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A REVIEW: THE EFFECTS OF PARTICLE PROPERTIES ON SOLID PARTICLE EROSION FOR OIL AND GAS PIPELINES APPLICATIONS

Dinesh Kanesan and Mysara Eissa Mohyaldin
Universiti Teknologi Petronas, Seri Iskandar, Perak Darul Ridzuan, Malaysia
E-Mail: dinesh.kanesan@utp.edu.my

ABSTRACT

The production of sand along with hydrocarbons has been a major problem faced by the oil and gas industry ever since the discovery of oil and gas. The production of sand from the reservoirs may result in erosion, accumulation, plugging and contamination by sand particles. Sand particle erosion may lead to failure of piping components or equipment, leaks in pipelines, and also hazard to personnel on site. Hence, the prediction of solid particle erosion rate is critical in ensuring the integrity of equipment and the safety of the system. Empirical models are developed by performing experiments to measure erosion rate at different particle properties and flow parameters. Particle properties include particle size, shape and hardness. Any change in these properties will result in a change in the erosion rate. In this review paper, the findings of previous researchers on the effects of particle properties on solid particle erosion rates were identified and reviewed. In addition, the limitations in some of the research done were highlighted to enable researchers to further study on the identified areas. This current work would be beneficial to researchers who are developing empirical models by identifying the key particle properties to be included in their solid particle erosion prediction models.

Keywords: solid particle erosion, empirical model, particle size, particle shape, particle hardness.

1. INTRODUCTION

The production of sand together with the reservoir fluid has become one of the major concerns in the oil and gas industry. Sand production can be defined as the migration of the formation sand due to fluid flow from the reservoir. The flow of reservoir fluids results in the increase in inductive effective stresses on the formation and when the induced stress exceeds the formation in situ strength, the formation will fail, leading to sand being produced from the initiated failure [1]. The production of sand would increase at higher fluid flow rate, viscosity and drawdown[2]. There are a variety problems associated with sand production such as damage to well components, erosion in piping system, loss of production due to accumulation of sad in the well bore, increased corrosion rates, damage to rotating equipment, reduced separation efficiency at the separator, faulty instrumentation and control system, and loss of production from shut downs due to sand removal process. However, sand management strategies are usually adopted to minimize sand production and to ensure the field is commercially attractive to develop. Down hole sand exclusion mechanisms such as gravel packs and sand screens are usually installed if sand production is anticipated in the early stage of production. In cases where sand production starts to occur at a later stage, down hole sand exclusion mechanisms can be placed from the beginning of the production and completed when the sand production starts or to design the facilities which are capable of handling produced solids without placing a down hole sand exclusion mechanism.

The knowledge of sand production and erosion is important to ensure that sand production is kept at optimal rates at acceptable erosion levels, maintaining equipment integrity and safety of the system. Sand erosion monitoring systems are used to monitor the effect of sand erosion on equipment and pipelines. Sensors are placed in key pipeline elements and would be very costly and impractical for offshore conditions. Hence, the development of erosion models would be a practical and effective solution for quick prediction in the absence of comprehensive approach to predict erosion problems in pipelines. The estimation of sand erosion in a multiphase flow is a complex phenomenon. Models to predict erosion can be categorized into three different categories, namely empirical, semi-empirical and computational fluid dynamics (CFD). Empirical models are developed by performing experiments to measure erosion rate at different particle properties and flow parameters. Particle properties include particle size, shape and hardness. On the other hand, flow parameters include pressure, temperature and velocity. The main objective of this paper is to provide a comprehensive review on the particle properties which affects the solid particle erosion rate. The review on the effects of particle properties on solid particle erosion would enable researches to focus on the key properties which impacts the erosion process the most when developing empirical models.

2. EFFECTS OF PARTICLE PROPERTIES ON SOLID PARTICLE EROSION

Research has shown that there are numerous particle properties which influence solid particle erosion rates. The properties of solid particles such as its size shape and hardness has significant effects on erosion rates. These properties have to be studied individually to enable a better understanding of the effects of each parameter on the erosion rate. The following section summarizes the experimental conditions and the findings of various researchers on the effects of particle size, shape and hardness on solid particle erosion rates.

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2.1 Particle size

Particle size is an important parameter to be analysed in solid particle erosion as it has a major influence on the erosion magnitude. Many experimental investigations have been conducted to understand the basic mechanism of the erosion process and to identify the effect of different parameters on erosion rates. The effect of particle size on the erosion rates has been studied extensively and the general findings suggest that the increase in particle size corresponds to an increase in erosion rates until a limiting value of particle size. This is because bigger particles possess higher kinetic energies compared to smaller particles travelling at the same velocity. Higher kinetic energies transferred from the larger particles results in quicker erosion process compared to lower kinetic energies transferred by smaller particles which has less impact to erode the surface.

