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Slurry Wear Characteristics of a Zinc-Based Alloy

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An attempt has been made in this investigation to assess the wear behavior of a zinc-based alloy in slurry. The influence of the sand content of the slurry and traversal speed and distance on the wear response of the alloy has been examined. Tests were also conducted in the liquid-only medium to assess the role played by the suspended sand particles in the medium. Testing the samples in the liquid-only medium (i.e., without sand particles) caused maximum wear rate. It was also observed that an intermediate sand concentration in the liquid exists wherein the samples experienced maximum wear rate (although less than in the liquid-only medium). Further, increasing the speed of rotation of the specimens in the liquid plus sand environments led to higher wear rate while the trend tended to reverse in the sand-free liquid environment. The alloy initially displayed increased wear rate with increasing traversal distance. This was followed by the attainment of the maximum, a decrease in the wear rate and then a steady state value at longer traversal distances. Wear behavior of the alloy under different experimental conditions was further substantiated through the features of the affected wear surfaces and subsurface regions (perpendicular below the affected surfaces).

Keywords material removal mechanisms, slurry wear behavior, zinc-based alloy

1. Introduction

In practice, a variety of working situations exist wherein engineering components encounter muddy environments.[1-7] Soil/mineral engaging/handling machinery components and structural members in coastal areas fall in this category.[4-7] The nature of attack/damage to the component material in such cases is dependent on the characteristic features of the liquid (electrolyte): corrosive nature, shape, size, and content of the suspended solid mass in the liquid, and the mode of working. In general, three modes of wear damage have been observed to be corrosion, erosion, and abrasion.[1-7] Slurry wear testing by sample rotation method is one of the effective ways to simulate the working conditions of soil/mineral processing/handling machinery components.[4-7]

Zinc-based alloys have emerged as potential cost- and energy-effective substitute materials to a variety of ferrous and nonferrous alloys in several engineering applications.[8-10] In many of the applications, the possibility of the components encountering muddy environments exists.[4-7] Thus the assessment of the wear response of the zinc-based alloys in liquid environments with/without suspended solid mass could greatly widen the range of applications of the alloy system. Interestingly, practically no information appears to be available with respect to the behavior of zinc-based alloys in liquid environments (with/without solid suspension) in spite of great potential in this direction.

In view of the above, the wear behavior of a zinc-based alloy has been studied in this investigation. The effects of traversal speed and distance and the concentration of the suspended sand particles in the liquid environment on the wear characteristics of the samples have also been examined. The observed behavior of the alloy under a given set of experimental conditions has further been supplemented with the nature of wear surfaces and subsurface regions (perpendicular below the wear surfaces); the latter also increased understanding of the operating wear mechanisms.

2. Experimental

2.1 Alloy Preparation

The zinc-based alloy (Zn-37.2% Al-2.5% Cu-0.2% Mg) was prepared by the foundry technique in the form of 20 mm diameter, 150 m long cylindrical castings. Cast iron molds were used for solidifying the alloy melt poured at ~615 °C.

2.2 Slurry Wear Tests

Wear tests were conducted on metallographically polished (15 mm diameter, 10 mm thick) samples using the sample rotation method. A schematic view of the test apparatus is shown in Fig. 1. The radius of the circular path of rotation of the samples fitted on the disk was 7.5 cm. Speeds of rotation of the samples used were 600 and 900 rpm, corresponding to linear speeds of 4.71 and 7.02 m/s, respectively. Weight loss measurements were taken at definite intervals in the traversal distance range of 15-500 km. A Mettler microbalance (Mettler, Toledo GmbH, Greifensec, Switzerland), capable of recording the weight of samples up to as small as 10^{-5} g was used for the purpose. The range of variation in weight measurement with the balance was $\pm 2 \times 10^{-5}$ g corresponding to $\pm 0.45 \times 10^{-11}$ m^3 volume of the alloy sample. The samples were thoroughly cleaned prior to and after the wear tests. The liquid electrolyte for conducting the tests comprised 5 cm^3 concentrated sulphuric acid plus 4 g sodium chloride and 10 l water. The physical properties of the test environment were varied by changing the solid-loading fraction (212-300 μm sand) from 0 to 20%, 40%, and 60%.

