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RESEARCH

Influence of Heat Treatment on Tribological Behavior of Zn-Al Alloys

The effects of heat treatment on the microstructure, hardness, tensile properties and tribological behavior of ZA-27 alloys in conditions of dry sliding were examined. The heat treatment of samples consisted of heating up to370 °C for 3 or 5 hours, and quenching in water. The temperature selected for solutionizing was.

The heat treatment of ZA-27 alloys influences microstructure changes, decreasing of strength and hardness, but causes increasing of elongation. The rates of changes increase with increasing solutionizing duration. On the other hand, tribological tests results show that heat treatment of castings has a significant influence on improvement of their tribological properties. There, heat-treated samples casted in steel molds attained and even exceeded tribological antifriction and wear resistance behavior of sand casted samples.

Keywords: ZA-27 alloy; Heat treatment; Tribological behavior

1. INTRODUCTION

High aluminum zinc alloys (ZA alloys) in the past few decades are occupying attention of both researchers and industry, as a tribomaterial of significant potential [1 - 13]. It can be said, that, at this moment, commercially available ZA alloys, due to good castability and unique combination of properties, have become the alternative material primarily for many aluminum cast alloys and bearing bronzes, then for cast iron, plastic materials, even for steels for manufacturing the tribomaterials for operation in conditions of high mechanical loadings and moderate sliding speeds (namely, moderate exploitation temperatures). Interest for extending the practical application of these alloys, has besides the tribological, the economic and ecological character. Namely, the subject here is the cheap material, which is being casted energetically efficiently and without endangering the environment.

In the real casting, conditions the ZA alloys have the typical dendritic structure, which size depends on the applied casting structure. Namely the cooling speed imposes a strong influence on the structure fineness, during the cooling in the mold. The consequences of the dendritic structure are manifested, primarily, in the lower ductility of the casted alloy, as well as in relatively high inhomogeneity of the mechanical properties, [14].

The second important problem is related to high aluminum zinc alloys and it refers to dimensional instability, which is caused by presence of metastable phases [15]. One of the possible measures for overcoming these deficiencies is the heat treatment of the castings. In references are usually quoted the following procedures of heat processing: a) artificial aging of samples at temperatures from 90 to 150ºC mainly for purpose of optimizing the strength to elongation ratio [16, 17]; b) homogenizing annealing (usually from 320 to 370ºC) with subsequent slow cooling to the room temperature [18, 19] and c) solutionizing annealing with subsequent quenching [20, 21]. In the last case, if one wants to achieve additional hardening of the self-hardened samples, those should be exposed to additional artificial aging (T6 type of heat treatment).

However, besides this aspect, one should bear in mind that the heat treatment is influencing the microstructure, mechanical and tribological characteristics, what represents very challenging area for research from the aspect of the total effects. Results of such a complete research approach are presented in this paper. Two types of the ZA-27 castings are considered, castings made

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in sand and castings made in steel permanent molds.

In general, it is known sand cast ZA alloys displayed better tribological characteristics than pressure die cast and permanent molded alloys. However, casting of ZA alloys in the permanent molds, with achieving of the improved mechanical and tribological properties of the castings, is very important from the practical aspect, i.e., from the aspect of possibility of larger batches. Due to that, this investigation has as a goal to check the possibility of desired improvement by the heat treatment of the castings by the procedure comprised of solutionizing annealing at temperature of 370^{o}C during certain time, and quenching in water.

For functioning of the real tribomechanical systems, very important is the tribological behavior of the triboelements in the limited lubrication conditions. Those are the conditions that appear even in the very well lubricated systems during each start from the stationary state. This is why the tribological behavior of the tested alloys and effects of the heat treatment are analyzed based on the results about friction and wear obtained by the tribological tests of dry sliding.

2. EXPERIMENTAL PROCEDURE

2.1. Alloy preparation

For the tests castings were prepared of ZA-27 alloys using two types of casting techniques: casting in sand molds (50 mm circle cross-section, 100 mm long castings), and casting in cast iron mold (30 X 20 mm rectangular cross-section, 100 mm long castings). Castings produced using the cast iron mold were subjected to heat treatment by annealing at 370°C for 3 h, or 5 h followed by quenching into water at ambient temperature. The chemical compositions of the alloys are given in Table 1.

