Effects of Silicon Addition and Test Parameters on Sliding Wear Characteristics of Zinc-Based Alloy Containing 37.5% Aluminium

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This study describes a few observations pertaining to the effects produced through the addition of silicon on the tensile and compressive properties and sliding wear response of a zinc-aluminium alloy. The influence of test temperature on the tensile (strength and elongation) properties and sliding speed and pressure on the sliding wear behaviour of the alloys has also been examined. The nature of different microconstituents of the alloys has been taken as a base to explain the characteristics of the specimens. The study shows that addition of silicon to the alloy system becomes beneficial under test conditions involving higher operating temperatures while the trend reverses at low temperatures. The former has been attributed to the thermal stability attributed by the element at elevated temperatures. On the contrary, the predominating microcracking tendency introduced in the alloy system by the element (silicon) leads to inferior properties under low temperature conditions. Moreover, the lubricating and load bearing capabilities of phases like $\alpha$ and $\eta$ become effective towards improving the response of the silicon-free alloy under low temperature conditions only and their positive effects cannot be realized at high temperatures in view of their low melting points. Thus, addition of silicon becomes helpful under specific conditions only.

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I. Introduction

Zinc-aluminium alloys have emerged as potential cost and energy effective substitute materials for several ferrous and non ferrous alloys in a variety of engineering applications\(^{(1)-(4)}\). Mechanical and sliding wear properties of the materials/components become a matter of significant concern amongst many requirements set forth for the applications. Accordingly, characterization of the relevant properties of the potential substitute materials becomes imperative in order to appropriately select them for different applications. As far as zinc-aluminium alloys with large aluminium contents are concerned, so far only three alloy compositions namely ZA8, ZA12 and ZA27, digits in the alloy designations indicating their approximate aluminium content\(^{(5)}\), have been recognized internationally and are in use. Interestingly, their popularity is principally based on their performance under actual working conditions and scientific information with regard to their characteristics still appears to be lacking. Moreover, one of the major shortcomings of the conventional alloy compositions is their property deterioration to a great extent at operating temperatures exceeding $\sim 100^\circ\text{C}\(^{(3)-(4)}\). This in turn limits the use of the alloys in applications involving operating temperatures within the mentioned limit. Although several potential applications exist at present for the conventional zinc-aluminium alloys\(^{(1)-(4)}\), yet improving upon their working temperature limit can greatly widen the horizon of their utilities. Obviously, attempts made towards enhancing the thermal stability of the alloys would serve the purpose. Available information indicates that the thermal stability of the alloys could be made better through alloying them with high melting point elements like silicon, nickel, nickel plus silicon etc. However, very limited efforts\(^{(6)-(21)}\) have been made to explore such possibilities. The majority of studies have focused their attention on Zn–25 to 27 mass% Al-based alloys\(^{(8)-(12)}\) and moreover the elements have been added as partial substitutes to copper. In a recent study, the influence of aluminium content on the mechanical and sliding wear properties of the alloy system has also been investigated wherein limited improvement in the response of the alloys containing 37.5 mass% Al was observed under test conditions involving elevated temperatures\(^{(12)}\). The influence of adding silicon to the alloy composition has also been examined under low temperature conditions in a few studies\(^{(9)-(10)}\).

In view of the above, an attempt has been made in this investigation to understand the influence of adding silicon on the tensile strength and elongation (over a range of test temperatures) and sliding wear response (at different sliding speeds and pressures) of a zinc-based alloy containing 37.5 mass% Al along with copper. The response of the alloys under different test conditions has been explained on the basis of factors like thermal stability and microcracking tendency of silicon and lubricating and load bearing characteristics of remaining microconstituents like $\alpha$ and $\eta$ phases.
II. Experimental

1. Alloy preparation

Alloys were prepared by liquid metallurgy route in the form of 20 mm diameter, 150 mm long cylindrical castings using permanent moulds. Table 1 represents the chemical composition of the alloys.

2. Microscopy

Microstructural studies were carried out on metallographically prepared samples (20 mm in diameter, 15 mm thick) after etching them with diluted aqua regia. A Leitz optical microscope was used for the purpose.

3. Determination of hardness, density and electrical conductivity

Hardness of the specimens was determined with a Vickers hardness tester while density was measured by water displacement technique using a Mettler microbalance. Similarly, electrical conductivity was found with the help of a Technofour type 757 conductivity meter. The data points represent an average of three observations.

4. Compression and tensile tests

An Instron universal testing machine was used for carrying out compression and tensile tests. The compression tests were conducted at ambient temperature on 8 mm diameter, 15 mm length cylindrical specimens. The strain rate adopted in this case was $2.28 \times 10^{-3}$ s$^{-1}$. The specimens subjected to tensile tests were 4 mm in gauge diameter and 22 mm in gauge length. The tensile tests were carried out at 35, 60, 100, 150 and 200°C at a strain rate of $1.52 \times 10^{-3}$ s$^{-1}$. In each case, an average of three observations was considered.

