Lubricated and Dry Sliding of a Heat Treated Zn-based Alloy

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Abstract. The effect heat treatment on microstructure, hardness, tensile properties and wear behaviour during lubricated and dry sliding of ZA27 the zinc-based alloy was studied. A heat treatment consisting of a short-term annealing in the single-phase region followed by water-quenching markedly improved the elongation, while the strength was maintained high. The wear rate increases with load, and under dry sliding conditions the wear rate is approximately two orders of a magnitude higher than under lubricated conditions. The best wear behaviour displayed by the water-quenched specimens during dry sliding was attributed to a very fine mixture of α and η phases.

Introduction

The high-aluminium zinc-based alloys comprise a new family of die-casting alloys that have proven themselves in a wide variety of demanding applications. These alloys feature clean, low temperature and energy-saving melting, excellent castability, high as-cast strength and hardness, corrosion resistance and equivalent or even superior bearing and wear properties as compared to standard bronze bearing [1]. Many of such applications experience sliding wear situations wherein sliding of the alloy occurs against steel components.

The ZA27 alloy (containing 25-28Al, 2Cu and up to 0.05Mg, the remainder is Zn; the chemical compozition in this paper is given in wt.%), a high strength alloy among family of ZA alloys, is reported to have properties equivalent to some aluminium alloy. Sliding wear of zinc-based alloys has been studied extensively [2-6], but the role of microstructure *via* heat treatment on the wear properties attracted attention only in a few papers [2,4]. Considering these facts, an attempt was made to access the effect of heat treatment on the microstructure, mechanical properties and wear behaviour of ZA27 alloy under lubricated and dry sliding conditions.

Experimental

The ZA27 alloy having a nominal composition of 25Al, 3Cu and remainder Zn, was prepared by the liquid metallurgy route. The melt was overheated to 580^{o}C and poured into a preheated Al_2O_3-based ceramic shell mold prepared for investment casting of tensile test specimens and rectangular specimens for wear tests. The as-cast specimens were annealed for 3 hours at 370^{o}C, followed by water-quenching or furnace-cooling.

Microstructural characterization of as-cast and heat treated alloy was carried out on specimens cut off from the central sprue. After usual polishing procedure (etching was not performed), microstructure of specimens and worn surface after sliding were examined by the scanning electron microscope (SEM) "Philips XL30".

Hardness measurements were carried out on polished specimens at an applied load of 49.05N using Vickers hardness tester. Room temperature tensile tests were performed on an "Instron 1185" mechanical testing machine at a strain rate of $1.3x10^{-3}s^{-1}$. The gauge length of tensile specimens was mechanically polished before testing. Specimens were 3mm in diameter, with 30mm gauge length.

Wear tests were carried out utilizing a disc-on block type "Amsler" wear tester. A high carbon tool steel disc (counter face) having hardness of $60HR_c$ was driven by a motor and the sliding distance was calculated by multiplying the rotation speed by the circumference of the disc. The radius and the thickness of the disc were 22.5 and 11mm, respectively. Before testing specimens were machined to dimensions 25x10x5mm, the counter face was ground and then polished. Specimens were weighed using "Mettler" microbalance with an accuracy of ±0.01mg. Lubricated conditions during the wear tests were executed by immersing the disc in "DAC Galaxmatic SAE90" oil. Wear test conditions were as follows:

- sliding speed: 0.45m/s
- test duration: 18min
- applied load: 294.3, 490.5, 686.7 and 882.9N (for lubricated conditions); 245.3, 294.3, 392.4 and 490.5N (for dry sliding conditions).

Before each test the disc was cleaned with organic solvents to remove contaminants. After wear tests specimens were cleaned thoroughly and weighed again. The wear rate was calculated by a weight-loss method.

Results

The microstructure of as-cast and heat treated specimens is shown in Fig. 1. The microstructure of the as-cast alloy is distinguished by the presence of cored dendrites (Fig. 1a). The dendrite structure of water-quenched specimen (Fig. 1b) is rather changed, i.e. dendrite core (DC) together with interdendrite regions (IR) are reduced to a rather small fraction, whereas a fine mixture (M) of constituents prevails in the microstructure. The furnace-cooled microstructure exhibits a distinct pearlite-like morphology with the complete absence of dendrites (Fig. 1c).