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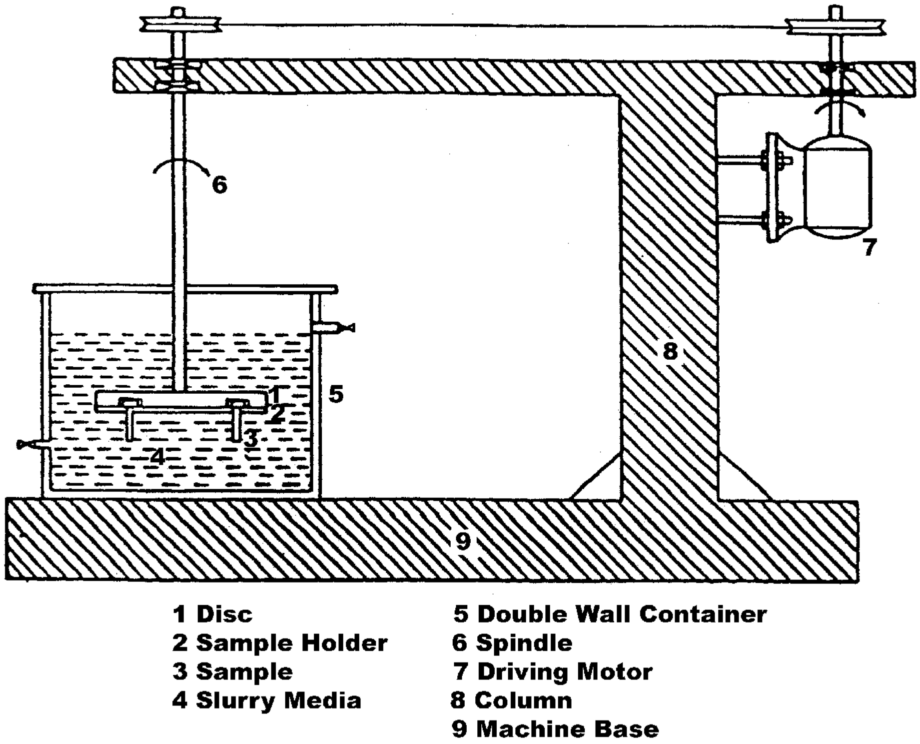

Fig. 1 Schematic view of the slurry wear tester

2.3 Microscopy

Microstructural studies of the samples were carried out after polishing them metallographically and etching with diluted aqua regia. A Leitz optical microscope, (Ernst Leitz, Wetzler GmbH, Germany), was used for the purpose.

Affected surfaces and subsurface regions (perpendicular below the affected surfaces) of typical samples after wear testing were also examined by using a JEOL 35 CF (JEOL Ltd., Tokyo, Japan), scanning electron microscope (SEM). All the specimens were mounted on brass studs and sputtered with gold prior to SEM examination. The samples for subsurface studies were mounted in polyester resin, polished metallographically, and etched with diluted aqua regia before placing them on the brass studs.

3. Results

3.1 Microstructure

The microstructure of the as-cast alloy is shown in Fig. 2. Primary α dendrites (white regions), eutectoid $\alpha + \eta$ (dark patches), and ε (white tiny particles within the dark patches) in the interdendritic regions were observed (regions marked by A, B, and arrow respectively). The η phase is a solid solution of aluminum in zinc containing 1% aluminum at 382 °C, which decreases to ~0.6% at 275 °C and to as low as 0.05% at room temperature.[11] The α-phase is a solid solution of zinc in aluminum in which the solid solubility of zinc decreases from 31.6% at 275 °C to nearly 5% at room temperature.[11] The ε ($CuZn_4$) phase is an intermetallic compound of copper and zinc.[12]

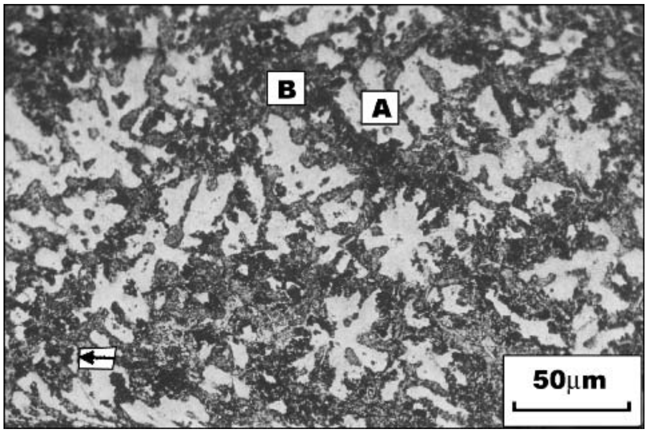

Fig. 2 Microstructure of the alloy sample [A (white regions): primary α, B (dark patches): eutectoid $\alpha + \eta$, arrow (white tiny particles within the dark patches): ε]

