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Effect of Impact Angle on Erosive Abrasive Wear of Ductile and Brittle Materials

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***Abstract*—**Erosion and abrasion are wear mechanisms reducing the lifetime of machine elements like valves, pump and pipe systems. Both wear mechanisms are acting at the same time, causing a "Synergy" effect, which leads to a rapid damage of the surface. Different parameters are effective on erosive abrasive wear rate. In this study effect of particle impact angle on wear rate and wear mechanism of ductile and brittle materials was investigated. A new slurry pot was designed for experimental investigation. As abrasive particle, silica sand was used. Particle size was ranking between 200-500 µm. All tests were carried out in a sand-water mixture of 20% concentration for four hours. Impact velocities of the particles were 4.76 m/s. As ductile material steel St 37 with Vickers Hardness Number (VHN) of 245 and quenched St 37 with 510 VHN was used as brittle material. After wear tests, morphology of the eroded surfaces were investigated for better understanding of the wear mechanisms acting at different impact angles by using Scanning Electron Microscope. The results indicated that wear rate of ductile material was higher than brittle material. Maximum wear rate was observed by ductile material at a particle impact angle of 30^0 and decreased further by an increase in attack angle. Maximum wear rate by brittle materials was by impact angle of 45^0 and decreased further up to 90^0. Ploughing was the dominant wear mechanism by ductile material. Microcracks on the surface were detected by ductile materials, which are nucleation centers for crater formation. Number of craters decreased and depth of craters increased by ductile materials by attack angle higher than 30^0. Deformation wear mechanism was observed by brittle materials. Number and depth of pits decreased by brittle materials by impact angles higher than 45^0. At the end it is concluded that wear rate could not be directly related to impact angle of particles due to the different reaction of ductile and brittle materials.

***Keywords*—**Erosive wear, particle impact angle, silica sand, wear rate, ductile-brittle material.

I. INTRODUCTION

EROSION wear is the removal of the material from the target after many cycles of impacting particle to the surface in a particle-liquid medium. Erosion failure analysis was investigated first by Finnie [1], [2] and Bitter [3], [4]. Erosion wear has a dominant affect in pump, pipes, valves and sharp corners in the fluid transportation systems. To reduce the effect of wear, different methods are applied like; using suitable materials, new processing techniques and modified surface treatments and coatings [5], [6]. Many parameters are effective on erosive wear such as liquid type, solid particle size and shape, amount of solid particles in the liquid, particle impact speed and attack angle, medium temperature [7]-[10]. Also material properties; hardness and toughness of material have a major role on wear of the material [11], [12]. To determine the effect of different parameters on erosion wear, several test methods are developed [13]-[15].

Effect of impact angle on wear rate and wear mechanism is very important. Different researchers have investigated the effect of impact angle on wear rate and wear methodology [16], [17]. Neilson et al. [18] developed an equation emphasizing the relation between wear rate and attack angle of the particle. Desale et al. [19] observed that maximum wear rate of a ductile material is between 15^0-30^0 impact angle which decreases continuously with further increase of the attack angle up to 90^0. Desale et al. [20] investigated aluminum (90 VHN) and stainless steel (210 VHN) and observed maximum wear rate at angle as 15^0 and 22.5^0 impact angles for aluminum and 304L steel, respectively. According to different scientists [21]-[23], maximum wear rate of ductile materials were observed by particle impact angles between 15^0 and 40^0, while brittle materials such as glass, showed a maximum wear rate at 90^0.

