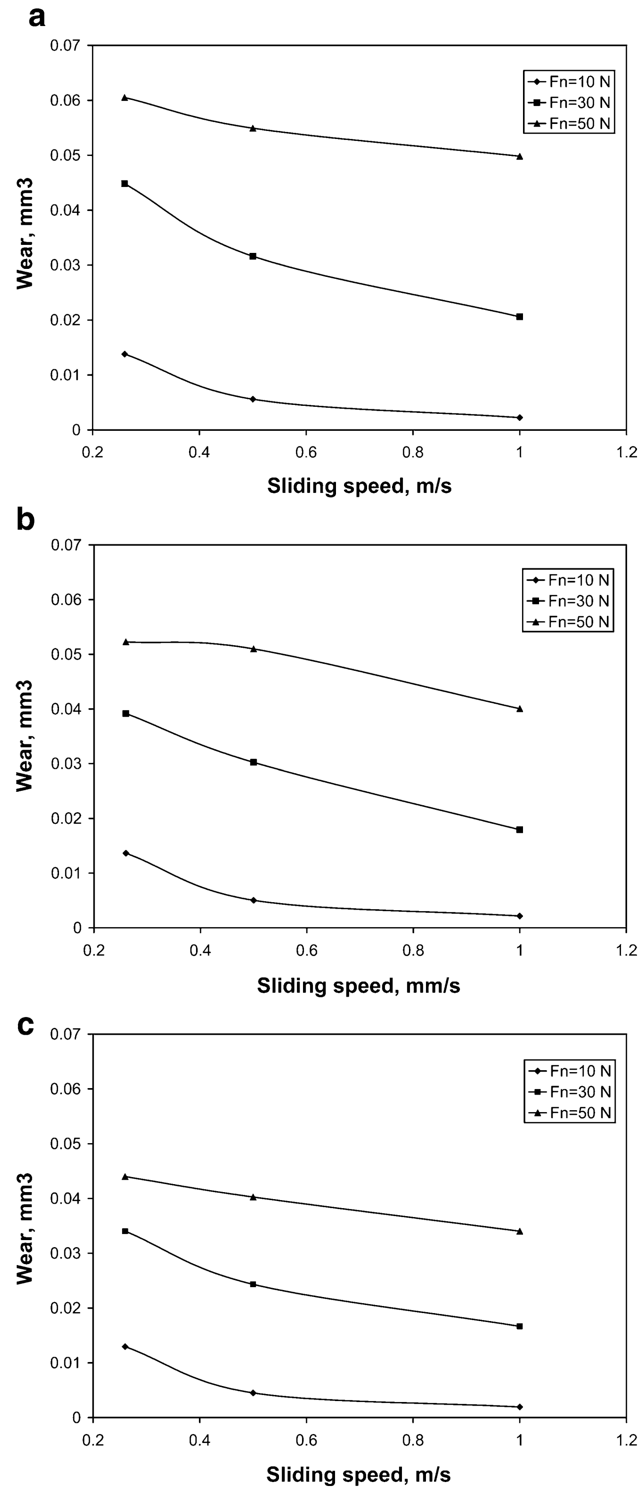

Fig. 7 Wear loss of tested alloys versus sliding speed for different applied loads: **a** ZA27 as-cast, **b** ZA27 HT3, **c** ZA27 HT5

These differences in the frictional behavior of the heat-treated alloys relative to the as-cast alloy versus speed-to-load ratio are also apparent in Fig. 6. It can be seen that the Stribeck curves for the heat-treated alloys lie below and to the left with respect to the curve that corresponds to the as-cast alloy. This shows that higher loads and lower speeds can be tolerated by the heat-treated alloys.

The comparative wear losses of the tested alloys for all the three levels of normal force and sliding speed are shown in Fig. 10. The presented results clearly show that in the whole range of load and sliding speed, the wear loss of the heat-treated alloys is significantly lower as compared to that of the as-cast one. The decrease of the wear volume, expressed in percents, is somewhat more prominent at the highest contact load.

