THE INFLUENCE OF STRONTIUM ADDITION ON THE TRIBOLOGICAL PROPERTIES OF Zn25Al3Si ALLOY IN BOUNDARY LUBRICATED CONDITION

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Abstract
The zinc-aluminium based casting alloy ZA-27 is well-established alloy and is frequently used materials for sleeves of plain bearings. It has good physical, mechanical and tribological properties. However, one of the major disadvantages is its dimensional instability over a period of time (ageing). To overcome this, the copper in the alloy may be replaced by silicon. Coarsening of the silicon particles is controlled by suitable additions of strontium. The influence of the strontium addition on friction and wear properties in boundary lubricated conditions was done on block-on-disc tribometer. The tests were carried-out for three Zn25Al3Si alloys with variable strontium content (0 wt. %, 0.03 wt. % and 0.05 wt. %), and, for the purpose of comparison, for standard ZA-27 alloy. Tests have confirmed that the wear rate of zinc-aluminium alloys with silicon is lower than the standard ZA-27, and have shown that the strontium addition lowers that rate additionally, with the slight increase of the coefficient of friction.

Keywords: Zn-Al alloys, strontium addition, sliding, boundary lubrication, friction, wear.

INTRODUCTION

Zinc-aluminium (ZA) alloys are zinc alloys with high aluminium content (8 to 28 wt. %). They have been used for decades to produce castings for various applications [1]. The alloy with 25 to 27 wt. % Al (ZA-27 alloy) is characterized by the highest strength and the lowest density of all conventional ZA alloys. In addition, this alloy is distinguished with excellent casting properties and easy machining, as well as with good tribological properties and high corrosion resistance in natural atmospheres [1,2]. Due to the high strength and good wear resistance the alloy is used for making sliding bearings intended for high load/low speed applications [3].
The main disadvantages of ZA-27 alloy are porosity (due to the wide temperature range between liquidus and solidus temperatures), deterioration of mechanical properties at temperatures above 80 °C [1,2] and dimensional instability caused by the presence of copper in the alloy [4]. In order to improve the dimensional stability of ZA-27 alloy, copper in the alloy has been replaced with silicon [5]. Produced Zn-Al-Si alloys were shown to possess higher dimensional stability and more favourable tribological characteristics compared to the standard ZA27 alloy. However, Zn-Al-Si alloys with silicon content above 2 wt. % have shown an increase in porosity, which resulted in the deterioration of mechanical properties of these alloys [5].

Properties of aluminium-silicon alloys were improved due to the modification with strontium [6,7], which brought about strontium addition in the ZA-27 alloy containing silicon instead of copper [8].

The aim of this work was to make a set Zn25Al alloys with 3 wt. % of silicon and different content of strontium (0, 0.03 and 0.05 wt. %), and to examine basic tribological properties of these alloys.

EXPERIMENTAL DETAILS

Materials

Four sets of specimens were used for testing; one was fabricated from the commercial ZA-27 alloy, for the purpose of comparison, and the other three were: Zn25Al3Si alloy, Zn25Al3Si-0.03Sr alloy and Zn25Al3Si-0.05Sr alloy. Technically pure zinc and aluminium were used to obtain the Zn25Al1Si alloys, with the addition of master alloys Al7Si and Al18Si for achieving the desired content of silicon. Strontium was added in the alloys using the master alloy Al10Sr. The alloys were melted in the laboratory electric resistance furnace. The molten alloys (570 °C) were poured in the steel moulds preheated to 200 °C. Immediately before pouring the melts were intensively mixed by hand. Prismatic castings with dimensions 120 x 30 x 20 mm were obtained. Samples for structural, mechanical and tribological examinations were obtained via machining of the castings. The casting procedure was the same for all specimens and materials.

Structural investigations were carried out using optical microscopy on plate-like samples (15 × 15 × 6 mm). The samples were ground using silicon carbide papers of progressively fine grades (P80, P360 and P600 grit) and then polished using a polishing cloth and polishing paste with Al_2O_3 particles. Etching of the samples was performed in a water solution of HNO_3 (9 vol. %). The microstructures are shown in Figure 1. The microstructure of the conventional ZA-27 alloy is dendritic (Figure 1a). Dendrites are complex and consist of the core rich in aluminium (α phase) and the periphery (a mixture of α and η phase). The η phase (containing about 93 wt. % zinc [9]) is located between the dendrites, as indicated in Figure 1a. The solidification rate of the alloy has a large impact on the structure of dendrites and porosity of the alloy. A fine dendritic structure is achieved at higher solidification rates, although with increase in the alloy porosity. In this work casting of the conventional ZA-27 alloy was carried-out in the preheated steel moulds, in order to achieve a favourable relationship between the fineness of structure and porosity.