According to [24], by the impact of particles normal to the target surface, deformation wear is produced and by particle velocity parallel with the surface is defined as cutting (microploughing) wear. Beside impact angle, material properties; hardness and toughness have also a strong effect on wear mechanism [23]-[25]. Unfortunately very limited studies were carried out to investigate effect of material hardness on erosion wear rate and mechanism. Oka [26] performed experiments to different materials to estimate wear rate by using sand blast type erosion test rig, by reaching velocities up to 130 m/s, but this impact velocities are not realistic values. Only maximum velocity of 20 m/s is reached in pumps or valves where erosion-corrosion is observed. Researches on the effect of both attack angle and hardness of metal materials on wear rate simultaneously has been investigated very limited [23]. Clark et al. [27] concluded that by increase of material hardness, not only wear rate increased, but also deformation wear rate increased with increase of impact angle by using test environment as diesel oil. But [27] used Pyrex glass as brittle test material and not hard metal, which is not a realistic approach because metallic materials are widely used in pumps and pipes.

The aim of the presented research is to investigate the effect of impact angle and metallic material hardness on wear rate and mechanism. The investigated materials were non-heat treated and quenched St 37.

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II. SLURRY TANK AND MIXTURE DESIGN

To determine the effect of different parameters on erosive-abrasive wear mechanism, a test tank was designed, which has a diameter of 242 mm. The set-up consists of three baffles, a propeller, two specimens and a holder. The function of the propeller is to prevent precipitation of the hard particles during the rotation of the propeller at the bottom of the tank and to suspend the particles homogenously in the liquid-solid mixture. The propeller is fixed close to tank surface to prevent accumulation of the sand at the bottom of the tank. Baffles are added to prevent rotational movement of the hard particles. This will cause an upwards movement of the particles resulting in suspension inside the liquid, which causes a secondary flow. This secondary flow causes a homogenous liquid-solid mixture, which is desired for a realistic test analysis. Samples are fixed on the holder and their position can be changed to determine the effect of impact angle on specimen surface. The main dimensions of the test set-up can be seen in Fig. 1.

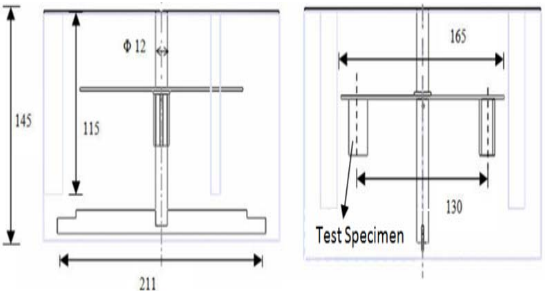

Fig. 1 Main dimensions of the set-up

Test analyses were carried out at 700 rot/min. As wear specimens St 37 steel was used. To increase the hardness of St 37, material was heated up to 850 ^{0}C and then quenched. Shimadzu microhardness tester with a Vickers indenter was used for determining the microhardness (HVN) of the materials. Hardness values of non-heat treated and quenched St 37 were measured as 245 HVN and 510 HVN, respectively. The specimen sizes were 20 mm x 35 mm and the thickness is 4 mm. Specimens were polished with up to # 1000 emery paper and alumina. Wear specimens are cleaned with tap water, rinsed in acetone and dried with hot air blower before and after each test. Mass loss of the wear specimens before and after 4 hour tests is measured by an electronic balance having least count of 0.01 mg. All tests were carried out in 20% weight concentration of hard particle-water mixture. As hard particle, silica sand was used. Particle average size of silica sand was 350 µm. To eliminate the effect of rounding of sand particles and decreasing wear effect, the slurry was changed ever one hour. The mixture is rotated by using a drilling machine having potentiometer and electronic speed control and the rotation velocity is also measured by a tachometer. Particle impact velocity is 4.76 m/s.

III. RESULTS

A. Wear Rate

To determine the effect of hardness on wear rate, non-heat treated St37 (VHN 240), quenched C45 steel (VHN 850) and quenched and heat treated C45 at 400 ^{0}C for one hour (VHN 450) were used. Average particle size was 650 µm. The wear rate of the specimens can be seen in Fig. 2.

