Effect of Particle and Target Material Characteristics on Erosion Wear by Solid Particles

Alok Shrivastava[1], Amit Suhane[2]

[1]Research Scholar, Department of Mechanical Engineering, MANIT Bhopal, 462003, India
[2]Assistant Professor, Department Of Mechanical Engineering, MANIT Bhopal, 462003, India

---

Abstract - *Erosive wear is the type of wear that occurs due to repetitive impact actions by hard solid particles on the target material. Erosive wear phenomenon is primarily concerned in the industrial applications like pneumatic conveying of hard abrasive particle, in cyclones and turbine wear and aviation applications. Erosive wear is governed by various parameters involving impact parameters like particle impact velocity, impingement angle, collision rate etc., particle properties like size and shape, density, hardness etc., target material properties and other environmental conditions. The paper focuses on the influence of predominant parameters like, particle impact velocity, impingement angle, particle concentration, particle size etc. which play major role on erosive wear by reviewing the previous work presented in the area of conveying application. The overall understanding in field of erosive wear is presented and brief knowledge is provided on the fluid flow conditions and parameters affecting the erosion. Paper also gives an insight of the mechanisms that governs the erosion phenomenon of materials and finally concluding the researches done in this field.*

Key Words: Erosive wear, Impingement angle, Particle impact velocity, Particle concentration, Particle hardness, Collision rate

1. INTRODUCTION

Wear is the progressive material loss or deformation of materials from the surface of any component. Wear can be caused either by chemical action like corrosion or by rubbing action as abrasion. Wear can be classified as adhesive wear, abrasive wear, surface fatigue, fretting wear, erosive wear, corrosion and oxidation wear. If the hardness of the particles to be conveyed is higher than that of the system components, such as feeders and pipeline bends, then erosive wear will occur at all surfaces against which the particles impact. Solid particle erosive wear is the progressive loss of original material from a solid surface due to mechanical impact between that surface and solid particles [1]. Erosive wear is mostly undesirable apart from its useful applications like in sand blasting, abrasive deburring and erosive drilling of hard materials. Erosive Wear is inherent phenomenon and is undesirable in industrial applications like catalytic cracking of oil, coal turbine, hydraulic turbines, coal hydrogenation [2], ash conveying etc., leading to both direct and indirect losses. Direct loss in terms of part failure, production loss, time loss etc. and indirect losses like environmental loss, energy losses [3]. Wear cannot be avoided completely but could be minimized to an acceptable limit through proper designing and selection of system flow conditions and materials selection according to applications and purpose.

Erosive wear either due to its desirable applications or due to its undesirable characteristics in industrial processes, its estimation and prediction had been a necessary requirement. Study of erosive wear phenomenon has long past and some prior set of research has carried out in 1946 by Wahl and Hartstein [4]. An intensive research was carried out by researchers in this field between 1960s and 1970s [5-10]. Bitter[5] showed that ductile and brittle material wear out differently, while brittle materials wear by repeated deformation during collision whereas ductile material wear out by cutting action of free moving particles. Estimation of erosive wear or its prediction is difficult because of wide impact conditions and large impact parameters involved in the process including the material properties too as shown by Bitter. Among different material properties, hardness of material plays a major role in estimation of erosion. Apart from difficulty in prediction of erosion wear, some researchers had established various models for wear estimation[11-15] and some researchers carried out experiments and analysis to find out the role of individual parameters on erosive wear tendency. This paper presents an overview of erosive wear and primarily focuses on various impact parameters that dominates in the wear phenomenon through the study of previous work by researchers. The paper discuss the effect of these parameters in erosive wear and different mechanism proposed by researcher in this field and finally concluding the review by scope and recommendations to clear questions in field of erosive wear by solid particle.

2. Parameters influencing erosive wear

The Erosive wear results from the impact of particles against surfaces [1]. Erosive wear is predominantly significant in gas turbines of aircrafts, pulverized fuel supply lines in thermal power plants, pneumatic and hydraulic conveying pipelines particularly in transportation of abrasive bulk particulate materials. Erosion phenomenon has wide range of source as different applications have wide operating parameters. This paper limits its focuses on study of erosion phenomenon to industrial applications only. The problem in conveying of abrasive materials is its hardness which cause erosive wear of pipeline material particularly where particle likely to impact like diverter valve, T-joint, bends etc. Effect of wear of pipeline results in leakages and ultimately failure of the system leading to production loss, environment loss and may cause human loss too. Hence it becomes highly relevant to study erosive wear and the parameters associated with it.