3.2 Wear Response

Wear rate of the alloy is shown in Fig. 3(a) as a function of traversal distance in different test environments. Wear rate increased with distance in the beginning, attained a maximum, and decreased thereafter with a further increase in distance when tests were conducted in the liquid-only medium at 7.02 m/s. This was followed by the attainment of a steady state wear rate at still larger traversal distances (Fig. 3a). Further, lowering the traversal speed to 4.71 m/s deteriorated the wear behavior of the alloy in the test environment. Also, the steady state wear rate was not observed at the speed (Fig. 3a). Addition of sand particles to the liquid (electrolyte) followed a practically reverse trend (except at 40% sand in the environ-

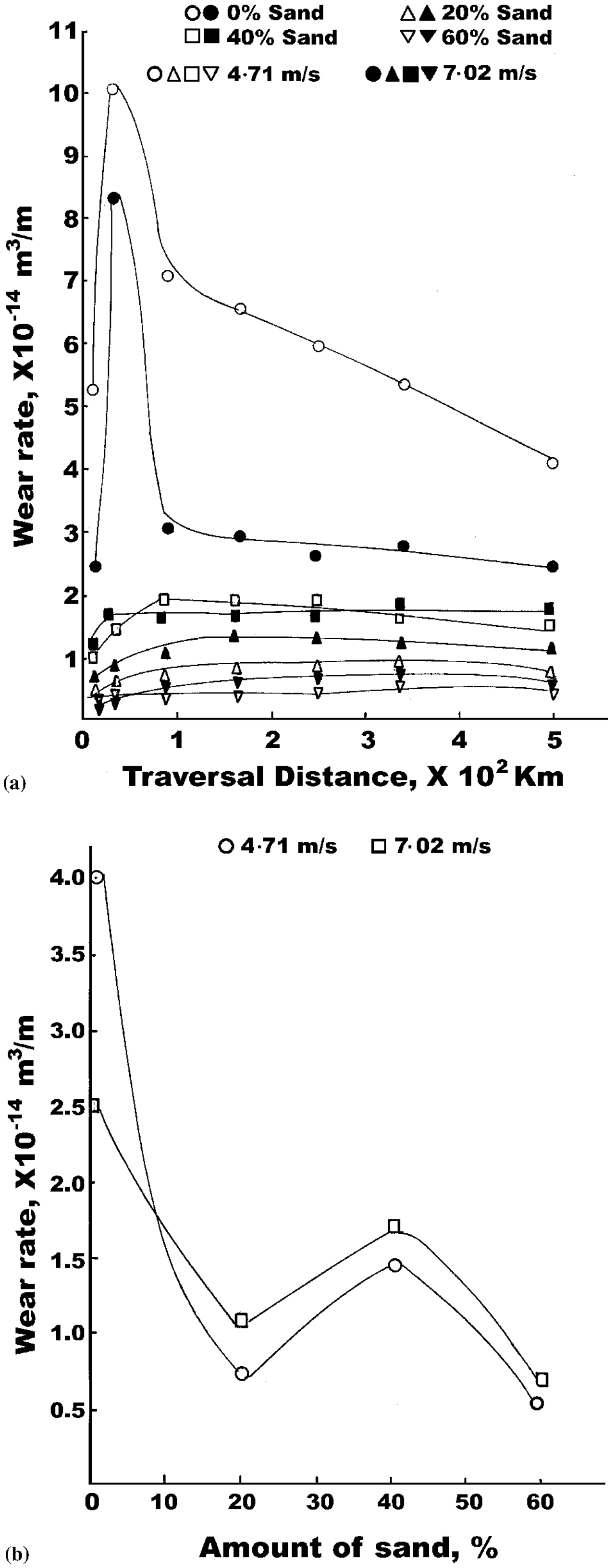

Fig. 3 Wear rate plotted as a function of **(a)** traversal distance at different traversal speeds and slurry compositions and **(b)** sand content in the liquid medium at different traversal speeds at a fixed traversal distance of 500 km

ment leading to a mixed trend) as far as the effect of traversal speed on the wear behavior of the alloy is concerned. Moreover, the wear rate of the samples decreased in the liquid plus sand environment as compared with the liquid-only medium (Fig. 3a).