Characteristic features of the worn surfaces of tested alloys, obtained in condition of the highest applied load (50 N) and the lowest sliding speed (0.26 m/s) are shown in Fig. 11. Generally, the parallel grooves and scratches can be seen over all the surfaces in the direction of sliding (Fig. 11, marked by G). The wear surfaces of the heat-treated samples were noticed to be smoother than those of the as-cast one (Fig. 11b, c vs. a). A relatively clean surface marked by shallow grooves (Fig. 11c, d) indicates the low wear loss. In contrast, significantly rougher worn surface with deep grooves, damages, and smeared material (S) corresponds to the as-cast alloy (Fig. 11a, b).

4 Discussion

The hardness and tensile strength of the heat-treated samples decreased while their elongation increased as compared to that of the as-cast alloy (Table 1). The softening rate of the alloy (12.4%) is practically constant with solutionizing duration. On the contrary, increasing of the solutionizing duration caused the strength to decrease and elongation to increase.

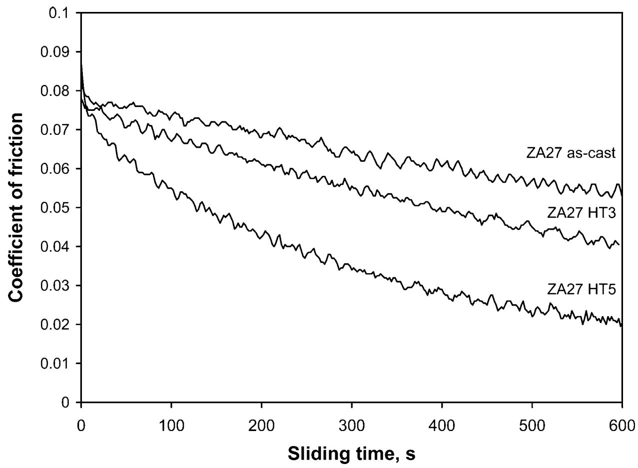

Fig. 8 Friction coefficient of tested alloys versus sliding time for 30 N of applied load and 0.5 m/s of sliding speed

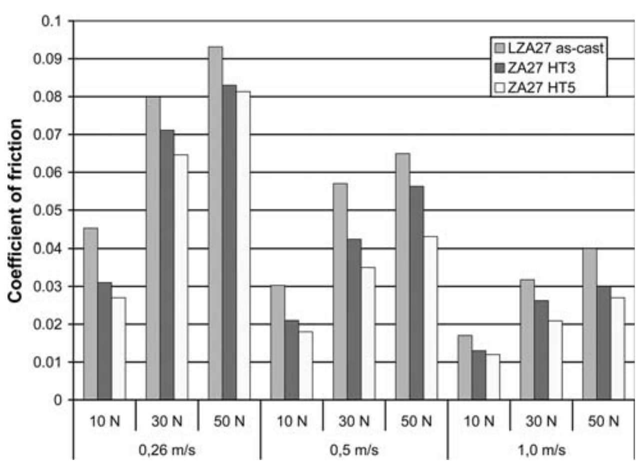

Fig. 9 Friction coefficient of tested alloys comparison

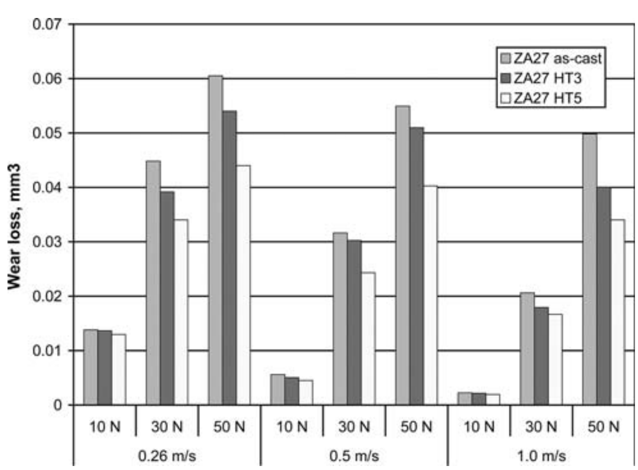

Fig. 10 Wear volume loss of tested alloys comparison

In spite of reduced hardness, the friction coefficient and wear volume loss of heat-treated alloy samples were significantly lower than that of as-cast alloy samples (Figs. 9, 10). The positive effects of the heat treatment on the ZA alloys in spite of reduction in hardness and strength have been suggested also by Prasad [19, 20, 24].