The erosion of material is governed by a number of parameters both related to the material conveyed and the material of construction of pipeline line. Through the researches it is proved to predict and estimate the failure but some of the reasons which make it difficult to predict the failure of material because of following:-

i. The interdependence of numerous variables with each other makes it too complex.
ii. Behaviour of impacting particle is difficult to predict
iii. Duration of impact is too short to study it properly.

But it is well proven that by selecting and adjusting numerous parameters the life of conveying pipeline can be prolonged.

Over a period of time, in this field a various parameters involved in erosion has explored and they can be broadly categorised as:-

Table.1 Factors influencing erosion wear of material

1. Impact Parameters	
	- Particle velocity
	- Impingement angle
	- Collision rate
	- Laminar or turbulent Flow
2. Particle Properties	
	- Size and shape
	- Density
	- Hardness
	- Composition
	- Strength
3. Target Properties	
	- Microstructure
	- Surface hardness
	- Composition
	- Strength
4. Environmental Factors	
	- Temperature
	- Carrier gas composition.

These parameters widely vary with condition and applications and in some cases are interrelated with each other making it a complex process for estimation. Impact parameters determined by fluid flow conditions and system design. Some of the significant parameters are discussed below separately.

2.1 Particle Impact velocity

Among all the influencing parameters, impacting velocity is the most influential in erosion of material, more specially in pneumatic conveying. J.E. Goodwin et.al [7] had performed some set of prior experiments in this field to found out influence of velocity on erosion of different materials. They concluded that erosion is dependent upon a simple power of velocity (V) shown in eqn.2.1, i.e.

$$\text{Erosion} = \text{constant x (velocity)}^n \qquad \text{Eqn.2.1}$$

where the exponent n varies from 2.0 for 25 μm to 2.3 for the saturation erosion occurring for 125 μm and above. The test was performed with 25 μm, 40 μm, 60 μm and 200 μm particle size and all those shown similar exponential relation with impact velocities. In the Similar experiment been performed by G.P.Tilly and Sage [7] over a wide range of different materials and obtained very good agreement with respect to the exponent n, in each case. Result of the test is shown below:-

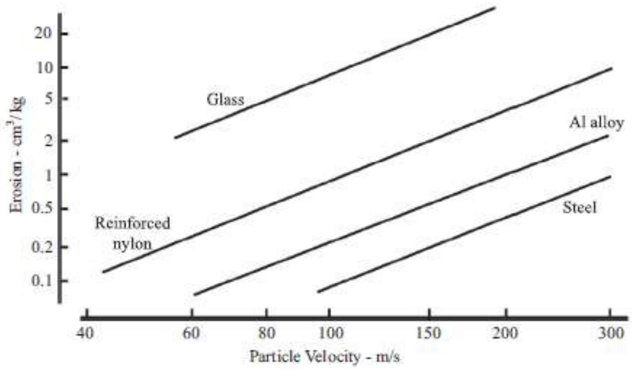

Fig.1 Variation of erosion with velocity for various surface materials[7]

The plot of erosion for different material have similar slope of approximately 2.3. Tests were carried out over a range of conveying air velocities from 15 to 35 m/s and at solids loading ratios from 0.5 to 8. Steel bends of 53 mm bore were eroded by 70 μm and 230 μm sand, and over the ranges tested the velocity exponent was found to be consistent at 2.65. A velocity dependence similar to that given by equation has been noted by Finnie and Kabil [16] who found values for the velocity exponents varying from 2.05 to 2.44. G.P.Tilly [6] concluded that erosion is dependent upon size and velocity of the impacting particles. For the ductile type of materials, increasing particle size causes an increase in damage till a saturation level is reached beyond which no further change occurs. For small particles, erosion is proportional to V^2 but for sizes above - 100 μm it can be approximated to $V^{2.3}$. Researchers have concluded that velocity plays major role in erosion process and hence it is recommended to limit the velocity to lower end to minimize it.