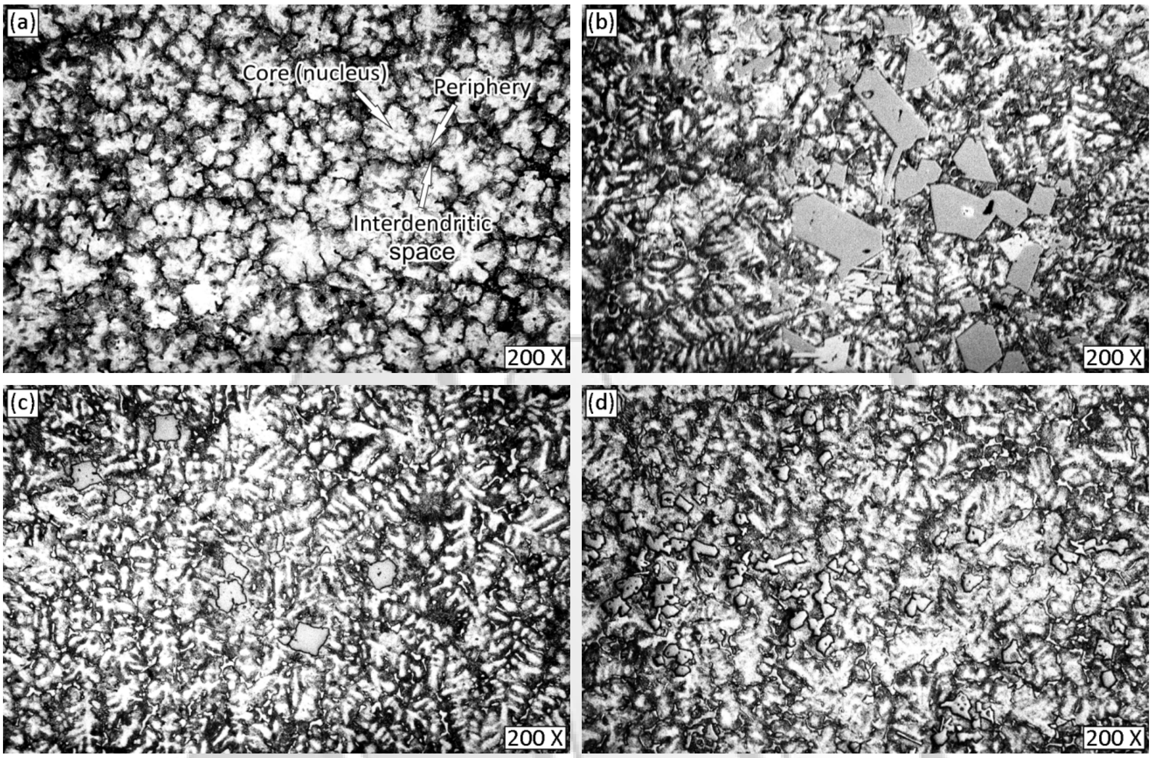

Figure 1. Microstructures of tested materials: (a) ZA-27 alloy, (b) Zn25Al3Si alloy, (c) Zn25Al3Si-0.03Sr alloy and (d) Zn25Al1Si-0.05Sr alloy

Microstructures of Zn25Al3Si alloy and alloys modified with strontium (Zn25Al3Si-0.03Sr and Zn25Al3Si-0.05Sr) are shown in Figures 1b-d, respectively. The addition of silicon in the Zn25Al3Si alloy has resulted with some reduction in the fraction of α phase, as well as with finer dendritic structure, comparing with the conventional ZA-27 alloy. This is in accordance with some previous experiments where Si content was 1 wt. % [10]. However, the shape and size of silicon particles have changed when its content is increased from 1 to 3 wt. %. Silicon particles are in the shape of plates (Figure 1b), and are much larger than the individual micro-constituents in the structure. By adding 0.03 wt. % strontium in Zn25Al3Si alloy, the morphology of silicon particles have changed. Silicon particles in the form of nodules are uniformly distributed in the structure of Zn25Al3Si-0.03Sr alloy (Figure 1c). Further reduction in size of silicon particles, rounding of the particles and an improvement of their distribution in the structure of the alloy has been noticed, when 0.05 wt. % strontium was added in the Zn25Al3Si alloy (Figure 1d).