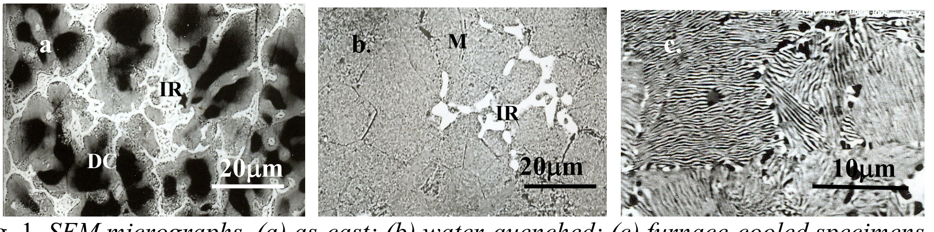

Fig. 1. *SEM micrographs. (a) as-cast; (b) water-quenched; (c) furnace-cooled specimens.*

The results of hardness and mechanical testing (tensile strength and elongation) are given in Table 1. It should be noted that the water-quenched specimens show higher hardness and strength and a marked increase in elongation compared to as-cast and slowly-cooled specimens (furnace-cooled). On the other side, furnace-cooled specimens exhibit the lowest strength and elongation.

Table 1. *Tensile properties and hardness of as-cast and heat treated specimens*

Alloy condition	Tensile properties		Hardness
	Tensile strength [MPa]	Elongation [%]	HV_{10}
As-cast	350	8	92
Water-quenched	360	24	105
Furnace-cooled	323	6	90

The wear resistance of ZA27 alloy expressed through the wear rate as a function of applied load for lubricated and dry sliding condition is shown in Fig. 2 a,b, respectively. The effect of microstructure (as-cast and heat treated conditions) is evident from these diagrams. The wear rate increases with applied load and is much higher (approximately two orders of a magnitude) during dry sliding conditions. Furnace-cooled specimens showed the best wear resistance when lubrication was applied (Fig. 2a). Somewhat less resistant were water-quenched specimens, and at the highest load they approached to furnace-cooled specimens. The least wear resistant were the as-cast specimens. On the other side, water-quenched specimens exhibited best wear resistance under dry sliding conditions (Fig. 2b). At 490.5N load the wear rate of this structure was lower than that of as-cast and furnace-cooled specimens at 392.4 and 294.3N, respectively. The furnace-cooled specimens showed the highest wear rate.

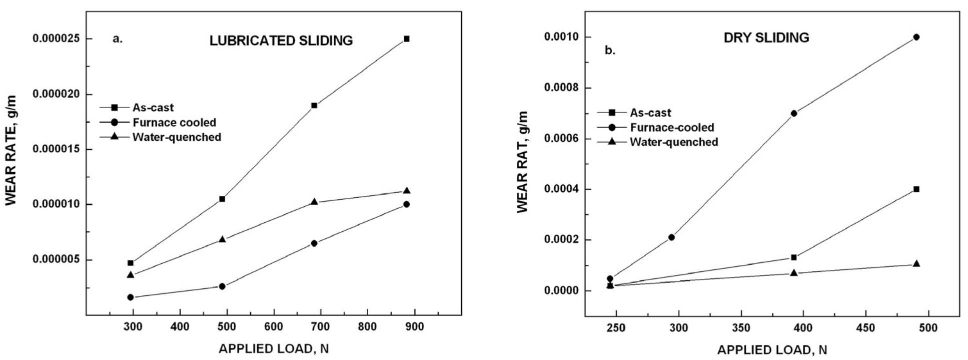

Fig. 2. *The wear rate as a function of applied load for lubricated and dry sliding condition.*

Discussion

The as-cast specimen exhibits a typical dendrite structure where dark areas represent dendrite cores (DC in Fig. 2a), a f.c.c. aluminium-rich solid solution (α phase), while grey areas surrounding dendrite cores are composed of a fine scale eutectoid mixture of α and a h.c.p. zinc-rich (η phase). In addition to $\alpha+\eta$ eutectoid, an intermetallic $CuZn_4$ h.c.p. (ε phase) spreading like a continuous dark tiny web is present in interdendrite regions (IR). This obviously inhomogeneous structure is a result of a solidification under non-equilibrium conditions, i.e. under high values of temperature and concentration gradients.

These parameters have a strong effect on the size and the shape of dendrite branches, chemical composition of dendrite cores, ramification of dendrite branches etc.