2.2. Impingement Angle

Impact angle depends on the system design and fluid flow conditions. Although it is difficult to predict the true particle behaviour in fluid flow but researches has showed that it is possible to relate the impact angle in the erosion process. In 1963 Bitter [5] proposed that erosion at normal incidence was due to deformation Wear. Prior work performed in investigating influence of impact angle dependence is done by Tilly [6]. Figure 1.2 shows the variation of erosion with impact angle for Al alloy and glass surface materials as plotted by J. S. Mason and B. V. Smith[23]. The aluminium alloy is typical of ductile materials and it suffers maximum erosion at an impact angle of about 20 degrees and offers good erosion resistance to normal impact. Glass is brittle in nature suffers severe erosion under normal impact and offers good resistance at low impact angles. Tests were performed with sand particle of size between 60μm and 125 μm at the impacting velocity of 100m/s. The observation showed that ductile and brittle material behaves differently due to difference in mechanisms of material removal. Theories proposed to explain these phenomena consider that for ductile materials removal of material is predominantly due to plastic deformation like as with the cutting edge of a machine tool and that for brittle materials it is due to the propagation of fracture surfaces into the material. A design modification in bend portion is studied by Amit Suhane [24] .The bend erosion results have indicated that using the bends of a larger bore in a small bore pipeline loop has a advantage in terms of the erosion rate of the bends as it modify the impact angle and conveying velocity.

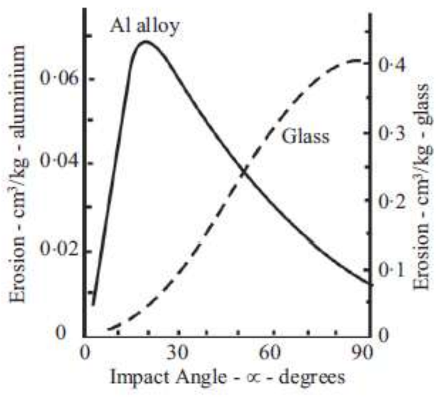

Fig.2 Variation of volume removal with incidence angle for various ductile and brittle materials [23]

2.3 Particle Size

Solid particle size plays significant role in the erosion process. Particle size effect is studied by various researchers[9, 17, 18]. Goodwin et al. [7] worked with crushed quartz particles of size 25μm to 210μm and tested at normal impact angle against 11% Cr steel at velocities of 130, 240 and 305 m/s and concluded that there is size effect on erosion of material which itself dependent upon impact velocity. They showed that there was a critical particle size above which erosion was not influenced by size and that this value appeared to increase linearly with velocity. G.P. Tilly [19] in his experiments showed with engineering alloys and resilient plastics there was an initial increase in erosion with particle size until the onset of a saturation plateau where it was independent of size but the observation was on resin and composite found a continual though varying increase in erosion with particle size. Results showed by Tilly[19] is presented in fig.3, shows that the threshold value increases with increase in velocity. The work was carried out for an investigation into the erosion of aircraft engines, which explains the high velocity range. Experimented in a shot blast type of test rig, in which abrasive particles were impacted against flat plates, was used for the purpose. Sage and Tilly [19] tested on glass, which suffered a rapid increase in erosion with particle size, and found that the erosion could be represented by a power law over the size range tested.

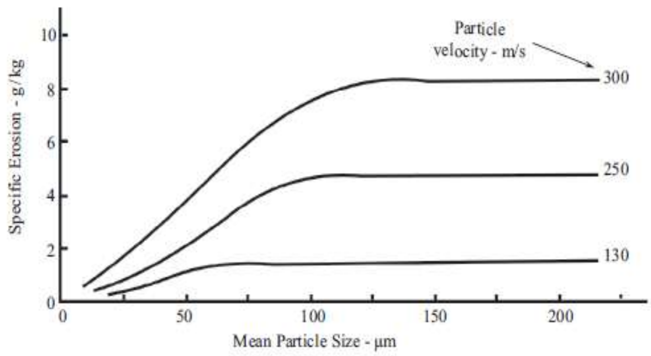

Fig.3 The influence of particle size and velocity on erosion[19]

D. Mill [9] carried out experimentation on actual pipe bends in pneumatic conveying system pipelines on the batches of sand with mean particle sizes ranging from 70 to 280 μm were used in six test bends in the one pipeline in monitoring for erosive wear in conveying trials and found out that the average mass eroded from each bend was found to be independent of particle size. On an individual basis, however, the bends showed a very interesting trend. The degree of scatter in the results increased markedly with decrease in particle size, as shown in fig.4 With the larger particles, the wear rates were remarkably consistent, but with the finer particles, the spread of the results was very wide due to the finer particles are influenced by the secondary flows and turbulence that can be generated by the bends and that this causes accelerated wear of some bends.

