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A REVIEW OF SOLID PARTICLE EROSION; SELECTED PUBLISHED INFORMATIONS

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ABSTRACT

Erosion caused by solid particles, such as sand grains, can occur under a variety of service conditions. Probably the most important erosion problems which occures in industry are those connected with gas turbines powering helicopter and equipment used in cracking oil. Solid particle erosion received little disciplined study before about 1960.
The scope of the present work is to review selected published informations on solid particle erosion in order to show how far the previous investigators have been succeeded in explaining the mechanisms of erosion and evaluating the dependance of erosion on experimental data.

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INTRODUCTION

Solid particle erosion is defined as the removal of material from surface of a body by fluidborne solid particles. In industrial applications, erosion is encountered in fluid transport pipe lines, equipment used in catalytic cracking of oil, high speed impact grinding mills, gas turbines powering helicopters and hovercrafts. The aerodynamic action induced by helicopter rotors tends to result in erosive thinning of tips of rotor blades (1) Operation of such vehicles can generate dust clouds containing particles up to 200 um in mean diameter (2) and concentration of dust in air of 14mg/ft3(3) The material lost as wear debris has no economical means of recovery. It has been reported (4) that the life of a gas turbine engine had been cut from a normal range of 1000 - 16000 hours to only 300 hours due to solid particle erosion.

In the laboratory, the damage is usually simulated by blasting airborne particles against a test piece (5,6,7) . Alternative methods involve dropping particles under vaccum on the face of a stationary specimen attached to the ends of a rotating arms (2,7). In general, it has been found that a relatively good correlation can be obtained between laboratory data and service damage (21) .

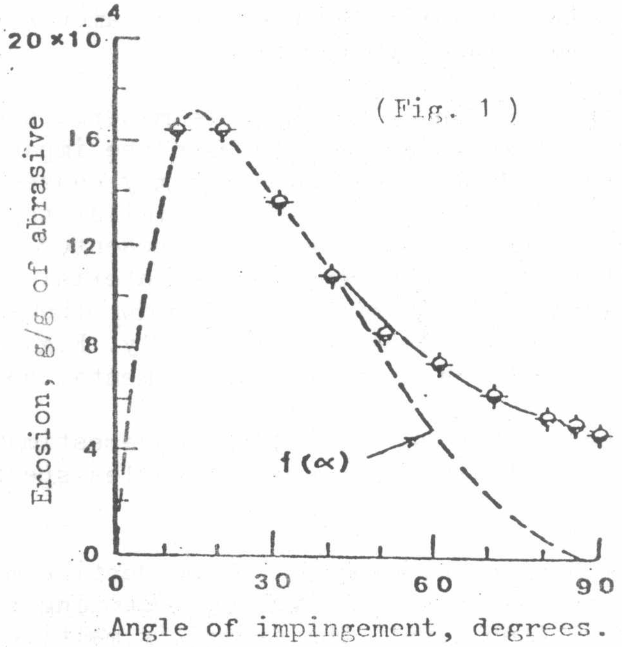
This paper reviews the current understanding of the solid particle erosion mechanism and the dependence of the erosion on the experimental conditions.

THEORIES AND MECHANISMS OF EROSION

In studying the erosion of materials, it is convenient to consider first two classes of materials, ductile and brittle materials. Erosion of ductile materials is characterised by a maximum erosion at small acute angles of impingement (15-25 degrees) and that of brittle materials is characterised by maximum erosion in vicinity of normal impingement angle. Of course, not all materials fall neatly into these categories.

Finnie is the first one to treat erosion of materials in a quantative manner. In studying the erosion of ductile materials, Finnie (8) likens the erosive particle to the cutting edge of a cutting tool and proposes that when the particle attacks the surface of the material, the material shows a constant resistance to deformation represented by a constant flow stress. The action of attacking particle is the deformation and the displacement of the material until it separates from the bulk material. The constant resistance of the material during erosion implies that the material under treatment is ideally plastic and the constant flow stress is equal to the fracture stress. So, the volume removed is determined simply from trajectories of the particles during their interacting with the surface. The volume removed from the surface is expressed by a model in which the volume removed from the surface is proportional to the reciprocal of the flow stress of the eroded material.

