Subsurface Behavior of Ductile Material by Particle Impacts and its Influence on Wear Mechanism

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Subsurface behavior of ductile material by particle impacts and its influence on wear mechanism

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Abstract

Erosion is observed in many industrial situations such as pneumatic conveying pipelines, shot peening and sand blasting where interaction between particle and surface is expected. A number of particle impact parameters and material surface properties are involved in the erosion process. Extensive studies have been conducted to understand the effects of the process parameters on erosion; however, only limited studies can be found in the literature associated with material surface and subsurface properties. In order to get a better understanding of the material surface and subsurface behaviour due to particle impacts for different parameters, erosion tests were performed for different impact angles and different particle velocities using a micro-sandblaster. Angular silicon carbide (SiC) particles were impacted on two different ductile surfaces, mild steel and aluminium, with a constant particle flux. Wear mechanisms were studied in terms of particle kinetic energy. Subsequently, the worn surfaces and their cross-sections were observed using scanning electron microscope (SEM) to relate the subsurface damage characteristics to different impact conditions, and to wear mechanisms. Results showed that at a lower impact angle, material was removed through cutting mechanism, while at a higher angle; material removed through predominantly deformation process. Also, subsurface cracking and subsurface damage were observed up to a certain depth from the worn surface. It appears both the depth of subsurface cracking and subsurface damages increases with increasing impact velocity. The variation is consistent with increase in surface and subsurface temperature at higher velocities. With increased temperature, the depth of the heat affected zone increases, which increases the work hardening layer thickness. In addition, subsurface microstructural damage is consistent with attainment of higher temperature which can be explained through the high strain-rate deformation and thermo-physical properties of the surface.

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1. Introduction

Removal of material from a solid surface by the action of impinging liquid or solid particles is known as erosion. In erosive wear, particles impact on the surface at a particular velocity and an angle of incidence, which causes damage to the surface. The erosive action of moving particles is a serious problem in many engineering applications. In the pneumatic transport of solid materials such as coal or grain, the pipeline elbow undergoes significant wear due to the impacts of particles on the surface. When this problem was recognized, reducing erosion by lowering the velocity has been a trend in pneumatic conveying systems used in industry. However, even if erosion is reduced by lowering the velocity, it cannot be totally eliminated.

It was recognized quite early that the impact parameters such as particle velocity and angle of incidence play a vital role in response to erosion. Tilly et al [1] illustrates the variation of erosion with impact angles for aluminum, and the results showed that the wear losses vary significantly on impact angle, and the maximum wear took place at about 20°. Tilly and Sage [2] tested a wide range of materials with different impact velocities and they concluded that the erosion rate increases with the increase of the velocity of all the materials tested and Hutchings [3] described an increased power can be expressed as “Erosion = constant x (velocity)^n”. Hutchings disclosed that the exponent of the velocity is typically in the range of 2 to 4.

Erosion occurs by different mechanisms depending on the impact parameters and surface properties. Bitter [4] introduced a model and describes that wear occurs through two different mechanisms such as deformation (material removed by repeated deformation) and cutting (removed by the formation of material chips). Both mechanisms usually occur simultaneously with a single mechanism is more dominant than the other. Neilson and Gilchrist [5] simplified Better’s model for the erosion of the material. They assumed that the cutting wear factor \( \phi \) (kinetic energy needed to release unit mass of material from the surface through the cut) and the deformation wear factor \( \varepsilon \) (kinetic energy needed to release unit mass of material from the surface by forming process) are involved in the erosion process. The major emphasis in the Nelson et al model was energy factors that determine the material removal in cutting and deformation processes, and proposed a simplified model as follows:

\[
W = \frac{1}{2} MV^2 \cos^2 \alpha + \frac{1}{2} M(V \sin \alpha - K)^2 \tag{1}
\]

Where, \( W \) is the erosion value, \( M \) is the mass of particles striking at angle \( \alpha \) with velocity \( V \). \( K \) is the threshold velocity component normal to the surface below which no erosion takes place in certain materials. \( \phi \) is cutting energy factor (unit energy for cutting) and \( \varepsilon \) is deformation energy factor (unit energy for deformation).