In one of the earliest investigations conducted on the effect of particle size on erosion using a slurry pot tester, Tsai *et al*. [3] found that erosion rates of metal alloys (304SS and 316SS stainless steel) increased as the erodent mean size was increased. In their experiment, coal and silicon carbide sized 24 µm and 150 µm respectively were added to kerosene to form slurry with concentrations of 30% and 50% weight of erodents. The slurry, at 25 ^{o}C was rotated at two different velocities, namely 20 and 40 ft/s for 2 hours prior taking the weight loss measurements of the target material. The analysis from using different sizes of coal and silicon carbide particles showed similar pattern in terms of the effect of particle concentration and fluid velocity. However, the erosion rates were found to be higher for the silicon carbide particles which were bigger in mean diameter since it has more kinetic energy compared to the smaller sized coal particles. In addition, silicon carbide particle resulted in higher erosion rates since it possesses higher average hardness and density compared to coal particles.

To enable representative results on the analysis of the effects of particle size on erosion rates, particles of the same composition has to be used. This was addressed by Levy and Hickey [4] who studied the effects of particle size on erosion rates in a similar experimental set up using slurry pot tester. They used two different meshes (30 mesh coal and 200 mesh coal) to produce two different sets of particle distributions as illustrated in Table-1. Their findings suggest that the erosion rates were higher at 4 times higher for large coal particles (30 mesh coal) compared to the smaller coal particles (200 mesh coal) used in the experiment. However, the presence of finer particles (less than 38 µm) may affect the overall findings of this research. This is because; the fine particles could form a barrier over the surface of the target material which reduces the impact velocity of the larger particles when it strikes the surface of the target material.

Table-1. The particle size distribution for 200 and 30 mesh coal [4].

Size range (µm)	**Particle size distribution** (wt %)	
	200 mesh coal	**30 mesh coal**
< 600	0.24	2.46
495 – 600	0.67	2.16
300 – 495	0.57	7.73
150 – 300	0.24	24.78
90 – 150	3.09	25.29
38 – 90	68.05	20.61
< 38	27.14	17.00

Similar findings were also reported when slurry jet testers were used instead of slurry pot testers. Brown *et al*. [5] studied the erosion rates of 70 µm and 210 µm sized silica spheres particles on aluminium alloy 1100 at a velocity of 122 m/s and an impact angle of 90^{o} using a gas blast rig. Figure-1 illustrates the experimental findings of their experiment. From weight loss measurement and extensive scanning electron microscopy investigations, they found that erosion rates were higher for large silica spheres compared to small spheres. Moreover, their reported findings suggest that there is an incubation period whereby an initial weight gain was observed for the target material followed by a steady state linear erosion rate. The initial weight gain was due to the embedment of erodent fragments on the surface of the target material. To avoid the inaccuracies due to embedment of erodents on the surface of the target materials, the target material should be cleaned and dried prior weight loss measurement or scanning electron microscopy (SEM) analysis.

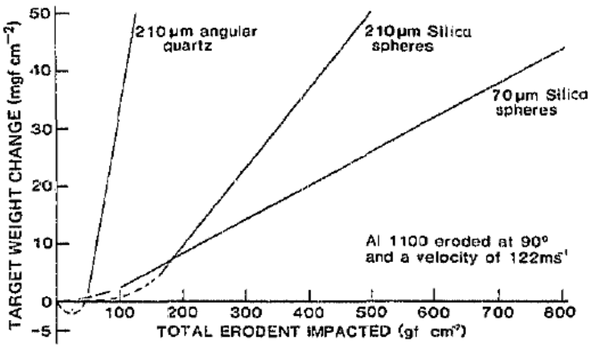

Figure-1. The weight change curve for aluminium alloy eroded by silica and quartz erodent. [5]

Levy and Liebhard [6] in their experiments using a nozzle erosion tester, spherical glass beads as erodents, air as the carrier fluid and steel 1018 as the target material, found that the erosion rate is a function of particle size and shape. Although in general erosion rate increased with the increase in particle size, they reported that angular particles displayed more erosive behaviour than spherical particles. They observed that erosion rate increased with

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particle size to a peak value and decreased at higher particle sizes for spherical particles. For angular particles, the erosion rate increased with an increase in particle size ranging from 44 µm to 200 µm and approached a constant erosion rate for particle sizes ranging from 200 µm-800 µm at particle velocity of 20 m/s but a direct proportional relationship was observed between erosion rate and particle size at particle velocity of 60 m/s. The difference in erosion rates can be attributed to the different threshold kinetic energy and cutting mechanism between angular and spherical particles.