Fig. 1 shows that the correlation of the model to experimental data is good in general form and in location of the angle of maximum erosion. At angles larger than the angle of maximum erosion, the theory underestimates the erosion and predicts zero erosion at 90 degrees.



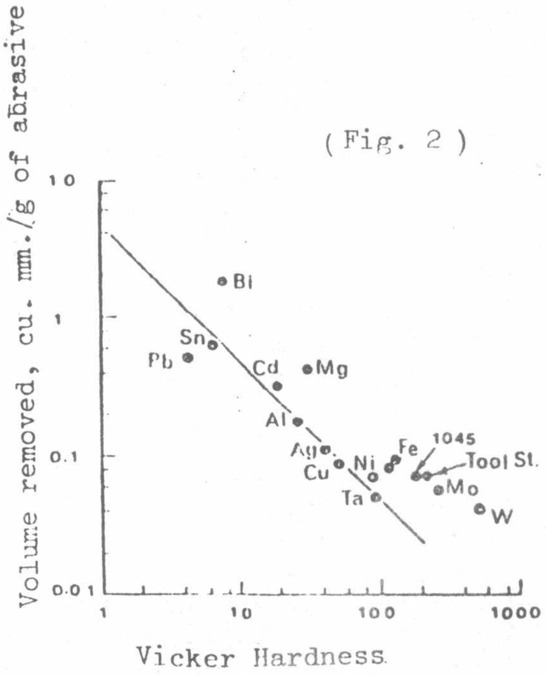


Fig. (1) Weight removed by erosion against angle of impingement for 1100 - 0 aluminium, Ref. 9.

Fig. (2) Volume removal as a function of VHN for metal eroded at = 20 deg. Ref. 9.

Finnie (9) plotted the volume removed from different pure metals against their hardness, Fig. 2. The figure shows that the volumes removed from the metals which has the same hardness (Bi, Sn – Mg, Al – Ni, Ta) are not equal.

Finnie (5,10) investigated the erosion of brittle materials and showed that the mechanism of erosion of the brittle materials is cracking of the surface under the effect of the attacking particles..Finnie used Hertz's equation to study the conditions for initial cracking of the surface of the material and suggested that, as a crack is formed, it flares out below the surface and form a mantle of a cone. The joining of the cracks leads to removal of the material.

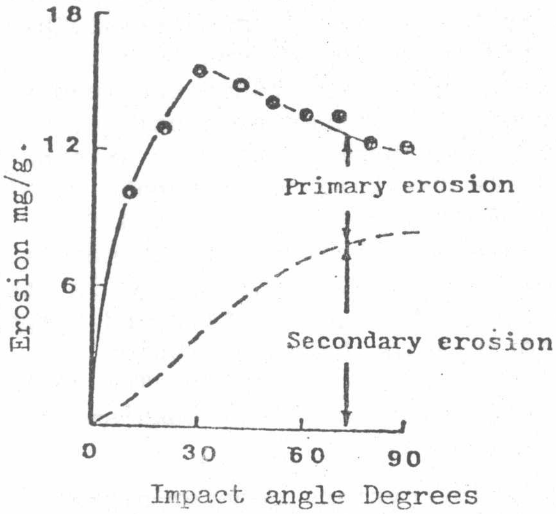
Bitter (11,12) hypothesized that the erosion of materials consists of two mechanisms occuring simultaneously, namely, cutting and deformation mechanisms. The cutting mechanism is similar to that proposed by Finnie (8) and prodominates in ductile materials at small impingement angles. For the deformation mechanism, it is assumed that the surface is work hardened and cracked under the effect of the repeated impacts of the attacking particles. Propagation and spreading of the cracks result in removal of the material. The deformation mechanism prodominates in the brittle materials at large impingement angles. Bitter did not define a specific parameter of the eroded material to which erosion resistance is related.

Tilly et al (13,14) suggested that the erosion of the ductile materials consists of two stages. The first stage (primary erosion) is when the impacting particles strike the surface and produce indentation and may cause removing of material. The erosion mechanism of this stage is similar to the erosion mechanism suggested by Finnie. The second stage is represented by break up of the particles and possibly results in removing of material (secondary erosion) . From the consideration of energy balance during the erosion process Tilly expressed the two mechanisms of erosion numerically. Fig. 3 shows correlation of the model suggested by Tilly to the experimental data.