Wear rate of the alloy at a fixed traversal distance of 500 km as a function of sand content in the test environment is shown in Fig. 3(b). Wear rate decreased with increasing sand content in the beginning (i.e., at 20%) and became more with a further rise in sand concentration up to 40%. The wear rate finally decreased again as the sand content was increased further to 60%; the best wear response was noticed in this environment. A rise in the traversal speed caused inferior wear response of the alloy samples when the tests were conducted in liquid plus (20-60%) sand environment. On the contrary, a reverse trend was noted in the case of testing the specimens in the liquid-only medium (Fig. 3b).

3.3 Wear Surfaces

Figure 4 reveals the wear surfaces of the alloy at the test speed of 4.71 m/s in various environments. Corrosive attack of the liquid electrolyte on the specimen surface was noted to be considerable even after a traversal distance of 15 km in the medium without any presence of suspended sand particles (Fig. 4a). The extent of the predominantly corrosive attack increased to a great extent with the increasing traversal distance under the circumstances (Fig. 4b). The presence of suspended sand particles in the medium decreased the corrosive attack of the electrolyte and erosive and abrasive attack became evident (Fig. 4c-f). The nature and extent of surface damage also depended on the sand content of the environment. For example, erosive attack along with an indication of decreased degree of corrosive attack was more prevalent when the test environment comprised 40% sand (Fig. 4c). A magnified view shows typical erosion indentations (Fig. 4d). Abrasion grooves were also observed to a limited extent on the specimen surface in this case (Fig. 4c, arrow-marked region). The degree of severity of erosive attack decreased when tests were performed in liquid plus 60% sand medium (Fig. 4e) while the abrasive attack became somewhat more prominent (Fig. 4e and f, arrow-marked region). Region marked A in Fig. 4f shows a typical erosion indentation mark.

Wear surfaces of the alloy tested at 7.02 m/s are shown in Fig. 5. The extent of the adherence of the corrosion product in the liquid-only medium was greater at that speed (Fig. 5a) than at 4.71 m/s (Fig. 4b). Further, in the case of testing the samples in liquid plus 40% sand environment at the speed (of 7.02 m/s), erosion pits were more prominent (Fig. 5b) than that at 4.71 m/s (Fig. 4d). Suspension of 60% sand particles in the test medium led to a higher extent of abrasive attack (arrow marked regions) on the specimen surface with increasing speed (Fig. 5c versus 4e).

3.4 Subsurface Regions

Subsurface regions (perpendicular below the affected surfaces) of typical wear tested specimens are shown in Fig. 6. Regions in a process of being detached from the bulk, a typical erosion indentation and the presence of microcracks are evident