Table 1. Chemical composition of experimental alloys

Alloys	Elements, %				
	Al	Zn	Cu	Fe	Mg
ZA-27 sand cast, as-cast (ZA-27 as-cast1)	27.79	69.44	2.59	0.053	0.011
Z A-27 cast into steel molds (ZA-27 as-cast2)	28.47	67.77	2.51	0.145	0.011
ZA27 cast into steel molds heated up to 370°C for 3 h and quenched (ZA-27 HT3)	28.63	68.66	2.46	0.117	0.012
ZA-27 cast into steel molds heated up to 370°C for 5 h and quenched (ZA-27 HT5)	28.42	68.81	2.49	0.139	0.010

2.2. Measurement of mechanical properties and micro structural characterization

Bulk hardness of all metallographically prepared samples was measured using a Brinell hardness tester with a 2.5 mm diameter steel ball indenter and under a load of 62.5 daN. The application time of the load was 60 seconds.

The tensile samples prepared had 4 mm gauge diameter. A universal testing machine was used for carrying out the tensile tests. 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 metallographically polished according to standard practices and etched suitably. Diluted nitric acid (5 vol%) in water was used as the etchant.

2.3. Sliding wear tests

The alloy specimens were tribologically tested using a block-on-disc sliding wear testing machine (Fig. 1.) with the contact pair geometry in accordance with ASTM G 77 standard (Fig. 2.). The test block is loaded against the cylinder wall of rotating the steel disk. This provides a nominal line contact Hertzian geometry for the contact pair.

Computer support to experiment was enabled by application of the Burr - Brown PCI 20000 data acquisition system integrated into the PC computer and general - purpose *LABTECH NOTEBOOK* software package.

Case-hardened chromium-nickel steel disk Č.5432 (8 mm thickness, 68 mm diameter, 55 HRC hardness) simulates the axle in a journal-bearing unit. The roughness of the ground contact surfaces was Ra = 0.3 μm. A fresh disc was used each time and before each test. The test blocks (6,35 mm width) were prepared of tested alloys. Their contact surfaces were polished to a roughness level of Ra = 0,2 μm.

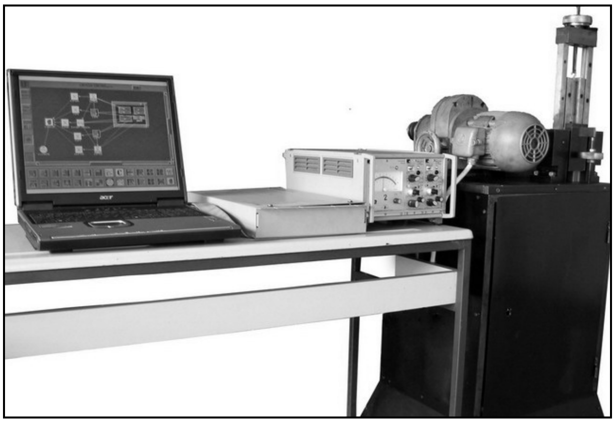

Figure 1. Tribometer

The tribological pairs were tested under dry (unlubricated) conditions using combinations of four levels of load (15 N, 30N, 50N and 100 N) and one level of linear sliding speed (0,26 m/s). The duration of each test was exactly 10 minutes.

It is necessary to emphasize that performing of such tests assumed very detailed previous mechanical and chemical cleaning of samples (blocks and discs), since presence of surface impurities can drastically distort the impression about the tribological behavior of the tested material in unlubricated tests.

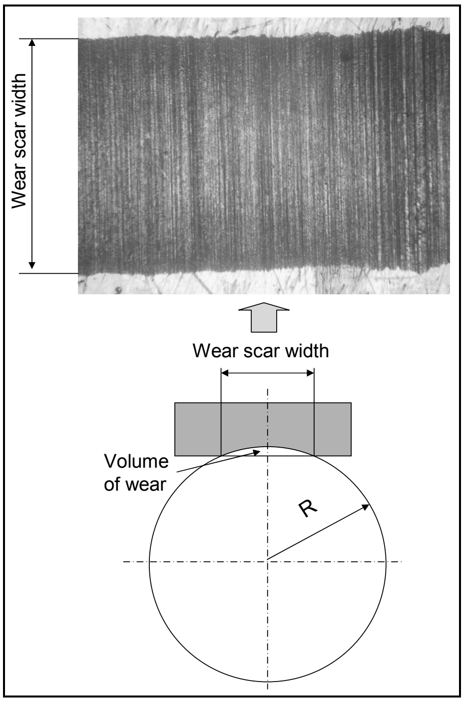

Figure 2. The contact pair geometry

The wear behavior of block was monitored by wear scar width. Using wear scar width and geometry of contact pair wear volume was calculated (Fig. 2.). SEM ("Philips XL30") was used to detect the worn surfaces of the tested wear blocks.