Although cutting and deformation wear mechanisms were found the main reason of erosion, it was also revealed that the material removal can be caused by surface cracking and crack propagation [6, 7]. Evans et al [8] concluded that material removal due to surface cracking and crack propagation is much higher than the mechanisms of cutting and plowing as recognized in situations of abrasion and erosion. Cenna et al [9] and Alpas et al [10] studied the wear mechanisms in ductile surface and described that wear proceed mainly by the mechanism of delamination via subsurface crack growth. Alpas et al [10] suggested that the competition between plastic deformation and hydrostatic pressure is responsible for generating a gradient of damage so that the detachment occurs at a certain depth, where the rate of damage accumulation is a maximum. Cenna et al [11] explains this phenomenon is considered as the effects of work hardening and the formation of the transfer film on the surface.

It has been well established that the unit energy is necessary for the elimination of unit mass of material from the surface. Hutchings [12] examined the energy balance of the material in order to observe the effects of strain hardening, strain rate and temperature during erosion and concluded that at least 90% of the initial kinetic energy of the particle is lost to the plastic deformation at normal incidence. Sundararajan [13] found that the depth of the work hardened layer in the ductile material eroded by the impact of particle is approximately the order of the eroded particle radius. When the work hardened layer is subjected to repeat or cyclical efforts, micro-cracks begin to appear. Heilmann and Rigney [14, 15] have stressed the importance of the energy expended during the deformation near the surface friction and wear. Metallographic observations of subsurface layers showed that the deformation results in the formation of a well defined cell structure elongated in the direction of loading [16, 17].

The main objective of this study is the subsurface behaviour of worn surface in understanding the fundamental mechanisms of wear [4, 5, 9, 18]. A good agreement was obtained from this study, which is applicable to develop reliable predictive erosion model.

2. Materials and methodology

Erosion tests were performed according to ASTM G 76-07 (Experiments were also conducted outside the range of test conditions of the standard in order to obtain a better understanding of the mechanism of wear for different impact parameters). The objective of the test was to study the erosion characteristics of the eroded surface due to erosion by angular particles and wear mechanisms linking the subsurface behaviour to the impact of particles.

Angular silicon carbide (SiC) particles (120 \( \mu \)m in diameter) were entrained in a stream of compressed air to the impact on the mild steel and aluminium target at different impact angles (15°, 30°, 60° and 90°) and velocities (30 ms\(^{-1}\), 45ms\(^{-1}\), 60 ms\(^{-1}\) and 90 ms\(^{-1}\)) using a micro-sandblaster. The micro-sandblasting enables flow control of both solid particles and the air pressure independently to carry out the test at different particle velocities. Mass flow rate controlled by a knob on the flow control unit.
The velocity of the particles was measured with precision by rotating the double disc method [19] and controlled by maintaining the pressure of compressed air for a particular particle velocity. The dimensions of the specimens used were 28 x 28 mm² and 7 mm thickness of the same material stock. Samples were placed at a distance of 10 mm from the nozzle exit for all impact angles. The mass flow rate of particles was controlled 2±0.5 g min⁻¹. The mass loss of the material was measured using an analytical weight balance with an accuracy of 0.0001 g.

Scanning electron microscopy (SEM) was used to analyze the mechanisms of wear and subsurface deformation to the different impact parameters. Each of these eroded specimens was cut perpendicular to the eroded surface. This sectioned area was then mounted in resin and polished with abrasive papers up to 600 grains followed by a further against a velvet fabric with 6 micron and 1 micron diamond polishing suspension. For metallographic analysis, the samples were then ultrasonically cleaned with acetone and etched in 2% Nital for mild steel, while Keller's reagent was used for aluminium.

3. Results and discussion

3.1. Erosion rate

The steady state erosion rate for each specific impact angle and velocity is defined as the mass loss from the specimen per unit mass of eroded, and is determined from the slope of the linear part of the mass loss–mass of erodent plot. Erosion rates are presented as a function of particle impact energy for mild steel and aluminium in Figure 1. It is observed that the erosion rate increases with increasing impact velocity and hence particle kinetic energy at a constant impact angle. A power-law dependence of the erosion rate on velocity and hence particle impact energy is observed from the Figure.