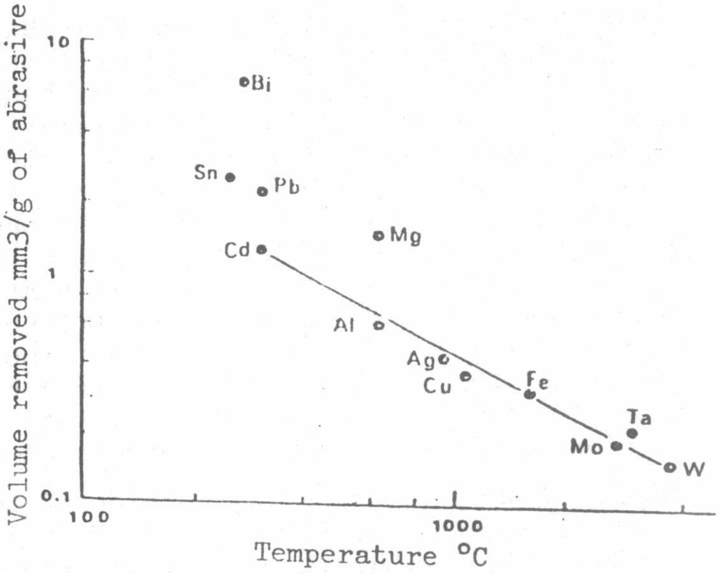
The secondary damage mechanism may be invoked to explain the underestimated erosion predicted by Finnie's model (8) at large impingement angles specially at 90 degrees.

Smeltzer et al (15) suggested two mechanisms of erosion of the ductile metals. The first is melting of the surface of the metal beneath the impacting particle followed by splattering of the molten metal. The second is melting of the surface of the metal beneath the impacting particle followed by soldering of the soldified molten metal to particles embeded in the surface which in turn are removed by subsequent impacting particles.They replotted the erosion data given in Fig. 2 against the melting temperature of metals as shown in Fig. 4 .
The figure shows that metals which have same melting temperature such as aluminium , magnesium and cadmium; lead, bismuth have different erosion rates. Unfortunately, the hardness and Young's modulus of metals are also related to the melting temperature.

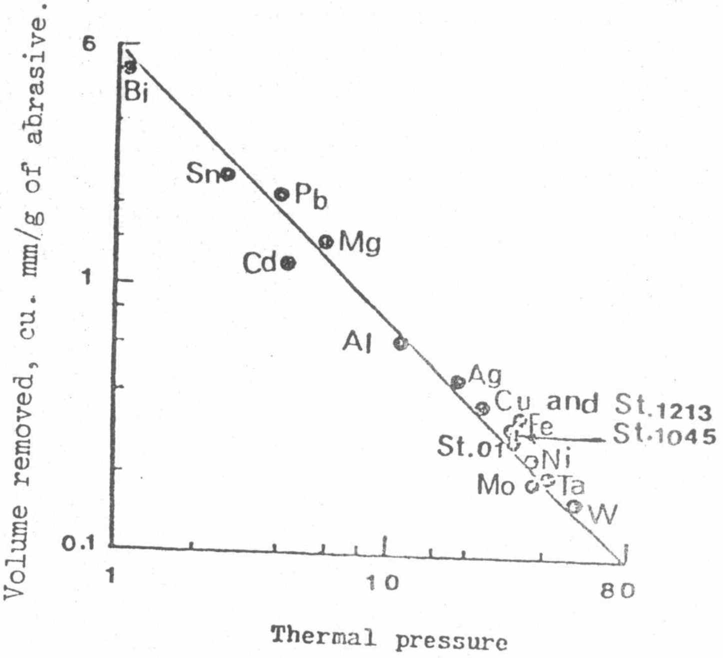
Ascarelli (16) assumed that on attacking a material with an angular particle the particle loses its kinetic energy which is rapidly transformed into heat. He assumed that the greatest heat was produced near the tip of the striking particle, where the particle has the sharpest corner. In this region of intense localized heating, the target melts. It was assumed that the melting process proceeds at constant volume (no change in the density of the metal during the process). The constant volume and the rise of temperature results in a (thermal pressure) in the material (thermal vibrations of the atoms). Ascarelli, assumed that the rise of the thermal pressure reduces the resistance to flow of the material and so the material is easily carried away by the stream of impinging particles. The probability of removal of the molten metal was assumed to be a function of the impingement angle. The true impingement angle was considered to be different from the nominal impingement angle due to the roughness of the surface. Ascarelli replotted fig. 2 against the thermal pressure as shown in fig.5 .The figure shows a better correlation than that previously obtained from the melting temperature.