The computed friction coefficient signals were obtained automatically during all the tests by means of the data acquisition software. Tests were conducted with five repetitions and in the described manner and each of them resulted in the time series of 600s for the friction coefficient and the wear scar width of the block.

3. RESULTS AND DISCUSSION

3.1. Mechanical characteristics

Investigation results of the mechanical characteristics of the Za-27 alloys are presented in Table 2. It can be seen that the highest tensile strength corresponds to sand cast alloy, and the highest hardness corresponds to steel mold casting. With regards to the alloys heat treatment in the steel mold, it can be observed that it contributes to decrease of the tensile strength. This decrease is increasing with duration of annealing at temperature of 370^o. Also, the heat treatment is reflected through the hardness decrease of the alloy casted in the steel mold.

Table 2. Mechanical properties of the tested alloys

Alloys	**Tensile strength R_m, MPa**	**Elongation, %**	**Hardness, HB**
ZA-27 as-cast1	379	3.2	121
ZA-27 as-cast2	318	2.4	138
ZA-27 HT3	301	5.2	121
ZA-27 HT5	283	6.4	121

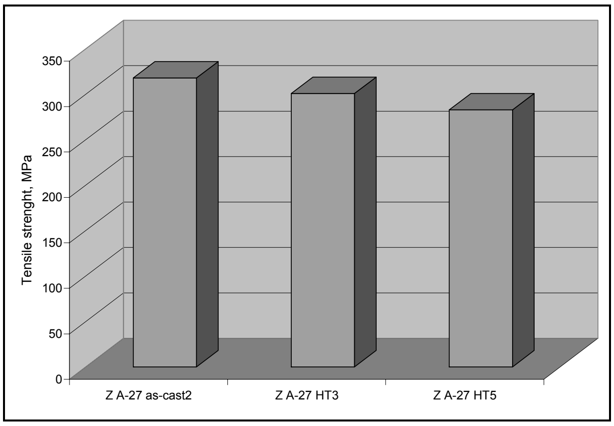

Figure 3. Heat treatment effects on tensile strenght of ZA-27 alloy

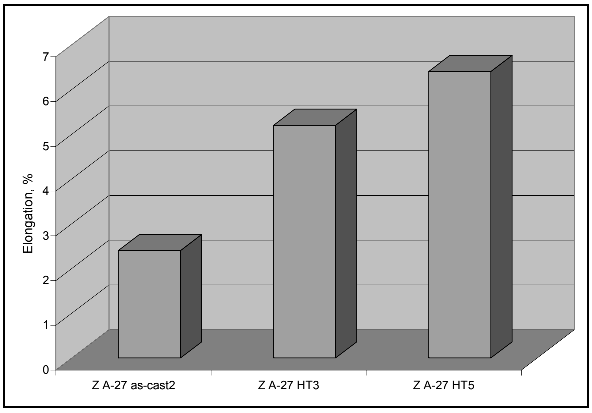

Figure 4. Heat treatment effects on elongation of ZA-27 alloy

The measurements results show that the heat treatment of the ZA-27 alloy, casted in the steel mold contributes to significant increase of elongation. Extension of the annealing time, at the same time, contributes to increase of the relative elongation (in %). The established effect of the heat treatment on the tensile strength decrease and simultaneous increase of ductility of the casting are graphically represented in Figures 3 and 4.

3.2. Microstructural characteristics

In Figures 5 to 8 are presented microstructures of the tested alloys. To alloys obtained by casting in sand and mold (Figures 5 and 6) correspond the typical dendritic structures. The microscopic structure is homogeneous and it consists of the light colored cores, rich with aluminum (the α-phase). Between them is the extracted eutecticum, gray colored, which consists of the α-phase and the η-phase rich with zinc. The CuZnAl ε crystals, rich with copper can be noticed on the figure as whitish areas.