Figure 1 also shows that erosion rate varies with impact angle. It is clearly observed that at 15° impact angle, both materials suffer the highest erosion than with the lowest erosion at 90° for both materials. The impact angle can be decomposed into two force components, namely, the force component parallel to the impact surface and the force component normal to the surface. The parallel force component determines quantity of sliding with the normal force component determining the duration of impact. Syubsequently, erosion mainly occurs by the combination of these two force components, however, one component is generally more dominant than another. It is also observed that at low impact angles, both materials suffer maximum erosion. In this case, the parallel force component has dominated the erosion process. On the other hand, at high impact angles where the erosion rate was the lowest, the normal force component was the dominating factor for erosion. In addition, a significant difference in slope for the erosion rate / velocity equation “Erosion = constant x (velocity)ⁿ” was found between the lower velocity region (30 and 45 ms⁻¹) and the region of higher velocity (90 ms⁻¹). It was also found that the erosion rates for the mild steel are always higher than the aluminium, and this difference may be due to the different mechanisms of erosion between the two, which will be discussed later.

3.2. Energy factors

Erosion rates were further analyzed based on particle kinetic energy dissipated into the surface. The Neilson and Gilchrist [5] model was used (equation 1) in this analysis to determine the energy factors. In the analysis, the effect of threshold velocity component ‘K’ was neglected as it has been found to be relatively small in comparison to the particle velocity [5].

Figure 2 shows the deformation energy factors of mild steel and aluminium as a function of impact velocity. The deformation energy factor is calculated from the erosions conducted at 90° impact angle of a surface and can be used for comparing erosion resistance of different materials during erosion. It is observed from Figure 2 that the deformation energy factor increases with increasing particle velocity for both mild steel and aluminium which means that more energy is required for removing a unit mass of material from the surface at higher velocities. The possible explanation is that with increasing velocity, the impact energy is increased resulting in a softening of the surface material and hence more energy is required for higher velocity to release unit mass of material. From these results it is clear that the erosion rate is inversely proportional to the deformation energy factor which may indicates that the deformation energy factor may have a strain rate dependency. This is because at higher impact velocity the surface deforms at higher strain rates which increase the local temperature. Increasing the temperature for ductile metals has been attributed to the increased ductility of the metal surface, from which more energy is absorbed by plastic deformation [20], and therefore less material is removed.
The cutting energy factor describes the energy required to remove a unit mass of material in cutting action primarily at oblique angles where the material removal is a combination of cutting and deformation. Figure 3 shows the cutting energy factor as a function of particle velocity at oblique 15°, 30° and 60° impact angles. Results in Figure 3 indicate that the cutting energy factor is increased with increasing particle velocity at a constant impact angle. The cutting energy factor also decreased with increasing impact angle, at constant impact velocity. From Figure 3 it can be interpreted that the energy expenditure into the surface is lower at shallow impact angles, while at normal impact angles, the maximum energy is absorbed by the surface during erosion. It is also observed from Figure 3 that the cutting energy factors are higher for aluminium than that of mild steel at constant impact angles for all tested specimens. These results, like the deformation energy factor, indicate that the erosion rate is inversely proportion to the cutting energy factor at oblique angles.

### 3.3. Erosion mechanism

Over a range of impact velocities and angles, three things may occur when a particle impacts on a surface [21]. Firstly, the particle only deforms the surface and rebounds off the surface without removing any material. Secondly, the particle may only plow into the surface and stop cutting. In this case, the particles have dissipated all the energy into the surface with no material removed from the surface. Lastly, particle may plow into the surface and leave from there through removing a small chip of material from the surface. In this case, the particles penetrate easily above the elastic limit and plastic deformation process then occurs where the material can be removed easily.

In the First case, the surface can accumulate the strain energy and progressively work-harden. This work-hardened layer can achieve higher initial erosion resistance capability from impacts, but ultimately can fail to protect the surface due to cracking and subsequent delamination of the hardened layer due to the spalling process. The second case is the most common case for particles interaction with the surface. If no material is removed from the surface, material can be deformed, i.e. plowed to the sides with the formation of frontal ‘lips’ in front of it. This deformed material can be removed easily in the subsequent impacts. In this case, the total particle kinetic energy is transferred into the surface and the surface is affected by local heating [22] or the particle may disintegrate [3]. The third and final case is possible for a high velocity and shallow impact angles in which the depth of cut is very small. In this case, the particle possesses enough energy to cut a chip from the surface and bounce off.
To further investigate the mechanisms described above, SEM analysis was conducted on eroded surfaces. Figure 4 shows the worn surfaces of mild steel (4a, 4b) and aluminium (4c, 4d) at 30 ms⁻¹ (4a, 4c) and 90 ms⁻¹ (4b, 4d) at an impact angle of 15°. Scanning electron microscope (SEM) was used to study the surface morphology of the worn surface. Figures 4a, 4b, 4c and 4d show that the particle effects are oblique to the surface, which confirmed that the mechanism of erosion is mainly dominated by cutting action. In the Figures, material is removed by cutting, plowing and the formation of lips are clearly visible in both the mild steel and aluminium surfaces.