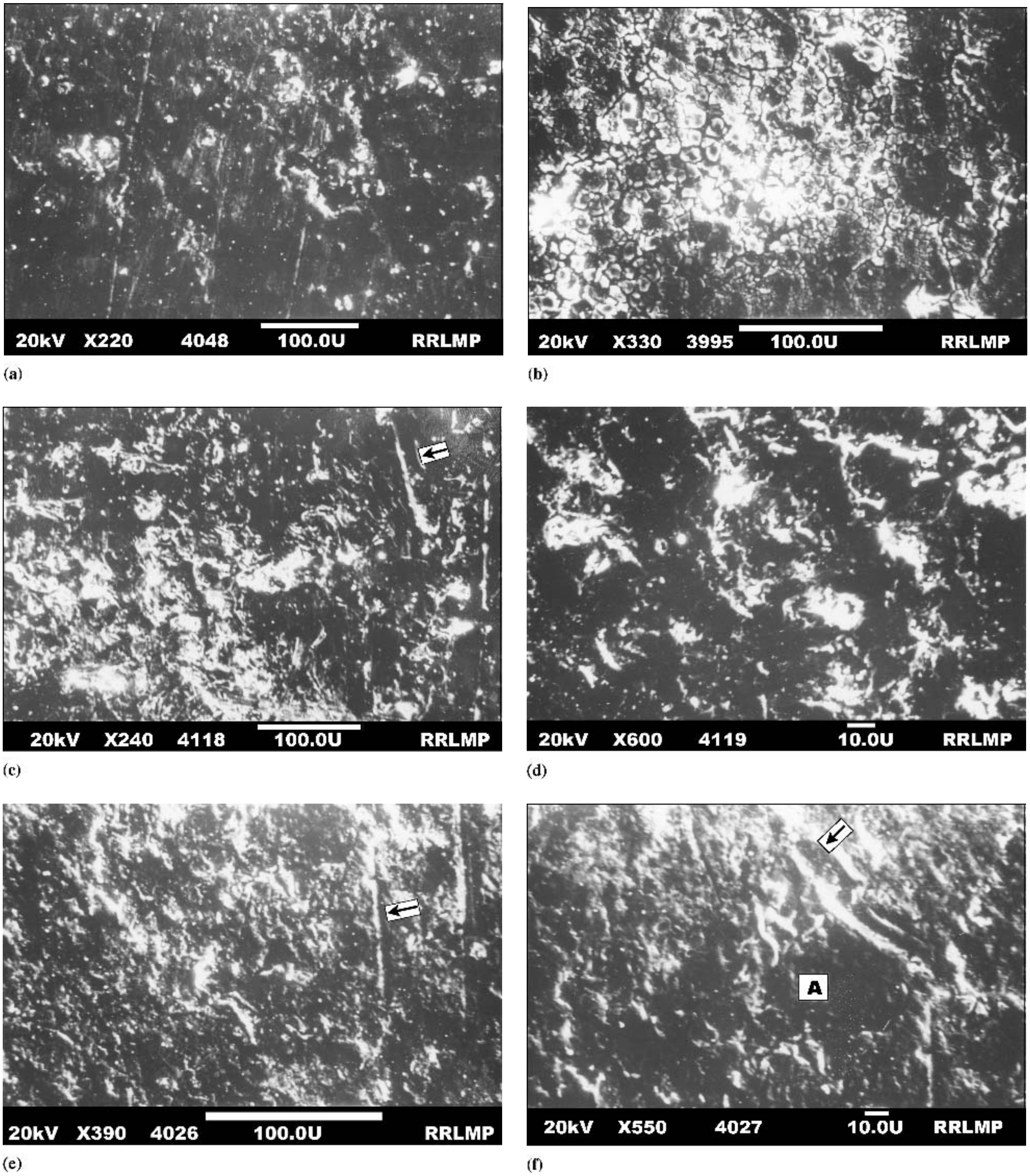

Fig. 4 Wear surfaces of the alloy tested at 4.71 m/s in the liquid medium containing **(a,b)** 0%, **(c,d)** 40%, and **(e,f)** 60% sand for the traversal distance of (a) 15 km, and (b-f) 500 km. [Arrow: abrasion grooves, and A: indentation mark]

near the affected surface (Fig. 6a, regions marked by A, B, and arrow respectively). A typical example of the entrapment of the sand particle (emanating from the liquid plus sand environment) in the indented region may be seen in Fig. 6(b) (region marked C).

4. Discussion

During slurry wear testing using the sample rotation method, the specimens fixed on a disk are allowed to rotate in a liquid of known composition. Important processes causing