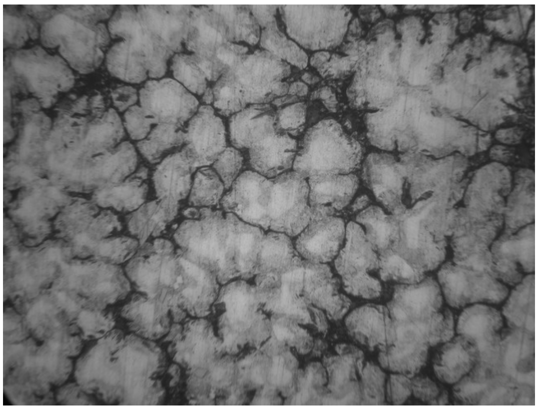

Figure 5. Microstructure of ZA-27 as-cast1 (X50)

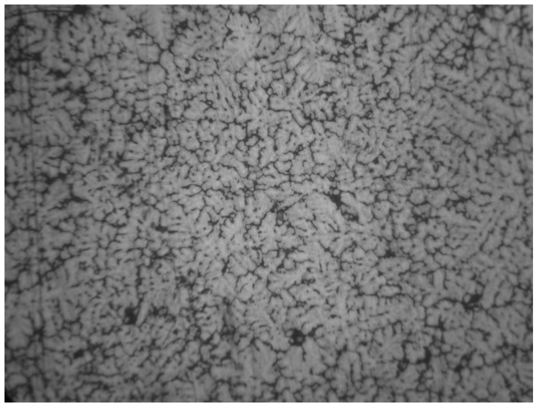

Figure 6. Microstructure of ZA-27 as-cast2 (X50)

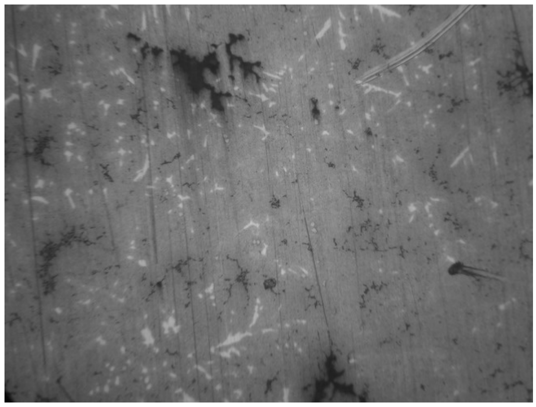

Figure 7. Microstructure of ZA-27 HT3 (X50)

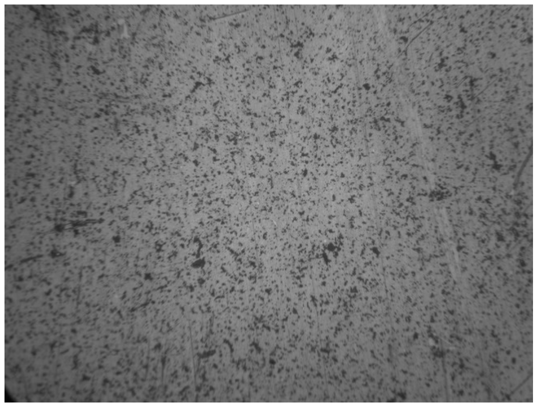

Figure 8. Microstructure of ZA-27 HT5 (X50)

The sand casted castings microstructure are characterized by distinct difference with respect to morphological characteristics. This is explained by the different solidifying conditions. In sand casting (where the sand has the insulating properties), the solidification is slower, what causes the appearance of the very developed dendrites, namely the larger size microstructure (Figure 5).

In mold casting (especially in steel molds) due to fast cooling, the significantly finer structure is obtained, but with the same constituents, i.e., only the dendrites are less developed and there are more of them per unit area (Figure 6).

In photograph of the ZA2-7 alloy's microstructure, which was annealed for 3 hours at 370ºC and then quenched in water (Figure 7), one can clearly distinguish the discontinuities that are caused due to heat treatment, i.e., the residual dendrites' cores (white), the residual "islands" of the interdendritic η-phase (dark) as well as the fine α+η mixture, which occupies the major part of the structure.

The recording of the structure, which was annealed for 5 hours with subsequent quenching in water (Figure 8), shows that the complete destruction of the dendritic structure has occurred. Besides that, noticeable is the coagulation of the interdendritic η-phase during the heating, which was maintained by quenching at the room temperature, while the dendritic cores can not be noticed any more. The structure seems as the equilibrium one, what is unexpected, since the matter of speaking is relatively short eating time in the area of the β-phase (morphologically similar structures, but of somewhat finer size, were obtained by the researchers after significantly longer heating annealing time with previous plastic processing by hot rolling).