(Fig. 3)



(Fig. 4)



(Fig. 5)

Fig. (3) The influence of impact angle for 135 um quartz against 46 steel, Ref. 14.

Fig. (4) Volume removed versus melting temperature for metals , = 20 deg., Ref. 15.

Fig. (5) The volume eroded mm3/g of abrasive is plotted against the thermal pressure, Ref. 16.

Winter and Hutching (17,18,19) noticed that the material removal consists of two stages. The initial stage is the formation of a lip at the exit of the crater, attached to the bulk material. The second stage is the removal of the lip from the bulk material. They found dark bands in the lips, within which the deformation is much greater than in the surrounding material. They presented evidence that this localization of deformation is due to adiabatic softening of the material. The mechanism by which the bands can lead to detachment is suggested to be a combination of shear stresses causing the chip to slide against the underlying material and tensile stresses arising from the inertia of the chip, causing a tensile fracture to propagate within the thermally softened material in the band. Hutching (20) replotted fig.2 against a product which is proportional to adiabatic heating of the metals as shown in fig. 6. C_p is specific heat of the eroded material, ρ is its density and ΔT is the difference between temperature of melting and temperature of room. The figure shows that the correlation between erosion of metals and the product $C_p \rho \Delta T$ is reasonable except for bismuth. The deviation of bismuth from the proposed relationship may be due to mechanism of erosion of bismuth (brittle mechanism of erosion (9)) .

Bassili (7) investigated the erosion of the alloy systems, copper-nickel, copper-tin and copper-zinc alloys. Fig. 7 shows that the erosion resistance of the copper nickel alloys is proportional to their melting temperature and the product $C_p \rho \Delta T$ rather than to the hardness of the alloy before or after erosion or to the toughness of the alloy. Examination of the eroded surface shown in the plate indicates that the metal was ploughed and a lip was formed at the crater exit and the formed lip partially torn at its root. The appearance of the surface in the plate do not show melting of the surface. So it can be assumed that the erosion mechanism of metals is thermo-mechanical in nature. The mechanical contribution is the deformation and ploughing of the metal and the thermal contribution is the separation of the deformed metal from the bulk metal due to thermal effect.

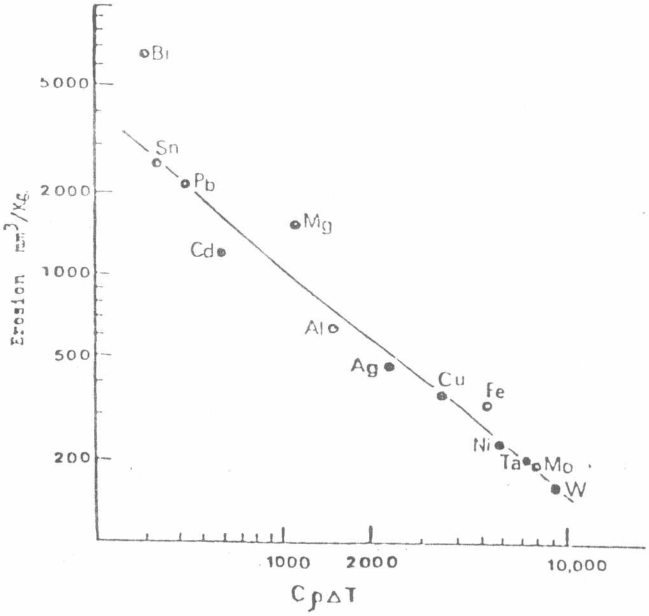


Fig. (6) Volume removed plotted against the product $C\rho\Delta T$; ref. 20.