Hardness of tested materials was measured five times at different locations on each sample, and the averaged values are given in Table 1. The measured hardness of the ZA-27 alloy is in accordance with the value prescribed in the standard [11]. Hardness of Zn25Al3Si alloy reached the hardness of ZA-27 alloy. Zn25Al3Si alloy with 0.03 wt. % strontium is characterized by the highest hardness value. The increase in hardness with addition of strontium can be explained by its influence on the morphology of the silicon particles and their distribution in the alloy structure. The increase in strontium content to 0.05 wt. % resulted with a certain decrease in hardness. It can be assumed that 0.05 wt. % strontium is the limiting value and that further increase of strontium content would have an adverse effect on the hardness of the alloy.

Table 1. Hardness of the zinc-aluminium alloys (average values)

Alloy designation	Hardness HV5
ZA-27	119.0
Zn25Al3Si	119.2
Zn25Al3Si-0.03Sr	125.7
Zn25Al3Si-0.05Sr	114.0

Tribological testing

Tribological tests were carried out on the block-on-disc tribometer under lubricated sliding conditions, in ambient air at room temperature (≈ 28 °C). A schematic diagram of tribometer is presented in Figure 2a. Rectangular blocks of tested materials having 6 mm width and 16 mm length were used as wear test samples. Disc (hereafter referred to as counter body) of 44 mm diameter and 10 mm thickness was made of steel C60E (46 to 48 HRC). Lubrication was provided by revolving of the disc which was sunk into oil container (Figure 2a). Lubricant was mineral engine oil (SAE 15W-40, ACEA E3). Lubricant temperature during the tests was more or less constant (at the end of test it was ≈ 31 °C).

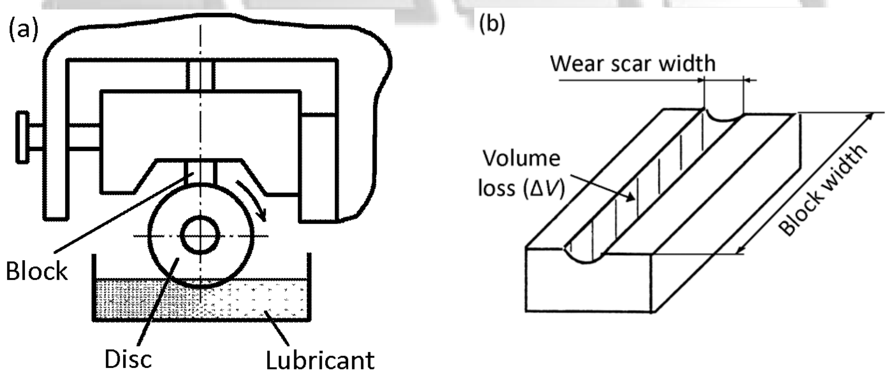

Figure 2. Tribological testing: (a) schematic diagram of the block-on-disc tribometer and (b) block wear scar measurements

Before and after testing, both the block and the counter body were degreased and cleaned with benzene. Wear scars on pins were measured in accordance with ASTM G77 [12] with accuracy of 0.05 mm, after each test to calculate the volume loss ΔV (Figure 2b). The values of oil temperature, friction coefficient, normal and friction force were monitored during the test and through data acquisition system stored in the PC. Tests were carried out at selected test conditions: sliding speed of 0.5 m/s, sliding distance of 1000 m and normal load of 100 N. Calculated pressure at the end of tests was app. 5 MPa for ZA-27 alloy and app. 11 MPa for the other alloys. After testing, worn surfaces of blocks were examined by scanning electron microscope (SEM).