3.3. Tribological behavior

Examples of the friction coefficient variation during the sliding process are presented in Figure 9. In accordance with the friction nature, without presence of the lubricant, during the sliding process the friction coefficient increases. This increase is of the different intensity, depending on the type of alloy and loading. Regarding the fact that here the case is of the contact of the bearing alloys and steel, during the tests there were no conditions for the seizeing phenomenon, what would be registered by the appearance of the sudden increase of the friction coefficient signal.

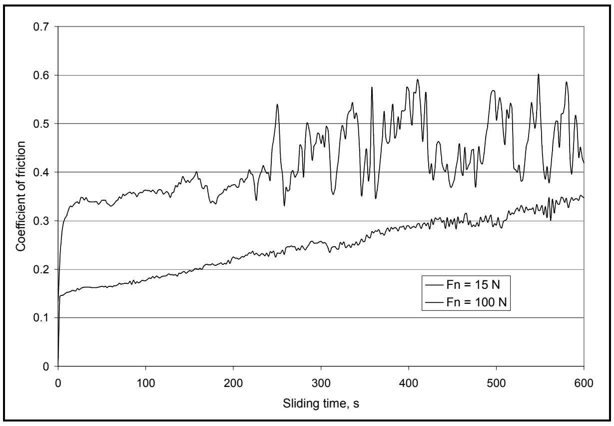

Figure 9. Examples of friction coefficient variation during sliding time

To lower loadings of 15N and 30N correspond very "quiet" friction coefficient signals in all the alloys, what testifies about the very good sustaining of the sliding friction without lubricant's presence in those conditions. To higher loadings, and especially loading of 100N, corresponds amplification of the signal's dynamics, what testifies about worsening of the contact conditions and generating of the greater quantity of the wear products.

The obtained results show existence of the significant differences in the frictional behavior of the tested alloys. The example of those differences is presented in Figure 10 for the case of friction at the lowest contact load of 15N. It can be seen that the highest friction coefficient, during the whole friction process, corresponds to the alloy, which was casted in the steel mold. In the first half of the friction process duration, the lowest friction coefficient belongs to the alloy which was annealed for 5 hours, and in the second half this friction increases, thus the lowest friction coefficient belongs to the alloy which was annealed for 3 hours. Between these two extremes is the friction coefficient of the alloy, which was sand casted.

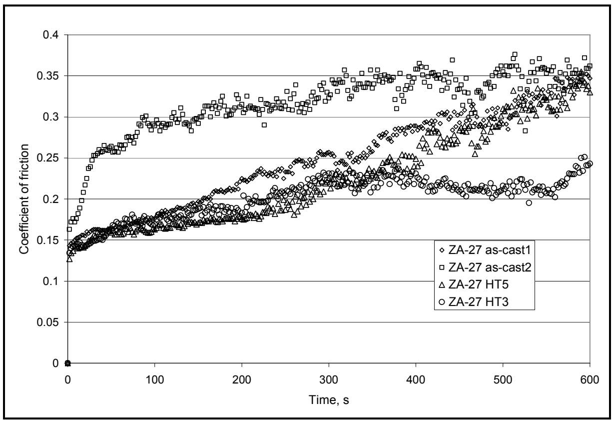

Figure 10. Coefficients of frictions tested alloys (F_N=15 N, v=0,26 m/s)

For analysis of the obtained results for friction, which possess the described variation with the friction time, the two friction parameters were used: the friction coefficient value after 60s of the friction process duration and the average value of the friction coefficient during the total friction process time.

The first parameter is significant since it points to the way how the tested materials would behave in the transition regime, i.e., in moments of transition from the stationary state to the state of sliding friction, when the lubricant supply to the contact surfaces is critical. The second parameter describes the frictional behavior of the tested alloys under the friction without presence of the lubricant and it represents the indicator, which is important for more complete evaluation of the tribological potential of those alloys.