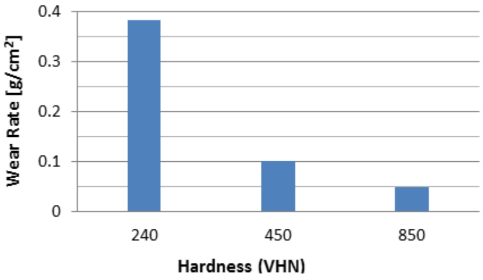

Fig. 2 Effect of material hardness on wear rate

In Fig. 2 it can be seen that wear rate decreases with increase of material hardness. St 37 (240 VHN) showed lowest wear resistance. By increasing hardness value from 240 to 850 VHN, wear rate decreased almost eight times.

To determine the effect of impact angle on wear rate of ductile and brittle materials, tests were performed. The mass loss of the wear specimens measured after 4 h exposure at 4.76 m/s velocity for different particle impact angles on wear rate can be seen in Figs. 3 and 4.

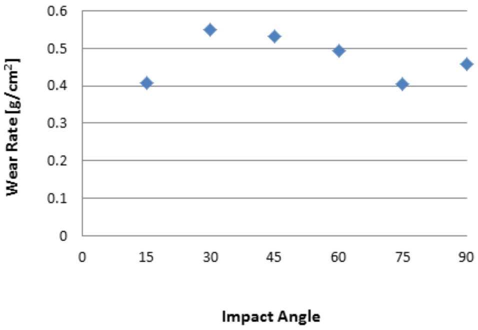

Fig. 3 Effect of impact angle on wear rate of non-heat treated St 37

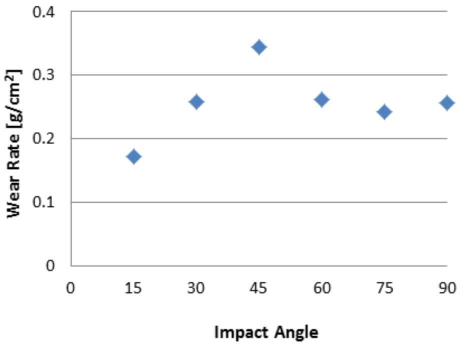

Fig. 4 Effect of impact angle on wear rate of quenched St 37

In Figs. 3 and 4 it can be seen that effect of impact angle on wear rate of different materials indicates different characteristics. From Fig. 3 it can be concluded that wear rate of non heat treated St 37 increased with impact angle and reached maximum value at 30^0. By further increase of impact angle, wear rate decreased and reached minimum value at 75^0. Interesting is to examine that wear rate decreases slightly with increase of impact angle after 30^0. By quenched St 37, wear rate increased by increase of attack angle and reached maximum value at 45^0. By further increase of impact angle, wear rate of heat treated St 37 decreased sharply. From Figs. 3 and 4 it could be concluded that by an increase of material hardness, wear rate decreases and maximum wear rate impact angles increases. This statement is in accordance with [22], [23].

B. Wear Surface

To determine the wear mechanisms at different impact angles on ductile and brittle materials, scanning electron microscope (SEM) views of worn surfaces were analyzed. The SEM photographs at different orientation angles can be seen in Figs. 5-9. By worn surface investigation, impact angles of maximum and minimum wear rate values of the analyzed materials are considered.

In Figs. 5-7, SEM images of worn surfaces of ductile material at impact angles of 30^0 and 75^0 can be seen. In both specimens craters, formed by the abrasive particles can be clearly seen. The number of craters in worn surface of particle impact angle of 30^0 is more compared with specimen with a particle attack angle of 75^0. On the contrary, the depth of the craters in specimen with impact angle of 30^0 is less compared with specimen with a particle attack angle of 75^0. Ploughing worn mechanism is detected in worn surface of particle impact angle of 30^0, which is typical for ductile materials at low impact angles. Microchip formation at impact angle of 30^0 can be clearly seen in Fig. 5 (b) (white arrow), which are typical marks of low impact angles of ductile materials. Microcracks on the surface were detected by ductile materials as can be seen in Fig. 7 (white arrows). These cracks are nucleation centers for crater formations.