The explanation for the obtained results should be looked for in heat treatment effects on the microstructure of alloy. The influence of the microstructure on tribological behavior of samples can be manifested directly and indirectly. The former one refers to the direct influence of the microstructural characteristics on the tribological behavior of an alloy. The latter one is manifested via the residual stresses influence on micro-scale and ductility of alloy in contact layers, which can be directly related to the established wear mechanisms of samples.

The dendritic microstructure of the as-cast alloy was characterized by the non-uniform distribution of micro constituents. The heat treatment has, by diffusion, dissolved the non-equilibrium dendritic structure, and contributed to high increased share of the two-phased $\alpha + \eta$ mixture in the final material structure.

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). In addition, this phase with face-centered cubic crystal structure (f.c.c.) is characterized by good work hardening capability that contributes to wear behavior improvement of the alloys [2, 25]. The η-Zn rich solid solution has a hexagonal-close-packed crystal structure (h.c.p.) with a higher c/a ratio than observed in ideally close packed hexagonal crystal system [2]. Thanks to that characteristic, the η micro constituent has very good smearing characteristics, acting as a solid lubricant. Moreover, the η phase also acts as a load-bearing phase because of its hexagonal structure [2, 3]. Effects of these micro constituents on tribological behavior of the alloy depend on their distribution, size, and operating temperatures.

Just the finer and well-distributed micro constituents (hard and soft phases), achieved by heat treatment (Fig. 2c, d), contributed to reducing the friction and wear. There, self-lubricating role of η micro constituent is especially precious during the running-in process, which is characterized by the boundary lubrication and intensive wear. As can be seen from Figs. 4, 5, 6, 8 and 9, the established level of the friction coefficient is generally low in all the combination of the contact loads and sliding speeds. That, as well as the very abundant presence of lubricant, suggests the conclusion that there were no conditions for generating the higher contact temperatures, which would diminish the positive influence of the favorable microstructure on tribological behavior of the heat-treated alloy.

Besides that, the changes of microstructure due to heat treatment are significant, on a micro-scale, from the aspect of residual stresses, which affect the wear mechanism. The dendritic non-homogeneous structure of as-cast alloy is

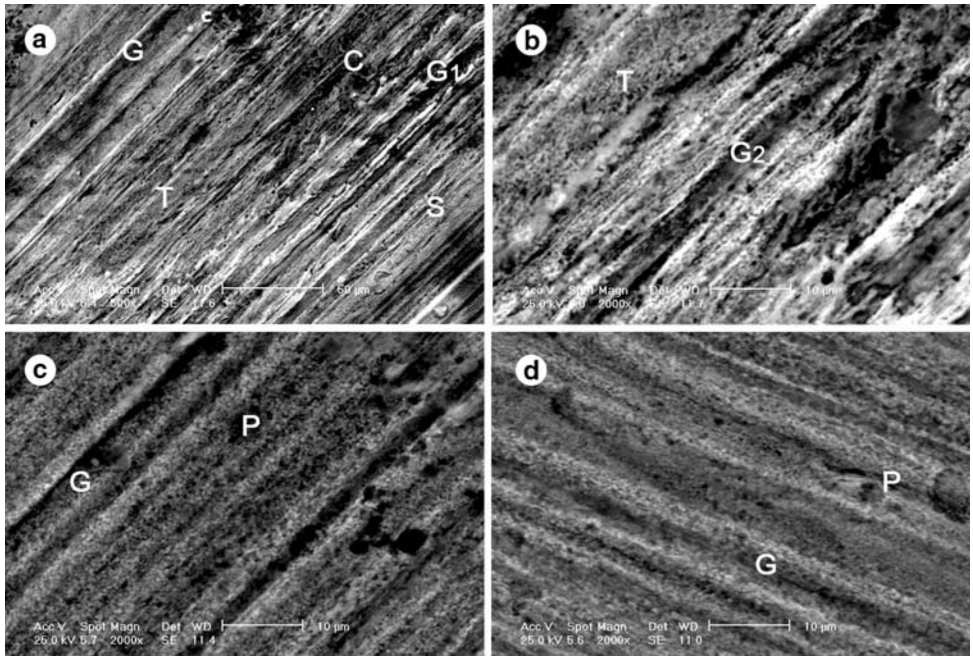

Fig. 11 Wear surfaces of the alloys for 50 N of applied load and 0.26 m/s of sliding sped: **a** and **b** ZA27 as-cast, **c** ZA27 HT3, **d** ZA27 HT5

characterized by presence of residual stresses on a microscale, which appear due to different thermal characteristics and mechanical properties of various phases [20]. Improvement of uniformity, due to the heat treatment, relieved the residual stresses, as is also evident from decreasing of hardness and strength and increasing of elongation (Table 1) after the heat treatment [20, 24].