RESULTS AND DISCUSSION

Tribological investigation of these materials was just an initial one, with preliminary results and some more experiments to be done to completely understand its tribological behaviour. In order to achieve a higher confidence level in evaluating test results, three to five replicate tests were run for all the tested materials. The values of the coefficient of friction are presented in Figure 3.

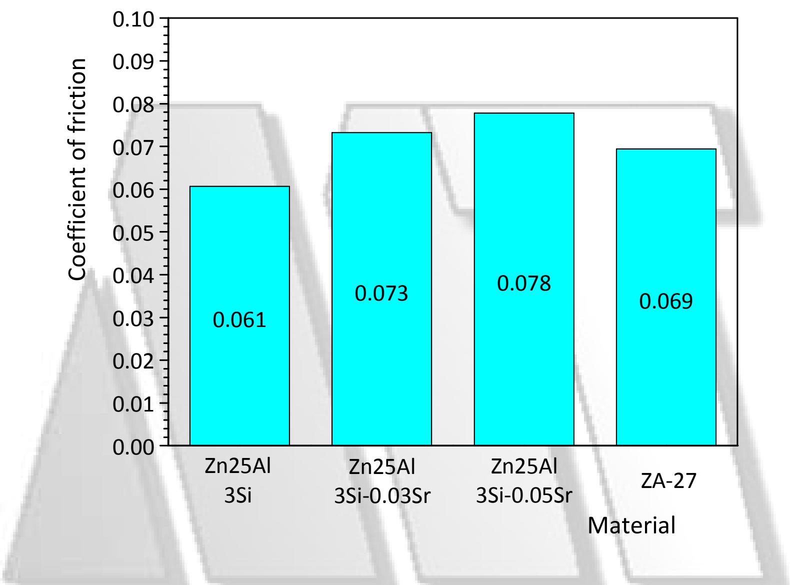

Figure 3. Steady-state averaged values of the coefficient of friction

The obtained values of the coefficient of friction (0.06 to 0.08) suggest that the sliding was performed in boundary lubrication regime (app. values for the boundary lubrication are from 0.05 to 0.15 [13,14]). The hardness of the materials (Table 1) did not have noticeable influence on friction values, since the test was not performed in dry sliding conditions. The value of the coefficient of friction for ZA-27 alloy is in accordance with the data from literature, obtained for the permanent mould casted ZA-27 alloy under somewhat similar conditions [15].

The Zn25Al3Si alloy shows the lowest values of the coefficient of friction, but the replacement of copper with silicon did not lowers the values of the coefficient of friction significantly (comparing to the conventional ZA-27 alloy). Generally all materials show similar values of the coefficient of friction. On the other hand, addition of strontium has negative effect on the coefficient of friction, i.e. with increase of Sr content coefficient of friction also increase. For the addition of 0.05 wt. % Sr coefficient of friction is even higher than for the conventional ZA-27 alloy. The same dependence of the coefficient of friction on Sr content in Zn25Al1Si alloy was obtained in some previous experiments [10].

The dominant wear mechanism, according to the SEM analysis (which is not presented in this paper), is a combination of adhesion and abrasion. Adhesive wear occur in highly-loaded, poorly lubricated sliding contacts, and was noticed at all sliding pairs. Abrasive wear was mostly pronounced at ZA-27 alloy, and this is the reason why this material showed the worse wear resistance (highest wear rate). Risdon et al. [15] tested differently obtained ZA-27 alloys on block-on-disc tribometer with slightly different geometry, i.e. the test specimens were blocks conformed to fit the ring geometry. The normal load was 6.9 MPa; sliding speed 0.15 m/s; lubricant was hydraulic oil (ISO VG 68) and lubricant temperature was 50 °C. Nevertheless the wear rate for the permanent mould casted ZA-27 alloy was app. between 5.2×10^{-4} and 1.7×10^{-3} mm^3/m. This corresponds to the value obtained in this study, which was 1.41×10^{-3} mm^3/m (Figure 4). Wear process was not tracked during the tests, hence, the results in Figure 4 present total wear rates.