Annealing and subsequent heat treatment through the effect of cooling rate from the β phase region (370°C) significantly changed the prior microstructure of the as-cast alloy. Besides some fragments of dendrite core, a fine mixture of globular particles of α and η phases prevails in the microstructure of water-quenched specimens (Fig. 1b). Previous investigations [7] showed that the supersaturated β phase is unstable transforming to very fine α and η lamellae at room temperature. Taking this fact into account it may be concluded that grain boundaries in Fig. 3a belonged to the prior β phase, whereas regions inside grains correspond to a very fine mixture of α and η phases, the result of the decomposition of the β phase that could not be prevented even with high cooling rates. Furnace-cooling from annealing temperature produces quite different microstructure compared to water-quenching. Obviously, the dendrite structure was completely annihilated and the distinct and a rather coarse α+η lamellar eutectoid was formed during slow cooling. Dark and light globular and plate-like particles precipitated at the prior β grain boundaries are the products of the β phase decomposition, i.e. aluminium-rich α phase (dark particles) and zinc-rich η phase (light particles).

The most interesting result concerning the effect of heat treatment is that specimens quenched from 370°C into the water possess high elongation, maintaining tensile strength slightly above the level of as-cast specimens. Slowly cooled specimens are characterized by low strength and low elongation. Considering the microstructural changes during heating and cooling, the increase in elongation in quenched specimens could be ascribed to the very fine dispersion of microconstituents. In the slowly cooled specimens beside coarse eutectoid lamellae, globular and plate-like α and η particles precipitated at grain boundaries may be the origin for the micro cracks formation which leads to the lower elongation.

Under dry sliding conditions the best wear resistance displayed by the quenched specimens seems to 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 in the same time. The as-cast alloy contains primary α dendrites together with eutectoid α +η mixture. Hardness and tensile strength are somewhat lower comparing to water-quenched specimens, and wear resistance is also lower. On the other side, specimens slowly cooled from 370°C are most susceptible to wear exhibiting the highest wear rate. Reason for this behaviour could be in a rather coarse lamellar α+η eutectoid together with α and η phases formed at boundaries of prior β grains. Water-quenched specimens showed the highest values of hardness and tensile strength, but these values of furnace-cooled specimens are the lowest. It is established that the wear loss is inversely proportional to hardness and tensile strength [8]. This means that as strength of the alloy increases the wear loss should decrease. Therefore, the result of this paper is in contradiction with the results reported by Prasad [9] who attributed the lesser wear rate of heat treated specimens to softer structure compared to the as-cast structure.

Lubrication strongly affects the wear behaviour. In comparison to dry sliding, the wear rate under lubricated conditions is much lower indicating a different wear mechanism. In this case the interaction of the lubricant and sliding surfaces is more important factor than hardness and strength of the alloy. Contrary to dry sliding, slowly cooled specimens exhibit the best wear properties. The soft mixture of a coarse α+η eutectoid lamellae has lubricating properties mostly due to the presence of η phase. Apparently, this microstructure contributes to the overall lubrication effect and decreases the material loss. The other two examined microstructures have a lower fraction of α and η phases and, consequently, a lower resistance to wear.

One other factor also influences the different behaviour of lubricated and dry-tested specimens. It was reported that the sliding effects produced by different microconstituents are effective as long as the alloy is thermally stable during tests [9]. During dry sliding much higher temperatures were developed and, as a result, the point where the thermal condition of the alloy becomes unstable is reached earlier causing higher wear rate.

Conclusions

- Annealing followed by heat treatment through the effect of cooling rate from the β phase region (370^{o}C) significantly change the previous as-cast cored dendrite structure.
- A fine mixture of α and η phases with a small fraction of dendrite core was produced by water-quenching, whereas a coarse eutectoid lamellar α+η mixture was obtained after slow cooling.
- Structural changes affect the mechanical properties to a great extent, i.e. a relatively large increase in elongation in combination with high strength was achieved in the quenched specimens. Slow cooling had a detrimental effect on both strength and elongation.
- The wear rate increases with applied load. Under dry sliding conditions the wear rate and the damage of the surface are considerably higher (approximately two orders of a magnitude) than under lubricated conditions. The best wear resistance displayed by the quenched specimens was attributed to breaking of dendrite structure, decreasing fraction of interdendrite regions and formation of very fine mixture of α and η phases. The strength of the alloy seems to play the most important role under dry sliding conditions, i.e. with increasing strength the wear loss should decrease.
- Contrary to dry sliding, slowly cooled specimens exhibit the best wear properties. The soft mixture of coarse α+η eutectoid lamellae has lubricating properties mostly due to the presence of η phase. During lubricated sliding the interaction of lubricant with the sliding surfaces is more important factor than the strength of the alloy.

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