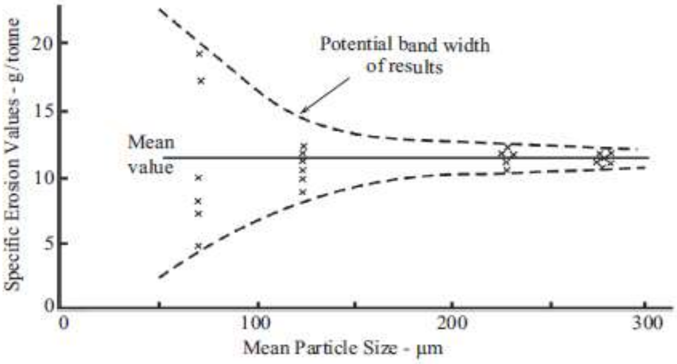

Fig.4 The variation of individual specific erosion values with mean particle size for bends in a pneumatic conveying system pipeline[1].

2.4 Particle Hardness

Potential and extent of erosive wear by solid particle is depended mainly on particle hardness. Significant work in this parameter is performed by J. E. Goodwin et al. [7] , where they tested with natural dust were sieved into the size range 125 to 150 μm and their erosiveness measured by testing an 11 per cent chromium steel at 420 ft/s for normal (90^0) impact. The research concludes that testing of a variety of abrasives confirmed that their erosiveness is dependent upon hardness (and sharpness by inference) as shown in the Fig. 5. The figure concludes that erosion increase with particle hardness. They further found that erosion is related to hardness by the expression eqn.2.2:

Erosion = constant x $H^{2.4}$ Eqn.2.2
Where,

H=Particle hardness.

There is a threshold value of particle hardness beyond which erosion remains essentially constant. D.Mill [1] in his work studied the potential influence of various particle hardness on the erosion of mild steel bends as shown in fig.6 .The Figure concludes that above certain hardness value, erosive wear does not depends on particle hardness.

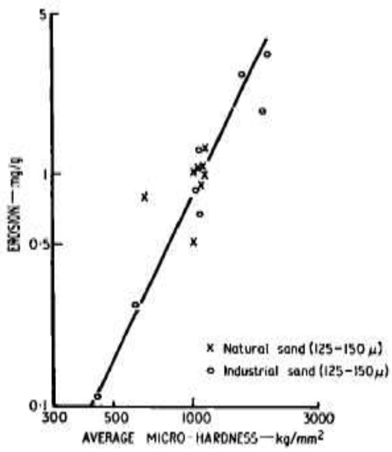

Fig.5 Effect of particle hardness on erosion of an 11 per cent chromium steel at 420 ft/s and 90^0 impact angle.[7]

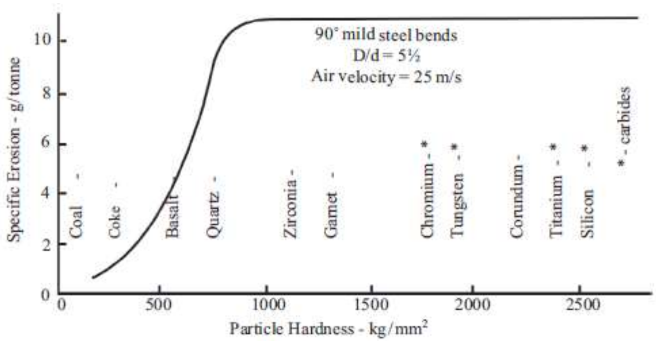

Fig.6 The influence of particle size and velocity on erosion [1]

2.5 Particle Concentration

Solid loading ratio or particle concentration is the number of particle striking per unit material surface. This parameter has received little attention in basic research work on the subject and generalized understanding is that erosion decreases only very slightly for a large increase in concentration .The gradual reduction in erosive wear with increase in solids loading ratio is that as the particle concentration increases, fewer impacts occur between the particles and the bend wall surface because of the interference of an increasing number of other particles [20]. D.Mills and J.S. Mason [10] through the experimentation on erosion of flat plates in sand blast type test rigs it has generally been concluded that the effects of particle concentration are very small. The graph of result in shown in fig.7, Showing the decrease in mass eroded with solid loading ratio.