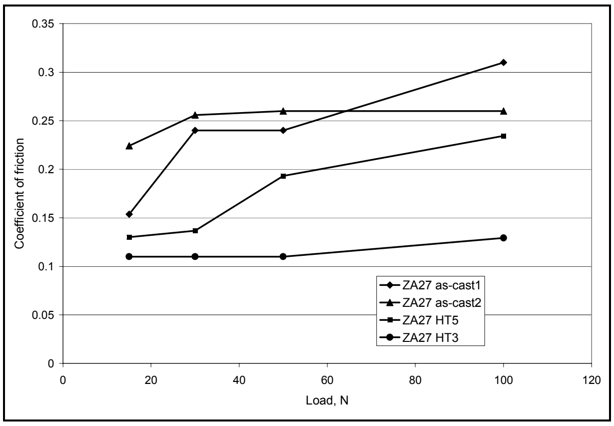

Figure 11. Average coefficients of friction of alloys for first 60s of sliding under different loads

The average values of the friction coefficient for the first minute, for all four levels of the normal force, are presented in Figure 11, and the average values of the friction coefficient during the tests are shown in Figure 12. There are presented the values that are obtained based on the 5 repeated tests for each combination of the contact conditions.

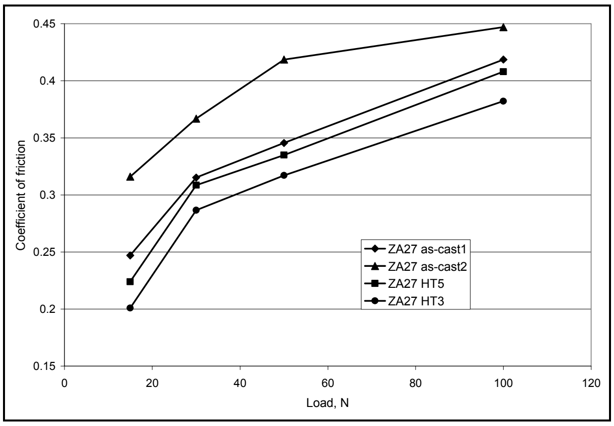

Figure 12. Average coefficients of friction of alloys for whole sliding time under different loads

In accordance with the nature of the dry friction, to the increase of the normal load corresponds the increase of the friction coefficient. In the first minute (Figure 11) of the process duration, those variations are more moderate than those for the whole process duration time (Figure 12). This is especially prominent for the alloys that were annealed for 3 hours.

It can be noticed that form all the contact loads, the lowest level of the friction coefficient, both for the initial stage of friction and the total duration of the process, corresponds to the 3hors annealed alloy. With the exception noticeable for the normal load of 100N, the highest friction level corresponds to the steel mold casted alloy without the subsequent heat treatment. Besides that, the relative differences in the frictional behavior are more prominent in the running-in period.

Based on the measured values of the wear scar for the five repeated series of tests, the average values of the wear rate were calculated, expressed in cm^3/h. The comparative diagrams of the wear rate of the tested alloys as a function of the normal loads are presented in Figure 13.

One can notice that in all the tested alloys, the intensity of wear increases with the increase of the normal force. However, the character of that increase is not the same for all the alloys. The most convincingly fastest increase corresponds to the steel mold casted alloy without the subsequent heat treatment. At the same time, for alloys that were heat treated by annealing and quenching, one can notice greater sensitivity to variation of the normal force in the area of the lower values of the same (1.5 to 3 daN), but also the lower sensitivity in the area of the higher values of the normal force (3 to 10 daN).

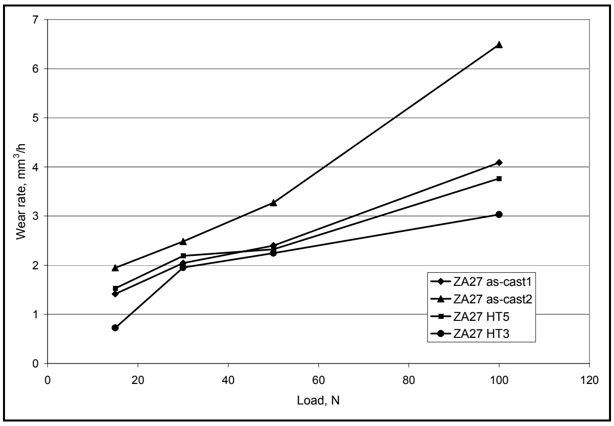

Figure 13. Wear rates of alloys under different loads

The presented dependencies of the wear rate on the normal load clearly show the relative relations of alloys from the aspect of wear. In the whole range of the normal forces, the lowest wear rate corresponds to the 3 hours annealed alloy, quenched in water, while the highest wear rate corresponds to the steel mold casted alloy. The comparison of alloy that was sand casted and the alloy that was annealed for 5 hours and subsequently quenched in water show moderate advantage of the former. Due to the different influence of the normal load increase on the wear rate increase for the tested alloys, difference in their tribological behavior are amplified in the area of higher loads.