5. Sliding wear tests

Dry sliding wear tests were conducted on 8 mm diameter, 53 mm length cylindrical specimens using a Cameron-Plint (U.K.) pin-on-disc machine$^{[12]}$. The disc in this study was made of EN25 (Fe-0.3 mass% C-0.7 mass% Cr-2.5 mass% Ni-0.5 mass% Mo) steel heat treated to RC 32 hardness. Wear tests were carried out at the sliding speeds of 0.42, 1.38, 2.68 and 4.60 m/s. Pressure on the specimens was increased in steps until the specimen seizure was indicated prior to traversing a predetermined sliding distance of 500 m.

The specimens were cleaned thoroughly and weighed prior to and after the wear tests. A Mettler microbalance was used for weighing the specimens while wear rates were computed by weight loss technique. Three tests were conducted and their average was taken for representing each data point. Temperature rise near the specimen surface was monitored as a function of test duration with the help of a chromel-alumel thermocouple inserted in a hole made at a distance of 1.5 mm from the contacting surface of the specimen.

III. Results

1. Microstructure

Figure 1 represents the microstructural features of the alloys. The silicon-free zinc-based alloy showed primary α dendrites along with eutectoid $\alpha + \eta$ and metastable ε phase (Fig. 1(a), regions marked A, B and arrow respec-

![Fig. 1 Microstructure of (a) the silicon-free and (b) silicon containing zinc-based alloys. [A: α, B: eutectoid $\alpha + \eta$, Arrow: ε and C and D: eutectic and primary silicon particles, respectively].](image)
tively). Addition of silicon led to the formation of eutectic and primary silicon particles (Fig. 1(b), regions marked C and D respectively); rest of the features of the (silicon containing) alloy remained identical to those of the silicon-free specimen (Fig. 1(a)). The microstructural characteristics of the alloy system have been discussed elsewhere. 

2. Hardness, density and electrical conductivity

Table 1 shows the hardness, density and electrical conductivity of the alloys. The presence of silicon led to an increase of the hardness of the alloy while the trend reversed with regard to density and electrical conductivity properties.

3. Compressive characteristics

Figure 2 reveals the reduction in height of the alloys as influence by the applied load under compressive loading conditions. Specific feature to be noted from the figure is the formation of a ‘dip’ in the reduction in height versus load curve in the case of the silicon-containing alloy while no such behaviour was shown by the silicon-free samples. Moreover, the degree of deformation was more in the event of the absence of silicon in the alloy system.

4. Tensile properties

Tensile strength and elongation of the specimens are shown as a function of test temperature in Fig. 3. A reduction in tensile strength with temperature can be noted in the case of both the alloys. However, the property of the silicon-containing specimens was less sensitive to the increasing test temperature as evident from its inferior strength to that of the silicon-free alloy at low temperatures and a reversal of the trend at higher test temperatures. The elongation of the alloys increased with temperature, attained a peak value and decreased at still higher temperatures (Fig. 3). Moreover, the presence of silicon caused the elongation of the specimens to reduce.

5. Sliding wear characteristics

Wear rate of the alloys has been plotted as a function of applied pressure at different sliding speeds in Fig. 4. The wear rate increased with applied pressure and speed. Moreover, the wear rate versus pressure plots assumed two slopes up to the sliding speed of 2.68 m/s wherein the slope was low up to a specific pressure and increased.
Fig. 5 Seizure pressure of the specimens plotted as a function of sliding speed.

Fig. 6 Temperature rise near the specimen surface plotted as a function of test duration at (a) 0.42, (b) 1.38, (c) 2.68 and (d) 4.60 m/s.
noted in the figure. This was followed by a relatively lower rate of temperature rise at longer test durations. Moreover, the silicon-containing specimens attained reduced degree of heating at higher speeds/pressures as compared to the silicon-free alloy, especially so at 2.68 and 4.60 m/s (Figs. 6(c) and (d), respectively), while practically a reverse trend was noticed at lower speeds (Figs. 6(a) and (b)).

Figure 7 shows the maximum temperature rise near the specimen surface as a function of applied pressure at different speeds. The pattern followed by the maximum temperature rise versus pressure curves (Fig. 7) was identical to that of the wear rate versus pressure plots (Fig. 4).

IV. Discussion

The mechanical and wear properties of the zinc-based alloys with and without silicon can be explained on the basis of the nature of their microconstituents like α and η and silicon particles. The α phase (i.e. the aluminium-rich microconstituent) imparts good deformability and load bearing capability to the alloys because of the face centered cubic structure of the phase. On the contrary, the η phase (α-zinc-rich solid solution of aluminium) having hexagonal crystal structure with c/a ratio larger than that of an ideal close packed hexagonal system, i.e. 1.633 provides solid lubrication characteristics by smearing on the mating surfaces during sliding wear and hence enables to maintain mild wear situation. The phase also imparts improved load bearing characteristics. Interestingly, the (α and η) phases are ductile in nature and have low melting points.