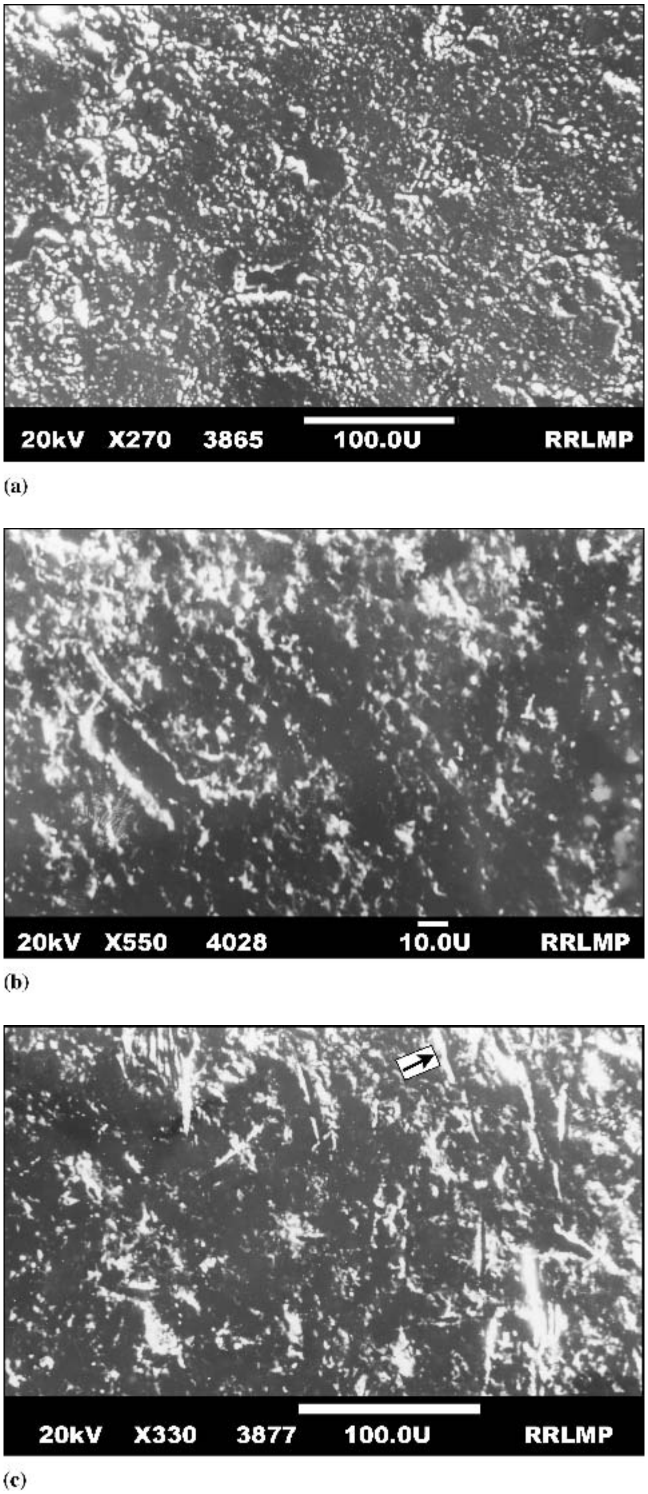

Fig. 5 Wear surfaces of the alloy after testing at the speed of 7.02 m/s in the liquid plus **(a)** 0%, **(b)** 40%, and **(c)** 60% sand medium for a traversal distance of 500 km [arrow: abrasion grooves]