The largest differences, which correspond to the loading force of 100N, are presented in percentage in Figure 14. The relative relations clearly show that the alloy that was sand casted has significantly better wear resistance with respect to alloy that was casted in the steel mold. However, this superiority of the sand cast alloy can be overcome by the heat treatment of the mold casted alloy, thus the convincingly the highest wear resistance corresponds to the alloy which was annealed for 3 hours and subsequently quenched in water. The decrease of the wear rate during friction without the lubricant's presence, realized by the heat treatment, compared to the as-cast alloy, amounts to 46 %, at 100N loading.

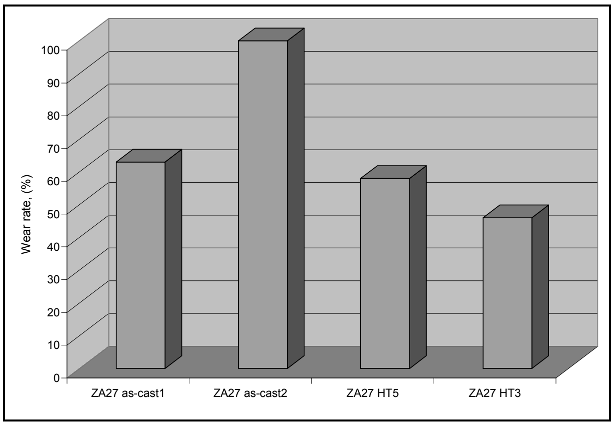

Figure 14. Wear rates of alloys under load of F_N=100 N

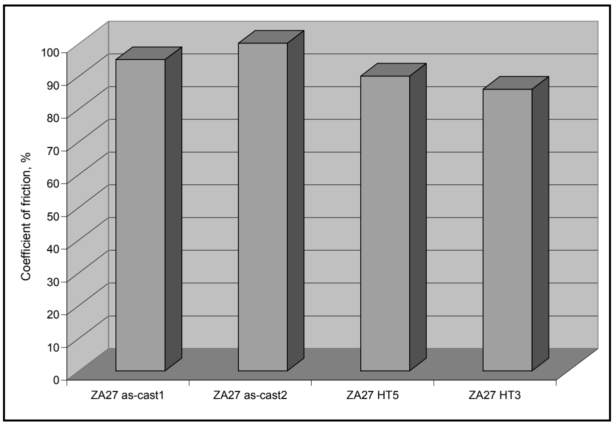

Figure 15. Coefficients of frictions of alloys underload of F_N=100 N

Thus, prominently expressed differences with regard to the wear rate are accompanied by the moderate differences in the friction coefficient levels (Figure 15). The order of the tested alloys there remains the same as before.

The relative relations of the tribological behavior parameters clearly show that the sand casted alloy has significantly better wear resistance with respect to steel mold casted alloy. However, this superiority of the sand casted alloy is overcome by the heat treatment of the mold casted alloy.

In Figures 16 to 19 are shown the SEM micrographs with enlargements of 500 of the worn surfaces of the tested alloys, under the following conditions: v=0.26 m/s and F_n=50N.