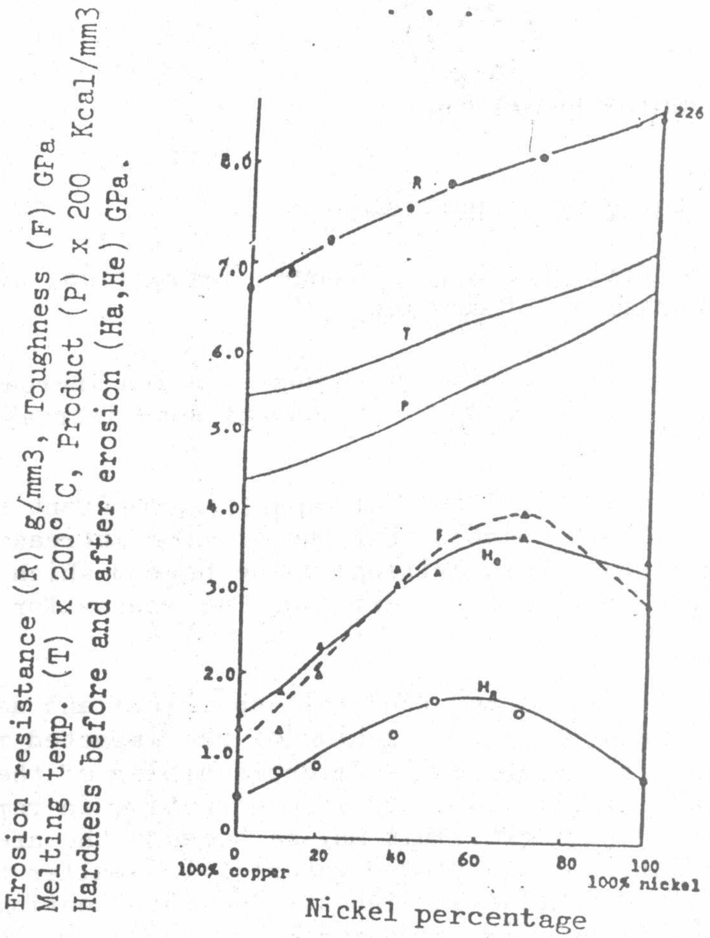
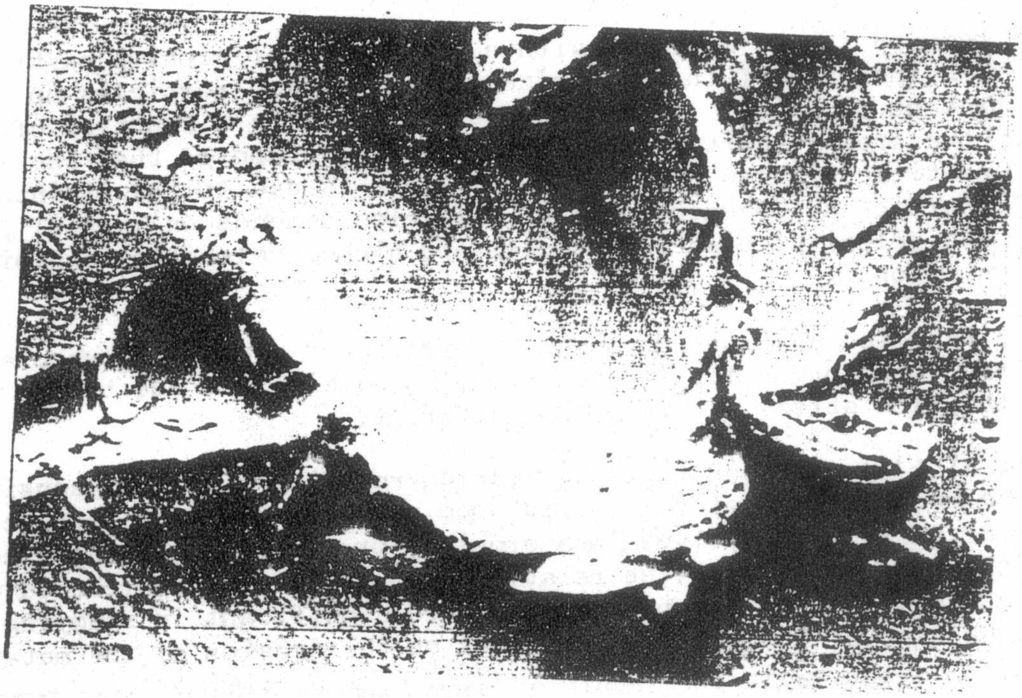


Fig. (7) Erosion resistance, melting temperature, product surface hardness (before and after erosion) and toughness of copper-nickel alloys VS nickel percentage in alloys, ref. 7 .