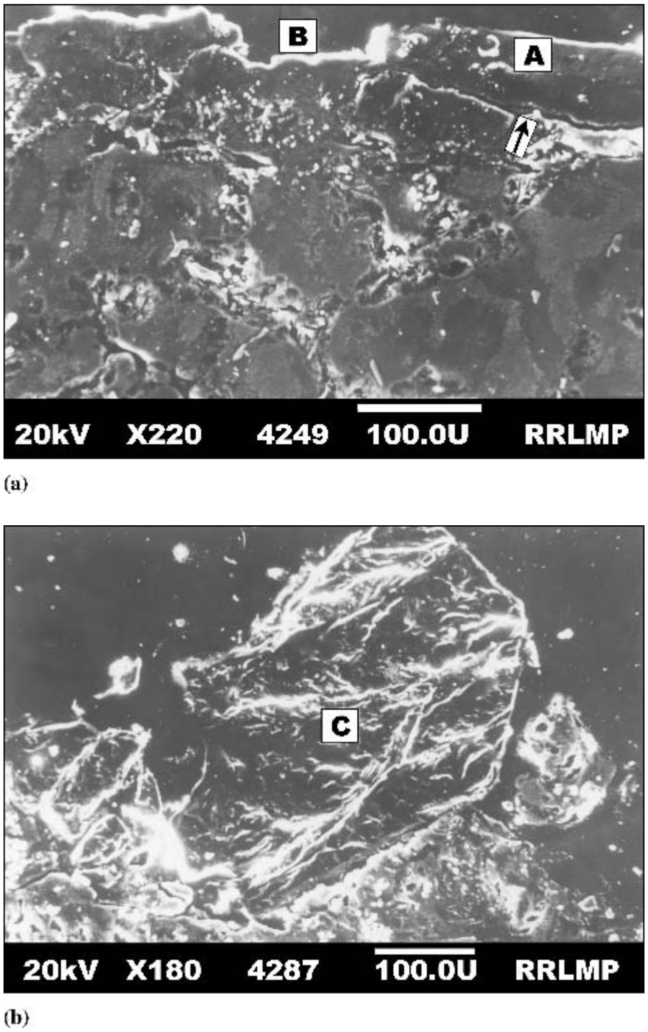

Fig. 6 Subsurface regions (perpendicular below the affected/ wear surfaces) of the samples tested for a traversal distance of 500 km at the speed of 7.02 m/s in liquid plus **(a)** 0% and **(b)** 40% sand medium. [A: region in a process of being detached from the surface, B: indentation mark, arrow: microcracks, and C: entrapped sand particle in an indentation mark]

damage to the specimen surface under the circumstances include the corrosive attack of the liquid and impinging action of the liquid droplets. When the liquid medium contains a suspension of (hard) solid particles, the specimen surface is additionally attacked by the suspended mass.[10,13] Many times, the impinging particles fragment (due to the impact being experienced therein) and become entrapped in the indentations/ cavities.[4,5,9,10,13] In general, the impinging particles leave the target (specimen surface) tangentially wherein the former move on the surface with some impact. Under the circumstances, abrasion of the specimen material takes place through the cutting action of the impinging mass causing material loss.[4,5] The overall influence of the action of the medium on the behavior of the samples depends on two processes namely the sticking of the reaction products (including the impinging solid mass in the case of the liquid suspended with solid particles like sand in the current study) onto the specimen surface and the removal of the products from the site of attack.

Material removal during slurry wear testing has been reported to occur in four stages,[6,10,13] namely (a) the incubation period, (b) accelerated attack, (c) decelerated rate of material loss, and (d) steady state wear rate. The incubation period (stage I) indicates the period until which the passive oxide film remains intact on the specimen surface and resists the corrosive attack of the medium.[6,10,13] The rupture/disintegration of the oxide film takes place facilitating the (corrosive) attack by the medium causing material loss to occur. As the severity of attack increases in due course, deep craters are formed on the surface of the samples leading to accelerated material loss (stage II). With a further increase in test duration, corrosion products adhere at/around the area of attack and gaseous bubbles created/entrapped therein,[6,10,13] retarding the rate of material loss further (stage III). At still longer durations/distances of traversal, the counterbalancing effects of accelerated material loss (through the formation of deep craters, stage II) and the retarding corrosive action (by way of the adherence of the reaction products formed inside/around the pits/cavities as well as through the entrapment of evolved gas bubbles in the cavity, stage III) cause the attainment of steady state wear rate, i.e., stage IV.

The alloy composed of zinc as the major element is expected to be quite prone to the corrosive attack of the liquid medium containing chloride and sulphate ions. It may be mentioned that the greater the volume fraction of the liquid part of the environment, the larger the extent of corrosion on the specimen surface would be. Addition of non-corrosive solid (sand) particles in the liquid medium would reduce the corrosivity of the environment, and the erosive and abrasive actions[4-6,9,10,13,14] of the medium would be more severe. Further, the overall influence of adding sand on the extent/rate of material loss would depend on whether the reduction in the corrosive attack is predominated by the abrasive and/or the erosive attack of the medium. Thus, the addition of eroding/abrading mass in the liquid medium would lead to less wear rate if the liquid were highly corrosive in nature. On the contrary, if the environment has negligible corrosivity, then the addition of the solid suspended particles would lead to increased wear loss.[10,13]