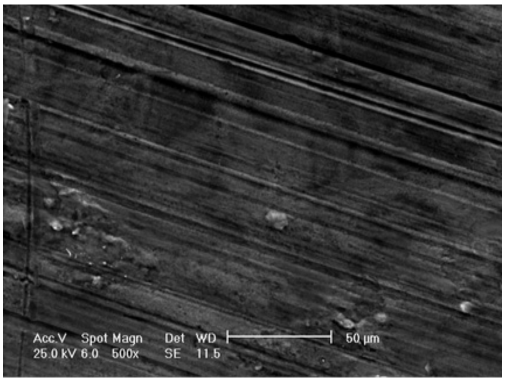

Figure 16. SEM image showing worn surface of ZA-27 as-cast1 alloy

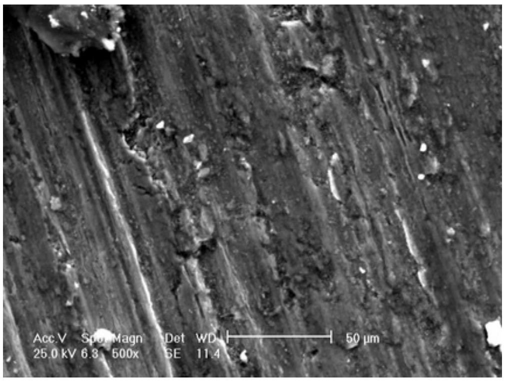

Figure 17. SEM image showing worn surface of ZA-27 as-cast2 alloy

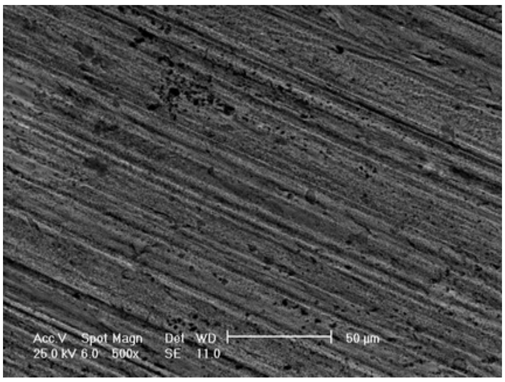

Figure 18. SEM image showing worn surface of ZA-27 HT3

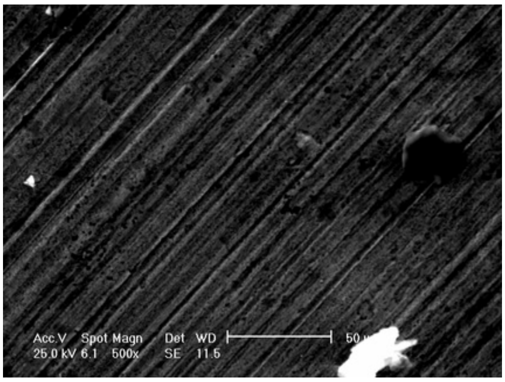

Figure 19. SEM image showing worn surface of ZA-27 HT5

On all the surfaces one can clearly notice the wear scars in the direction of the contact elements motions, what basically represents the consequence of the micro-abrasive wear of alloys specimens with the discs of significantly higher hardness. Besides this wear mechanism, existence of the material transferred to the contact surfaces of discs and the contact surfaces of the alloys made blocks (clearly visible in Figure 16) clearly point to presence of the adhesive wear. In addition, on contact surface one can notice the craters of different depths and shapes, which are the consequence of the fatigue wear.

Even by the superficial glance at the worn surfaces, shown in figures, one can easily notice the morphological differences that correspond to certain types of alloys. To the sand casted alloy and the heat treated alloys correspond relatively smooth surfaces with shallow wear scars. Significantly, rougher worn surfaces correspond to the pressed and the mold casted alloy. On those surfaces, one can notice the rougher wear scars, micro deformation and micro destructions traces.

CONCLUSIONS

The heat treatment, consisted of solutionizing during 3 or 5 hours, and quenching in water, affected significant changes of microstructure, mechanical properties and tribological behavior of ZA-27 alloys in conditions of dry sliding.

To alloys obtained by sand and mold casting, correspond typical dendritic microstructures, of various grain sizes, due to different cooling temperatures. Due to heat treatment of the steel mold casted alloy, it exhibits clear changes in microstructure. Annealing for 5 hours at 370ºC and subsequent quenching produced complete destruction of the dendritic structure. The resulting equilibrium microstructure was unexpected, since the heating time was relatively short in the area of the β-phase.

The heat treatment was manifested through decrease of the tensile strength and hardness and significant increase of the alloy's ductility, while the changes increase with time of holding the alloy at 370^{o}C.

Results obtained for as-cast alloys show, as it was expected, that in the total range of the normal contact forces during the sliding friction without lubrication, the alloy casted in sand, has significantly better tribological properties, as compared to mold cast alloy. However, the subsequent heat treatment showed positive affects on improving the tribological properties of the mold cast alloy, both from the aspect of friction and aspect of wear. The achieved tribological properties significantly superseded the sand cast alloy. The degree of improvement depends on the corresponding annealing duration time.

Results obtained for castings from the permanent molds point to possibility of the batch manufacturing of the high quality casted triboelements, which would be convenient substitutes of the expensive and defficit tribomaterials.

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