Brass 70/30 eroded by quartz particles at an impingement angle 30 degrees, X400, ref. 7.

EROSION PARAMETERS

Erosive Particles

Shape and impurities of the erosive particles

Properties of the erosive particles such as shape, impurities, hardness and size can affect the severity of erosion.

Natural sand contains variable percentages of quartz which increases with increase in size of sand. The erosiveness of natural sand increases with increase in quartz percentage (2) , (22) .

Uuemois and Kleis (23) studied the effect of impurities content in quartz sand on erosion of steel. They reported that the erosion increases with increase in impurity content up to a critical value beyond which further increase in the impurities decreases the erosion. The reason for this effect is not clear .

Sheldon (24) and Winter (25,17,18) reported that spherical and angular particles of small rake angle produce ploughing of the impacted material. Angular particle of large rake angle causes micromachining of the material. In general, the angular particles are more effective in removing the material than the round particle. This may be because the area of contact between an angular particle and eroded material is smaller than that for a spherical particle and results in high stresses and heating effect in the material. The rebound velocity of a spherical particle is also larger than for an angular particle (26,27). Therefore, the fraction of kinetic energy of the particle consumed in erosion of a material is larger for an angular than a spherical one.

Size of erosive particles

The volume removed from a material with a given mass of erosive particle increases with increase of the mean size of the erosive particles up to a certain plateau size (7) . The plateau size itself is a function of the velocity of the erosive particles (22). Tilly (14) proposed that the influence of particle size on erosion of materials is due to the disintegration of the particles. Fragmentation of particles depends on initial particle size and velocity; bigger particles and higher velocities exhibiting most fragmentation.

Bassili (7) reported that the decrease of erosion of a material when eroded with very small particles (beyond the plateau size) is due to the increase of the flow stress of the eroded material.

Smeltzer et al (15) proposed that the erosion rate is not a very sensitive index to the mechanism of erosion as it does not directly take into account the number of particles involved into erosion, or their individual size and mass, so, they suggested that the relationship of the volume removed per particle to the volume of the particle is more significant in studying the effect of the size of the erosive particles on the erosion of the materials.
The erosion is essentially the result of many impacts causing many types of damage, so the resultant erosion is an averaged figure and there is little point in covering the data to damage per particle .

Concentration of the erosive particles

Montgomery et al (28) reported that the influence of the concentration of the erosive particles in the range 0.001-0.007 mg./ft3 on the erosion of metals is insignificant. Charles and Epanschade (29) showed in a largest range of concentration 0.0005-0.03 mg./ft3 that the erosion rate of metals increases with the decrease in the concentration .

In study of erosion of polymers, Bassili (7) showed that there is a threshold value of erosive particles concentration. Below this value the erosion of the polymer is sensitive to variation of the concentration and vise versa. At very small concentration, the duration between the successive particles may be long enough; so that each particle erodes the surface and rebounds off it without interference with the successive impinging particles. At high concentrations, the rebounded particles and their debris may collide with the incident particles and result in change of direction, reduction of velocity and disintegration of the attacking particles.

Velocity of the erosive particles

The relationship of the erosion rate ($\mathcal{E}$) of a material to the velocity of the erosive particles (V) can be expressed by the,equation ,

$$\mathcal{E} = bV^n$$

Where b is a constant
Theoritical analysis predicts values for the exponent n equal to 2 (8,11,12,15) and 3 (24). However it has been shown that experimental values of n are about 2 (9,29,30) and about 2.3 (2) for a wide range of materials. Values as high as 6.5 have been reported for tests with steel spheres against glass (30). Tilly (14) showed that the secondary erosion caused by the disintegration of the erosive particles, produces values of n bigger than 2. Uuemois and Kleis (23) suggested also that particle fragmentation result in values for n bigger than 2.

It has been shown (31) that n is function of the size of the particle, increasing from 2 for a particle size of 25 um to 2.3 for a particle of 200 um.

It has been suggested (11,12) that there is a threshold velocity (less than 3 m/s) below which no erosion occurs.