The highly corrosive nature of the liquid part of the medium led to quick breakage of the passive oxide film[9,10,13] on the specimen surface. This was also evident from the corrosive attack of the medium shortly after starting the test (Fig. 4a). As a result, the incubation period passed before the first observation was made, and hence no incubation period could be noticed in the present investigation (Fig. 3a).[6,10,13] The initial higher rate of enhancement in wear rate with the traversal distance in the liquid-only medium (Fig. 3a) could be attributed to the considerable corrosive attack on the specimen surface (Fig. 4b). On the contrary, a reduction in wear rate at still larger traversal distances (Fig. 3a) was due to the adherence of the reaction products around the attacked regions on the specimen surface (Fig. 4b) and entrapment of evolved gaseous bubbles in the affected regions.[10,13] Entrapment of (fragmented) sand particles in the crevices/indentation marks (Fig. 6b) also could have attributed to decreased wear rate (Fig. 3a). Attainment of steady state wear rate (Fig. 3a) resulted from the counterbalancing effects of the corrosive attack of the medium (causing higher wear rates) and entrapment of gas bubbles and corrosion products on the specimen surface (leading to reduced wear rate), as explained earlier. The presence of the suspended sand particles in the medium reduced the extent of the increase in wear rate with distance (Fig. 3a) due to the decreased severity of the corrosive attack of (the liquid part of) the test environment (Fig. 4c-f versus 4b, and 5b and c versus 5a). Erosion indentations and abrasion grooves (Fig. 4c, e-f and 5c) suggest the erosive and abrasive attacks of the suspended sand particles in the (liquid plus sand) environments. The abrasive attack appeared to be somewhat more prominent at the maximum sand content (60%) of the medium (Fig. 4e-f and 5c) due to a decreased mobility of the sand suspension.[4,5] Under the circumstances, the eroding tendency of the test medium became less severe as is also evident from Fig. 4(e-f) and 5(c).[4,5] Indentation effect was more predominant at lower sand content (40%) wherein the sand particles enjoyed greater mobility to indent the surfaces (Fig. 4d and 5b).[4,5] A decrease in the wear rate of the samples in spite of the erosive/abrasive attack of the suspended sand particles in the medium, as compared with the liquid-only environment (Fig. 3), suggests the predominance of the corrosive attack of the liquid part of the medium over the abrasive/ erosive attack of the sand particles. This was also responsible for a relatively lower rate of increase in wear rate in the liquid plus sand medium in the beginning and the absence of a sharp decrease in wear rate with a further increase in the traversal distance therein (Fig. 3a). A decrease in wear rate with increasing traversal speed in the liquid-only environment (Fig. 3a) could be attributed to the less severe erosive/corrosive attack of the medium. This was also evident from the reduced surface damage of the specimens at the higher traversal speed (Fig. 4b versus 5a). On the contrary, the erosive/corrosive action of the sand particles suspended in the medium became somewhat more severe at a higher speed.[4,5] This led to higher wear rates at the (high) speed (Fig. 3) as also evident from larger surface damage in this case (Fig. 5b, c versus 4c-f).

The material removal mechanism operating in the current study seemed to be predominantly corrosion in the liquid-only medium (Fig. 4a-b and 5a) while erosion and abrasion also contributed to material loss in the liquid plus sand environments (Fig. 4c-f and 5b-c). Microcracking of the region surrounding an erosion/corrosion pit (Fig. 6a) was also thought to be responsible for material loss.

An appraisal of the observations made in this investigation suggests that slurry wear response of the (zinc-based) alloy studied is dependent on parameters like the sand content of the medium and traversal speed and distance. Interestingly, addition of sand particles to the liquid medium decreased the wear rate while intermediate sand content caused maximum rate of material loss (although less than in the liquid-only medium). The observations could be explained on the basis of the predominance of the operating wear mechanism(s) under a given set of experimental conditions.

5. Conclusions

1) The wear rate of the samples increased sharply with distance in the beginning of the tests and attained the maximum when tests were conducted in the liquid-only medium. This was followed by an equally sharp rate of reduction in wear rate thereafter. The rate of reduction in wear rate decreased at larger traversal distances at 4.71 m/s whereas a steady state wear rate was observed at 7.02 m/s.

2) In the liquid plus sand media, wear rate increased with distance initially. This was followed by the attainment of a practically steady state wear rate at larger traversal distances.
3) Addition of sand particles in the liquid medium reduced the wear rate of the samples. Further, maximum wear rate was noted at an intermediate sand content (40%), although less than in the liquid-only medium. Addition of maximum amount (60%) of sand in the (liquid) environment led to least wear rate.
4) Wear behavior of the alloy deteriorated with decreasing speed when tests were performed in the liquid-only medium while the trend reversed in the liquid plus sand test environments.
5) The wear surface characteristics agreed with the observed behavior of the alloy under different experimental conditions.
6) The predominant wear mechanism in this investigation was observed to be corrosion; erosion and abrasion played a secondary role.

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