In Figs. 8 and 9, SEM images of worn surfaces of brittle material at impact angles of 45^0 and 75^0 can be seen. In both specimens, pits formed by the abrasive particles can be clearly observed. The number and depth of the pits in worn surface of particle impact angle of 45^0 is more compared with specimen with a particle attack angle of 75^0. Crack formation on brittle material surface is not detected. Deformation mechanism is detected in worn surface of particle impact angle of 75^0, which is typical for brittle materials at high impact angles.

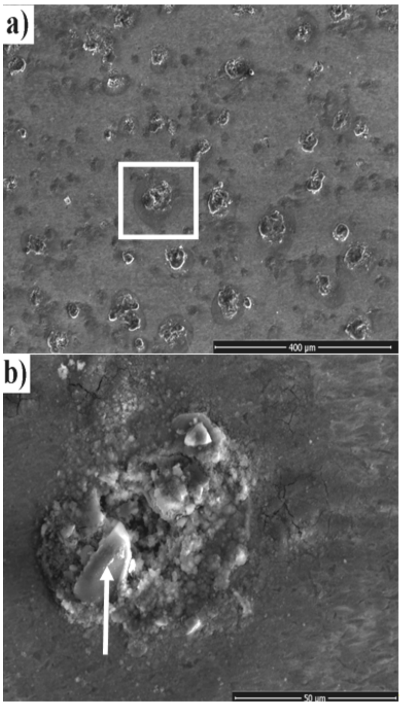

Fig. 5 SEM observations of non-heat treated St 37 samples at impact angle of 30^0 (a) x400, (b) x3000 magnification

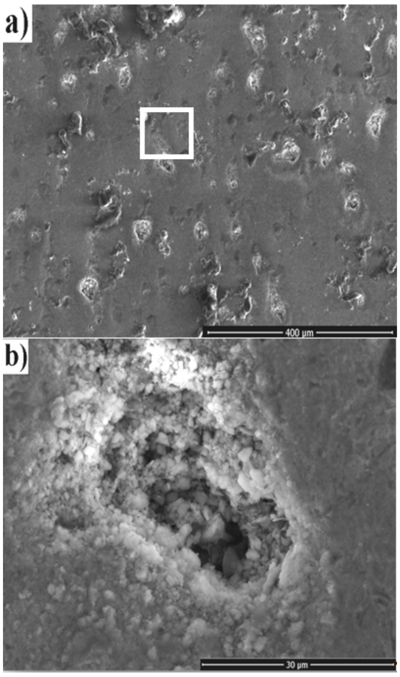

Fig. 6 SEM observations of non-heat treated St 37samples at impact angle of 75^0 a) x400, b) x6000 magnification

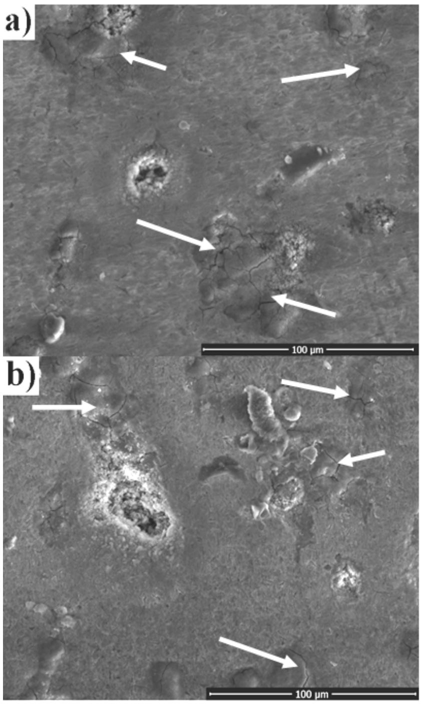

Fig. 7 SEM observations of non-heat treated St 37samples at impact angle of (a) 30^0 (x1600 magnification) and (b) 75^0 impact angles (x1500 magnification)