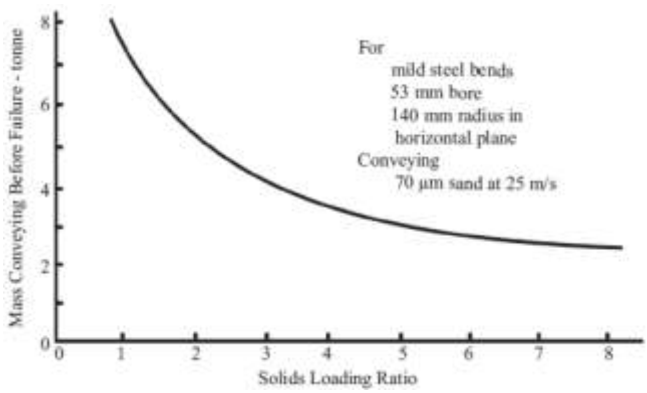

Fig.7 Influence of phase density on the conveying capacity of bends.[10]

D. Mills derived, the following relationship for erosive wear (Eqn.2.3):

Mass Eroded = Constant × Solids Loading $\text{Ratio}^{-0.1}$ Eqn.2.3

The further found that the depth of penetration of particles into the bend wall surface varies with particle concentration. As the solids loading ratio increases, the particles tend to focus on a smaller area of bend wall surface such that the rate of penetration of the particles increases In terms of the mass of metal that has to be eroded from a bend before failure occurs, the author has derived the following relationship eqn.2.4:

Mass Eroded = Constant × Solids Loading Ratio$^{-0.74}$ Eqn.2.4

2.6 Particle Shape-

The influence of particle shape on mass eroded has been reported by many researchers [20, 21]. This variable has also plays a significant role in erosive wear. The generalized result observed is that, smooth and rounded particles do not cause as much erosion as sharp angular particles, under similar conditions of impact velocity and surface and particle hardness. Markus Liebhard and Alan Levy [20] also found that the angular particle erosivity increased with particle size to a level which became more or less constant with size at lower velocities, but increased continuously at higher velocities. For test work on the erosive wear of pipe bends in pneumatic conveying system pipelines, there is generally a need to recirculate the conveyed material. As a result of recirculating the material, it degrades and the sharp angular corners and edges of the fresh material are gradually worn away, and they become more rounded and hence significantly less erosive. This is a major problem when test facilities are used to assess component life.

2.7 Surface material and Erosion mechanism

In context of ductile behavior, a remarkable feature is that the variation of the weight loss with angle of impingement is very similar for materials with widely different thermal and physical properties[22]. This is illustrated in Fig. 8 for three metals which behave in a ductile manner when eroded by small enough particles. The similarity of the weight-loss curves for materials with widely different properties suggests that the erosion mechanism the same in all cases. Bitter[5] and Finne[2] Through experimentation observed that ductile material wear out by the cutting action of solid particle while brittle and hard material erosion occurs by the propagation and intersection of cracks produced by impacting particles i.e. wear out by repeatative deformation by erodent particle.

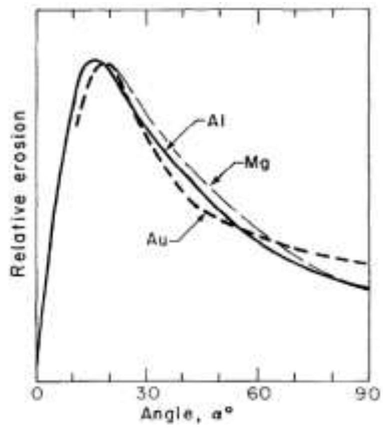

Fig.8 Erosion of Aluminum, gold and magnesium by 127 µm (120 mesh) SiC particles.[22]