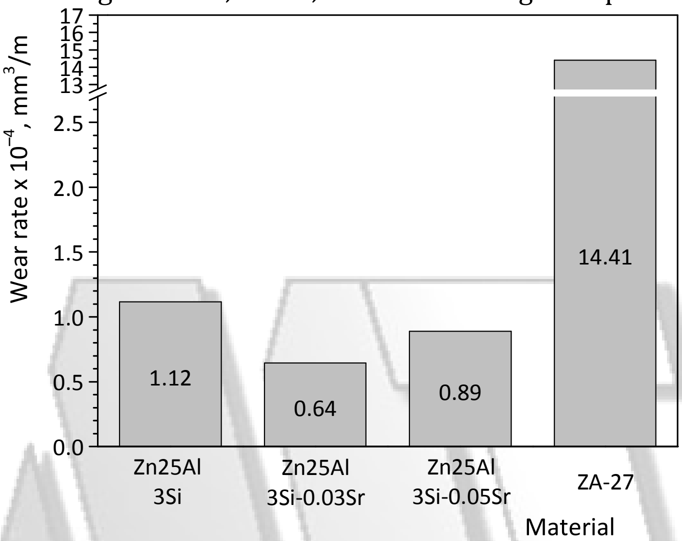

Figure 4. Total wear rates for the tested materials

The wear rate of ZA-27 alloy was more than one order of magnitude higher than the rest of tested materials (Figure 4), which suggests that the addition of Si instead of Cu in conventional ZA-27 alloy significantly improves its wear resistance.

Similar dependence was obtained by Savaskan and Murphy [16], who tested several Zn25Al based alloys with silicon and copper addition. The alloys were produced by gravity casting in the preheated (250 °C) steel mould. The testing conditions were as follows: block-on-disk tribometer (with conformed geometry of the block); normal load of 329 N (7.1 MPa); sliding speed of 1.73 m/s and motor oil (SAE 30) as a lubricant. The authors showed that the as-cast Zn25Al alloy containing 2.7 wt. % Si wear resistance was 4.5 to 12 times (after 1495 km and after 150 km sliding distance) higher than the same alloy containing 3.1 wt. % Cu. It is interesting to note that the wear rates of these two alloys were unproportional to its hardness, i.e. Zn25Al-2.7Si alloy showed higher wear resistance despite the fact that its hardness (81.6 HRF) were lower than the hardness of Zn25Al-3.1Cu alloy (93.7 HRF). Similar to this, in this study the hardness did not show significant influence on the wear rate, since the values of hardness for all materials were very similar (Table 1).

In the study conducted by Jian et al. [8] alloys containing Si instead of Cu also showed wear resistance one order of magnitude higher than the alloy containing Cu. All tested materials (Zn27Al, Zn27Al-2Si, Zn27Al-2Si-0.05Sr and Zn27Al-2Si-0.5Sr alloy) were sand casted. They used block-on-disk tribometer (with conformed geometry of the block); normal load of 8 MPa; sliding speed of 0.21 m/s and grease as a lubricant. The authors also showed that the modification with strontium additionally improves the wear resistance by reducing the silicon particle size. The alloy containing

0.05 % Sr showed the highest wear resistance. At the same time the alloy containing 0.5 % Sr showed wear resistance lower than the alloy that was not modified with Sr (Zn27-2Si alloy), suggesting that over modification with Sr is possible situation. Nevertheless, with further testing, by continuously increasing normal load from 4 to 18 MPa, the influence of strontium addition on wear rate becomes lower and insignificant.

The differences in wear rates between tested materials containing Si are not too high (Figure 4). One of the reasons could be the sufficiently high applied normal load in this study (at the end of test for these materials it were app. 11 MPa), so the full effect of strontium could not be seen clearly. Similar dependence of strontium addition on wear rate at higher normal load was, as previously noticed, observed by Jian et al. [8]. No matter what the addition of strontium did decrease the wear rate, and in the case of 0.03 wt. % Sr it was almost twice lower. The fact that the addition of 0.03 wt.% Sr decreased wear rate more than addition of 0.05 wt.% Sr suggest existence of the optimum value of Sr, which in this case was 0.03 wt. %. In addition this material showed the highest hardness (Table 1).

In a previous study [10] the authors investigated the influence of strontium addition on the wear rate of Zn25Al-1Si alloy. By comparing these results with the results obtained in this study it could be noticed that the wear rates were higher with Zn25-1Si alloy than with Zn25-3Si alloy containing the same strontium wt. %. In addition strontium wt. % in alloy that showed highest wear resistance was different. All this suggest that an optimal content of Si, as well as, optimal content of Sr should be determined for each particular combination, in order to get the best wear behaviour.