The described influence of heat treatment on improvement of tribological behavior of ZA27 alloy is in accordance with morphology of the worn surfaces that are presented in Fig. 11. The wear surface of the as-cast alloy is characterized by deep continuous grooves (Fig. 11 marked by G, G_1, G_2), scratches (S), pits/craters (C/P), and smeared material (T). These grooves and scratches resulted from the plowing action of asperities on the counter disc of significantly higher hardness, as well as due to the hard wear debris, emanating from fragmented and oxidized asperities of alloy and abraded surface of the steel disc [24]. On the worn surface of the as-cast alloy, different types of grooves could be clearly noticed. Only the rare grooves fit right into the material model removal and displacement in ductile abrasive wear (Fig. 11a marked with G). In this model, during abrasive wear the material does not simply disappear from the groove gouged in the surface by a micro abrasive element. Instead, a large proportion of the gouged or abraded material is envisaged as being displaced to the sides of the micro abrasive element path [28]. The dominant groove morphology points to the non-ductile abrasive wear. That was proved by the wear grooves characterized by micro cracks appearance in material displaced to the sides of groves (Fig. 11a marked with G_1). During the friction process, this material was removed as a product of wear, because of propagating micro cracks. In addition, the grooves with material spalled at the sides of grooves are present on the worn surface (Fig. 11b marked with G_2).

Besides the abrasive wear mechanism, existence of the material smeared onto the sliding surface (clearly visible in Fig. 11a, b, marked by T) shows presence of the adhesive wear. This material had been detached from the alloy surface by adhesion to the steel surface [25]. During the sliding, some of transferred material was lost, but some was re-embedded and was smeared over the alloy sample surface. In addition, the scanning electron micrograph shown in Fig. 11, exhibits moderate appearance of the surface fatigue damages after repeated unidirectional sliding of block over the disc (C).

The worn surfaces of heat-treated alloys (Fig. 11c, d) are relatively smooth with shallow wear grooves, resulted from mild abrasive wear. Also, no smearing was observed on the worn surfaces. Unlike the worn surface of the as-cast alloy, the wear grooves on surfaces of heat-treated surfaces are abraded in accordance with model of ductile abrasive wear (Fig. 11c, d, marked with G). That type of abrasive wear influenced increased ductility because of heat treatment (Table 1).

The positive effects of heat treatments on tribological behavior of alloy are slightly higher for longer time of solutionizing. This is also conformed by the SEM micrographs in Fig. 11c, d. It is in accordance with higher the uniformity of distribution and decreased size of various micro constituents and increased ductility.

5 Conclusions

1. The dendritic microstructure of the ZA27 as-cast alloy is characterized by the non-uniform distribution of micro constituents. The heat treatment dissolved dendritic structure and contributed to increased share of the two-phased $\alpha + \eta$ mixture in the final material structure. The microstructure of heat-treated samples is refined with uniform distribution of micro constituents.
2. The heat-treated samples attained the reduced hardness and tensile strength as well as the 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. Tribological response of the tested samples strongly depended on sliding speed and applied load. The friction coefficient and wear volume loss increase with applied load and decrease with the sliding speed. This is in accordance with the regime of lubrication.
4. In spite of moderate reduced hardness and strength, the heat treatment of alloy improved tribological behavior over as-cast one in all tested conditions, which provided boundary and mixed lubrication. This could be explained in terms of suitable heat treatment effects on the microstructure of the investigated alloy.
5. The worn surfaces of heat-treated alloys were relatively smooth with shallow wear grooves, without smearing of transferred material. Significantly rougher worn surface with deeper grooves and damages corresponded to the as-cast alloy. The worn surfaces morphologies of heat-treated alloys pointed to the more ductile mode of fracture than for the as-cast alloy.

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