3. CONCLUSIONS

(1) Particle impact velocity is the major influencing parameter in erosive wear of pipelines as it can be related to erosion wear by exponential power of 2-2.3. This makes it important to avoid any excessive increase in conveying velocity.
(2) Impingement angle is also a prominent factor which is to be taken in consideration specially in designing of bend section and diverter section.
(3) Solid loading ratio does not vary with conveying air velocity or pressure. And it should be kept above a significant value to avoid its influence in erosion of material.
(4) The shape of particles was a major factor in determining their erosivity, angular particles generally being an order of magnitude more erosive than spherical particles.
(6) Ductile and brittle material both erode in different manner, ductile material erode by cutting action of erodent while brittle material erode by crack propagation.
(7) Velocity and particle size are two of the major variables which must be considered in erosive wear.

REFERENCES

1) D.Mills , Pneumatic conveyimg design guide, Elsevier Butterworth-Heinemann, 2004

2) Iain Finnie, Erosion of surfaces by solid particles, Wear 3 (1960), 87-103

3) Anthony John Burnett, The use of laboratory erosion tests for the prediction of wear in pneumatic conveyor bends, 1996, The University of Greenwich, London

4) H. Wahl AND F. Hartstein, Strahlverschleiss, Franckh'sche Verlagshandlung, Stuttgart, 1946.

5) J. G. A. Bitter, A study of erosion phenomena, Wear, 6 (1963) 5-21

6) G.P. Tilly, Erosion caused by airborne particles, Wear, 14 (1969), 63-79

7) J. E.Goodwin, Study of erosion by solid particles, Proc lnstn Mech Engrs (1969) Vol 184 PI 1 No 15

8) Wendy Sage and G. P. Tilly, The Significance of Particle Size in Sand Erosion of Small Gas Turbines, The Aeronautical Journal of the Royal Aeronautical Society, 1969, VOL. 73

9) D.Mills and J. S. Mason, Particle size effects in bend erosion, Wear, 44 (1977) 311 – 328

10) D. Mills and J. S. Mason, Particle Concentration Effects in Bend Erosion, Powder Technology. 17 (1977) 37 – 53

11) I. Finnie, The mechanism of erosion of ductile metals, Proceedings of the Third National Congress on Applied Mechanics, New York, 1958 pp. 527–532.

12) G.P.Tilly, A two stage mechanism of ductile erosion, Wear, 23 (1973) 87-96.

13) W.H.Jennings, W.J.Head and C.R.Manning, Jr, A mechanistic model for the prediction of ductile erosion, Wear, 40 (1976) 93-112.

14) I.M.Hutchings and R.E.Winter, Particle erosion of ductile metals: A mechanism of material removal, Wear, 27 (1974) 121-128.

15) G. Sundararajan, The depth of plastic deformation beneath eroded surfaces: the influence of impact angle and velocity, particle shape and material properties, Wear, 149 (1991) 129 – 153.

16) I. Finnie, J. Wolak and Y. Kabil, Erosion of metals by solid particles, ASTM J. Mater., 2 (1967) 682-700.

17) R. Macchini , M.S.A.Bradley , T.Deng , Influence of particle size, density, particle concentration on bend erosive wear in pneumatic conveyors, Wear 303 (2013) 21–29

18) Ambrish Misra and Iain Finnie, On the size effect in abrasive and erosive wear, Wear, 65 (1981) 359 – 373

19) Tilly GP. Erosion caused by impact of solid particles. Treatise on Materials Science and Technology, vol. 13. New York: Academic Press; 1979. ,pg. 287-319.

20) Markus Liebhard and Alan Levy, The effect of erodent particle characteristics erosion of metals, Wear, 151 (1991) 381-390

21) Jia-wei Zhou et al., Effects of particle shape and swirling intensity on elbow erosion in dilute-phase pneumatic conveying, Wear380-381(2017)66–77

22) Iain Finnie, Some reflections on the past and future of erosion, Wear 186-187 (1995) l-10

23) J. S. Mason and B. V. Smith, The Erosion of Bends by Pneumatically Conveyed Suspensions of Abrasive Particles, Powder Technology., 6 (1972)

24) Amit Suhane and Vijay K. Agarwal, Effect of Bend Geometry on Erosion and Product Degradation in Pneumatic Conveying Pipeline Systems, IJERA, Vol. 2, Issue 4, July-August 2012, pp.129-136.