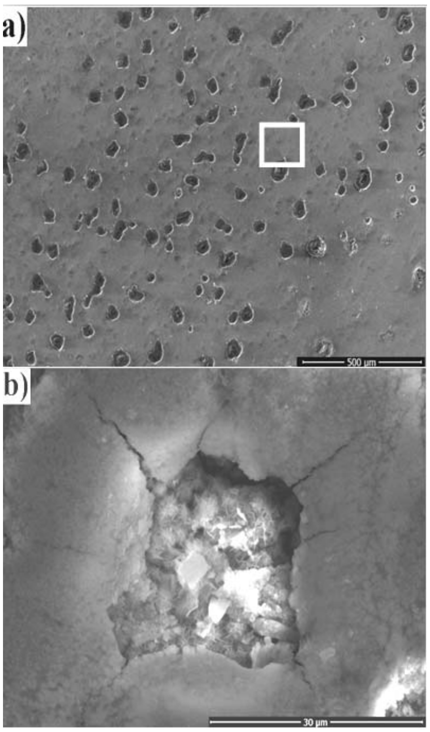

Fig. 8 SEM observations of quenched St 37 samples at impact angle of 45^0 a) x200, b) x6000 magnification

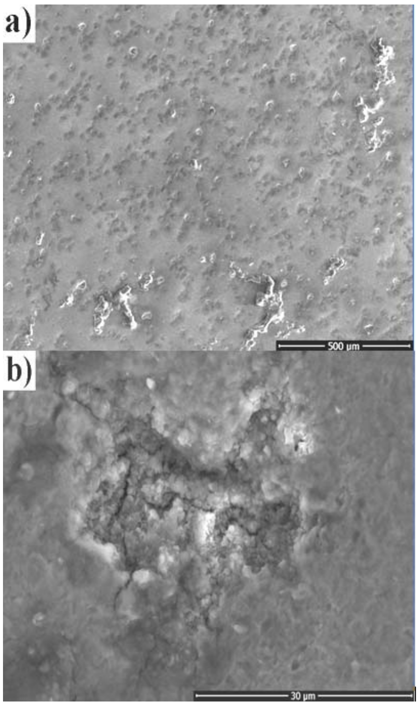

Fig. 9 SEM observations of quenched St 37 samples at impact angle of 75^0 a) x200, b) x6000 magnification

IV. CONCLUSION

The aim of the presented research was to investigate the effect of impact angle of hard particle and metallic material hardness on wear rate and mechanism. The investigated materials were non-heat treated (245 VHN) and heat treated-hardened St 37 (510 VHN). The results indicated that wear rate of ductile material was higher than brittle material. Maximum wear was observed by ductile material at a particle impact angle of 30^0 and decreased by further increase of impact angle. On the contrary, wear rate increased by brittle materials by an increase in impact angle and reached maximum value at 45^0 and decreased by increase of attack angle. Number of craters in ductile material worn surface of particle impact angle of 30^0 is more compared with specimen with a particle attack angle of 75^0, but the depth of the craters in specimen with impact angle of 30^0 is less compared with specimen with a particle attack angle of 75^0. Ploughing worn mechanism is detected in worn surface of particle impact angle of 30^0, which is typical for ductile materials at low impact angles. Microcracks on the surface were detected by ductile materials, which are nucleation centers for crater formation. The number and depth of pits in worn surface of particle impact angle of 45^0 in brittle materials was more compared with specimen with a particle attack angle of 75^0. Crack formation on brittle material surface was not detected. Deformation mechanism was detected in worn surface of particle impact angle of 75^0, which is typical for brittle materials at high impact angles. At the end it is concluded that wear rate could not be directly related to impact angle of particles due to the different reaction of ductile and brittle materials. This study will be developed by investigating the effect of both impact velocity and impact angle of ductile and brittle materials on wear rate.

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