Hardness of the erosive particles

Erosion resistance of a metal can increase or decrease according to the material of the erosive particles used. When the hardness of the metal exceeds that of the erosive particles, the erosion resistance of the metal improves(12,22,23,37) . The difference in hardness between the metal and the erosive particles affects the erosion resistance of the metals. The degree of disintegration of the erosive particles and consequently the degree of secondary erosion produced is expected to be dependent on the hardness of both the eroded and eroding materials.

It is reported (7) that when the hardness of the erosive particles is 0.7 times less than that of the eroded metal, the particles are not effective in metal removal.

Angle of impingement

Wallis (32) reported that ductile erosion reaches a maximum when the impingement angle is within the range 20 degrees to 50 degrees. The upper limit applies for particles with a mean size of approximately 5um and is explained in terms of curved trajectories which result in true incidences well below the apparent ones.

The lower limit of 20 degrees applies, in general, to the softer class of target material.

Brittle erosion reaches a maximum when the impingement angle is about 90 degrees.

Eroded Material

Hardness

Sheldon (33) suggested that the hardness of the eroded surface of the materials increase during erosion and the higher value is more relevant to the erosion resistance rather than the hardness before erosion which was previously suggested by Finnie. Using copper-nickel alloys, Sheldon showed that the hardness of the eroded surfaces of the alloys varies linearly from the hardness of the copper to the hardness of the nickel and the erosion rate of the alloys vary linearly with the composition. Bassili (7) reported that the hardness of the metal surface increases by erosion but this effect is irrelevant to erosion resistance of the metal as shown in fig.7 .

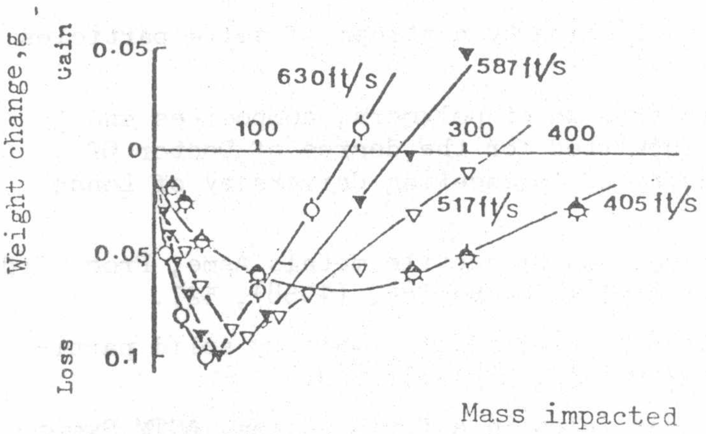
Incubation period

In the early stages of erosion, erosive particles embeded in the surface of the material (incubation period). Figs 8 and 9 taken from reference (6) show that the incubation period decreases with decrease of impingement angles and with increase of velocity of attacking particles. Soft materials such as aluminium and resilient plastics are very susceptible to embeding of particles (5,7). However, the surface quickly becomes saturated and the situation stabilises so that the erosion exceeds the incubation period and a linear erosion is established.

Temperature of the eroded material

Elevation of temperature of target material may increase or decrease the erosion depending on the material involved(34,35,36) . It has been suggested by Tilly (36) that the temperature dependence may be related to ductility of the materials, where the ductility may be an important parameter in determining the amount of energy dissipated in removing material from the material .

(Fig. 8)



(Fig. 9)

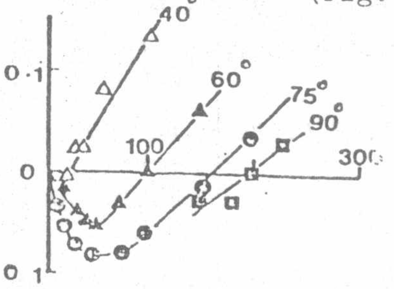


Fig. (8) Weight change vs. mass impacted for aluminium plates, = 90°, 210 um aluminium oxide particles, ref. 6 .

Fig. (9) Weight change VS. mass impacted for aluminium plates. 210 um aluminium oxide particles at 630 ftls, Ref. 6

Conclusion

From this review of solid particle erosion, it is clear that most of the parameters that affect the process of erosion of metals have been investigated in some detail. Investigators proposed that the erosion mechanism depends on mechanical or thermal properties of the eroded metal. It seems that both properties control the erosion process. These properties are important in connection with the erosion rating of different materials and the selection and development of suitable erosion-resistant alloys and coating .

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