It may be mentioned that the presence of hard and high melting silicon particles introduces enhanced microcracking tendency but, at the same time, imparts thermal stability. The predominance of one factor over the other, which in turn is controlled by the test conditions, in fact governs the overall performance of the alloys.

Having discussed the general characteristics of different microconstituents like (α and η) and silicon particles, we can explain the behaviour of the alloys.

High, hardness, low density and less electrical conductivity of silicon led to bring about the corresponding changes in the respective properties of the silicon-containing alloy (Table 1).

Tests involving low temperature conditions led to the predominance of the microcracking tendency of the silicon-containing alloy because of the presence of the silicon particles. This led to inferior tensile properties at low test temperatures (Fig. 3) and a relatively poor wear response at lower speeds (Figs. 4 and 5) in the case of the silicon-containing alloy than the silicon-free samples; the latter was also confirmed through the generation of less frictional heating (Figs. 6(a) and (b)). The appearance of a ‘dip’ in the reduction in height versus applied load plots of the silicon-containing alloy (Fig. 2) indicating the initiation of microcracking (which of course got healed up shortly due to the ductile nature of the phases other than silicon particles) was also because of the microcracking tendency imparted by the silicon particles. Under low temperature conditions, the soft and low melting (α and η) microconstituents performed their roles quite effectively leading to better response of the silicon-free alloy (Figs. 2-5).

Tests involving high temperature conditions made the low melting (α and η) phases quite ineffective in the sense that they tended to flow easily. This proved somewhat beneficial, when within limits, in the presence of hard silicon particles by way of improving the characteristics of the (silicon-containing) alloy to accommodate the silicon particles. In this case, microcracking tendency of the (silicon-containing) alloy was also suppressed. Under the circumstances, silicon became able to impart thermal stability, reduce the flowability of the alloy and share load in operation. As a result, the elevated temperature strength of the silicon containing alloy (Fig. 3) and its wear response at higher sliding speeds (Figs. 4 and 5) involving the generation of larger frictional heat (Figs. 6(c) and (d)) improved over the one not alloyed with the element. However, the generation of excessive (frictional) heat caused the matrix to be too soft to provide support to the silicon particles and as a result flow very easily causing large adhesion of the specimen material to the disc surface. This led to specimen seizure and practically identical wear response of the alloys with and without silicon (Figs. 4 and 5). Improved thermal stability of the silicon-containing alloy was also evident from the lower slope of its tensile strength and elongation versus test temperature curves (Fig. 3) and seizure pressure (resistance) versus
sliding speed (higher speed generates larger frictional heat) plots (Fig. 5).

Initially, the high rate of temperature rise with test duration (Fig. 6) could be attributed to the fragmentation followed by the oxidation of the contacting asperities. Such asperities constitute only a minor fraction of the apparent contacting surface of the specimen in the beginning. Under the circumstances, they are subjected to highly stressed conditions causing damage to them. The broken hard oxidized asperities produce abrasive action\(^{15}\) once they are entrapped on the mating surfaces and hence higher rate of frictional heating is experienced (Fig. 6). However, with the progress of wear tests, the asperity-to-asperity mode of contact changes into area-to-area mode making less severe stressing of the contacting regions\(^{15}\). Moreover, steady state heating is also attained by the specimen surface as the test progresses. These two factors jointly led to the reduced rate of temperature increase at longer test durations (Fig. 6).

V. Concluding Remarks

A critical appraisal of observations made in this study clearly indicates that the response of the alloys under different test conditions can well be explained on the basis of specific characteristics of their constituent phases whose effectiveness is greatly controlled by the conditions of testing.

Under low temperature test conditions, the silicon-free alloy performed better than the one not alloyed with the element since the soft and ductile phases (like \(\alpha\) and \(\eta\)) having low melting points were able to perform their positive effects (load bearing and lubricating characteristics) very effectively. The silicon produced a negative effect by increasing the microcracking tendency of the alloy which further deteriorated the characteristics of the silicon-containing specimens. On the contrary, under high temperature test conditions, the soft, ductile and low melting (\(\alpha\) and \(\eta\)) phases failed to produce their positive effects and facilitated fusion of the specimens with the disc. The presence of silicon particles proved beneficial in this case in view of the increased efficiency of the (\(\alpha\) and \(\eta\)) phases to accommodate the hard and thermally stable silicon particles enabling the alloy to attain suppressed microcracking tendency and better thermal stability i.e. reduced temperature sensitivity of properties. As a result, the silicon-containing alloy performed better than the one not alloyed with the element in this case. Thus, the addition of silicon to the zinc-based alloys could be beneficial as far as their performance at elevated temperatures is concerned.

REFERENCES