CONCLUSION

The microstructure of the Zn25Al3Si alloy was improved with addition of strontium. The addition of strontium (0.03 wt. %) changed the shape of silicon particles from plates to nodules and makes its distribution more uniform. Further reduction in size of silicon particles, rounding of the particles and an improvement of their distribution in the structure of the alloy were obtained by increase of strontium addition from 0.03 to 0.05 wt. %.

The hardness of the alloys containing silicon instead copper were very similar, and for alloy containing 0.03 wt. % Sr the hardness was even higher than the ZA-27 alloy.

Tribological tests have confirmed that the replacement of copper with silicon in the ZA-27 alloy gave greatly improved wear resistance (more than one order of magnitude), while the coefficient of friction value was slightly lower. Strontium modification of Zn25Al3Si alloy improved wear resistance additionally, with the slight increase of the coefficient of friction. The highest wear resistance showed alloy Zn25Al3Si-0.03Sr, which suggest that 0.03 wt. % Sr is an optimal value for this alloy.

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REFERENCES

[1] E.J. Kubel Jr., Expanding horizons for ZA alloys, Advanced Materials & Processes, 132 (1987) 1, 51-57.

[2] E. Gervais, R.J. Barnhurst, C.A. Loong, An analysis of selected properties of ZA alloys, Journal of Metals (JOM), 37 (1985) 11, 43-47.

[3] M. Babic, R. Ninkovic, A. Rac, Sliding wear behavior of Zn-Al alloys in conditions of boundary lubrication, The Annals of University "Dunărea de Jos" of Galați, Fascicle VIII, Tribology, (2005), 60-64.

[4] B.K. Prasad, A.H. Yegneswaran, A.K. Patwardhan, Characterization of the wear response of a modified zinc-based alloy vis-à-vis a conventional zinc-based alloy and a bearing bronze at a high sliding speed, Metallurgical and Materials Transactions A, 27 (1996) 11, 3513-3523.

[5] S. Murphy, T. Savaskan, Metallography of zinc-25% Al based alloys in the as-cast and aged conditions, Practical Metallography, 24 (1987) 5, 204-221.

[6] A.K. Dahle, K. Nogita, J.W. Zindel, S.D. McDonald, L.M. Hogan, Eutectic nucleation and growth in hypoeutectic Al-Si alloys at different strontium levels, Metallurgical and Materials Transactions A, 32 (2001) 4, 949-960.

[7] Q.G. Wang, Microstructural effects on the tensile and fracture behavior of aluminum casting alloys A356/357, Metallurgical and Materials Transactions A, 34 (2003) 12, 2887-2899.

[8] L. Jian, E.E. Laufer, J. Masounave, Wear in Zn-Al-Si alloys, Wear, 165 (1993) 1, 51-56.

[9] H. Lehuy, Mechanical properties of zinc-aluminium alloys extruded in the liquid-solid state, Journal of Materials Science, 23 (1988) 8, 2943-2950.

[10] A. Vencl, I. Bobić, F. Vučetić, B. Bobić, The influence of strontium addition on the tribological properties of Zn25Al1Si alloy in boundary lubricated condition, Tribological Journal BULTRIB, 4 (2014), 25-30.

[11] EN 12844:1998 Zinc and zinc alloys - Castings - Specifications.

[12] ASTM G77-98 Standard test method for ranking resistance of materials to sliding wear using block-on-ring wear test.

[13] A. Rac, *Basics of Tribology*, Faculty of Mechanical Engineering, University of Belgrade, Belgrade (Serbia), 1991, pp. 7-23 (in Serbian).

[14] B.J. Hamrock, S.R. Schmid, B.O. Jacobson, *Fundamental of Fluid Film Lubrication*, Marcel Dekker, Inc., New York (USA), 2004, ch. 1.

[15] T.J. Risdon, R.J. Barnhurst, W.M. Mihaichuk, Comparative wear rate evaluation of zinc aluminum (ZA) and bronze alloys through block on ring testing and field application, SAE Technical Paper 860064, (1986).

[16] T. Savaskan, S. Murphy, Mechanical properties and lubricated wear of Zn-25Al-based alloys, Wear, 116 (1987) 2, 211-224.