Figure 5 shows the worn surfaces of mild steel (5a, 5b) and aluminium (5c, 5d) at 30 ms⁻¹ and 90 ms⁻¹ at an impact angle of 90°. Figure 5a, 5b, 5c and 5d show that particle impacts were normal to the surface which confirmed that the erosion mechanism is mainly dominated by the deformation process. In these Figures, the First case (particles impact and rebound off without loss of material resulting in accumulate strain energy) is observed for both mild steel (5a, 5b) and aluminium (5c, 5d) a deformed surface is dominants micro-plowing and lip formations are prevalent in the image with apparently no material loss. Despite of deformation process, there are some cutting characteristics observed in the Figures (lips and plowing). This is may also be attributed to the angular particle shape and inter-particles collision through which particles impact at over a range of angles and may also have a rotational component at impact.

3.4. Subsurface behaviour

The worn mild steel and aluminium surfaces were sectioned, polished and then examined in SEM to study the subsurface behaviour. Figures 6 shows the subsurface zone beneath the eroded surface of mild steel (6a, 6b) and aluminium (6c, 6d) at 30 ms⁻¹ (6a, 6c) and 90 ms⁻¹ (6b, 6d) respectively at an impact angle of 15°. Subsurface cracks are clearly visible in both the cases of mild steel (6a, 6b) and aluminium (6c, 6d). These subsurface cracking plays a major role in the material removal rate from the surface. We can explicate this mechanism by two ways; firstly material removed directly through cutting and plowing where no visible cracks were found, and secondly, the material is removed through subsurface cracking. At shallow impact angle, when the particle strikes the surface, some material is removed expending some energy. The remaining kinetic energy is transmitted into the subsurface and converted to strain energy. This strain energy is then transferred into heat depending on strain rate into the subsurface. The heat affected zones are then work hardened and, after subsequent impacts, material is removed by displacing action. The formation of crack is due to the work hardening of the subsurface during impact on the surface.

Figure 6 also shows the crack propagation behaviour during erosion. Figures 6a, 6b, 6c and 6d show that the depth of subsurface cracking increases with increasing impact velocity for both materials. Cracks are created at the surface and extended from a depth of approximately 10 μm to 20 μm from 30 ms⁻¹ to 90 ms⁻¹ at impact angle of 15° for mild steel (6a, 6b), while at same velocities the value found for aluminium (6c, 6d) were about from 5 μm to 10μm, which was then propagates parallel to the surface. The crack appears to be formed along the grain boundaries without any direct contact of particles. So it can be explained that at shallow impact angles cutting, plowing and subsurface cracking mechanism occur simultaneously.

Figure 7 shows the subsurface zone beneath the worn surfaces of mild steel (7a, 7b) and aluminium (7c, 7d) at 30 ms⁻¹ (7a, 7c) and 90 ms⁻¹ (7b, 7d) at an impact angle of 90°. The subsurface damage is clearly observed in all the Figures, from which subsequent material removal has occurred. In this instance, the force components of the particle stream were dominated by normal impact components to the material surface which leads to increased strain-rates beneath the worn surface resulting in subsurface damage. It is expected that a large portion of the particle energy is dissipated into the surface which modifies the subsurface microstructure. Figure 7b (mild steel) and 7d (aluminium) also show that material is highly affected by the particles at higher velocity for both materials where the depth of subsurface damage is found to be approximately 25 μm for the mild steel.
and about 15 μm for the aluminium. This variation is again, likely due to the surface temperature increase (heating) with increasing particle velocity, as described earlier.

4. Conclusion

This paper relates erosion mechanisms to particle energy and surface properties at low and high impact angle and velocities for mild steel and aluminium. Scanning Electron Microscopy results confirmed that at shallow impact angles, erosion is dominated by a cutting wear mechanism; while at the higher impact angle, erosion is dominated through a deformation wear mechanism. In addition, for investigation of impact angles at 15° also confirmed that material was removed through subsurface cracking and at 90° the material was removed by the subsurface damage. Experimental results also revealed that both the depth of cracking and damage increases with increasing impact velocity.

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