Desale *et al.* [7] found a similar trend in their research using liquid as the carrier fluid instead of gas. In their experiments, aluminium alloy (AA6063) was eroded with quartz particles sized from 37.5-655 µm in a sand water mixture concentration of 20% by weight. The erodents were rotated in a slurry pot tester at a velocity of 3 m/s with impact angles of 30^o and 90^o. The results of their experiments are illustrated in the plot in Figure-2. It was found that the increase in particle size results in an increase in the average weight loss of the target materials. Figure-3 shows the kinetic energy of the particles as a function of particle size which was deduced from their studies [7]. At a constant velocity, the higher kinetic energy possessed by bigger particles resulted in a larger volume of material removed from the target material. In addition, from Figure-2, it is evident that the rate of mass loss rate of the target material is proportional to the increase in particle size for particle size above 200 µm and 256 µm for impact angles of 30^o and 90^o respectively. This was not the case for particle sizes less than 200 µm and 256 µm, whereby the increase in particle size does not correspond to the rate of target material mass loss. This phenomenon was investigated using SEM and it was found that particles less than 200 µm and 256 µm appeared to hit the surface of the target material, but craters were not formed at the surface due to the low kinetic energy at the time of impact.

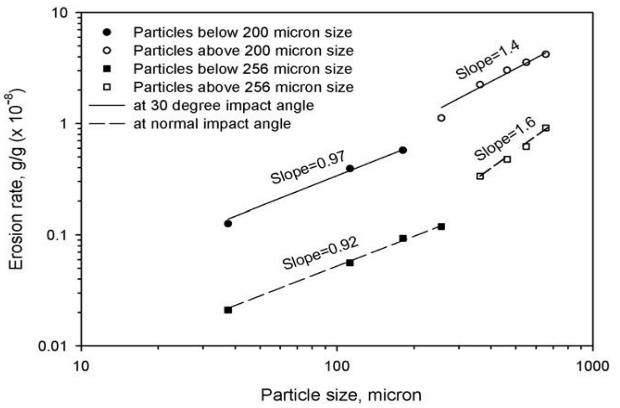

Figure-2. The effect of particle size on the erosion rates of AA 6063 target material at impact angles of 30^o and 90^o[7].

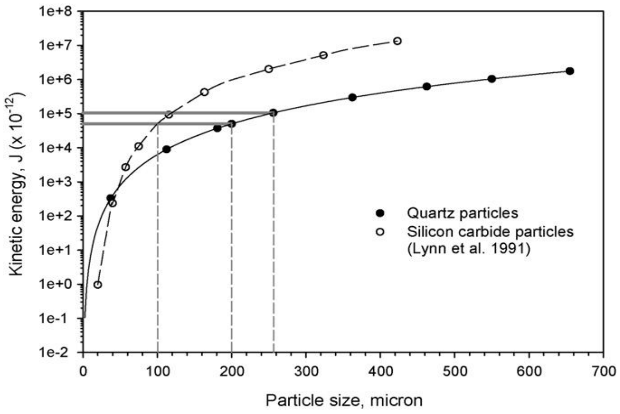

Figure-3. The kinetic energy of particles as a function of particle size [7].

In a similar study, Lynn *et al*. [8], found a linear relationship between erosion rate and particle size until a the critical particle size of 100 µm which is illustrated in Figure-4. In their experiment using a slurry pot tester, P110 steel was eroded with silicon carbide particles ranging from 20 µm to 500 µm with a concentration of 1.2 weight % in diesel oil at impact velocity of 18.7 m/s. In this study, the erosion rates reported were much higher than the findings reported by Desale *et al*. [7] since the fluid velocity was much higher, approximately 6 times higher. In addition, when the particle sizes are translated to kinetic energy upon taking into consideration the density and velocity of the particles, the kinetic energy calculated for the 100 µm and 200 µm particles were in the range of 5 x 10^{-8} Joules. This suggest that the threshold kinetic energy for craters to be formed at the surface of the target material to be in the range of 5 x 10^{-8} Joules. Moreover, the critical particle size identified in this study was also different which strongly suggests that the erosion mechanism is not solely dependent on the particle size but is a function of other flow and particle characteristics.

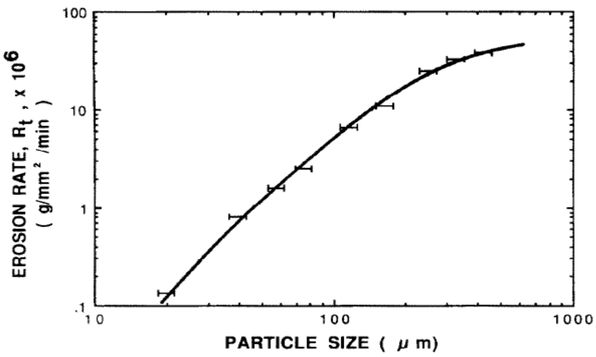

Figure-4. Erosion rates of P110 steel observed for different particle sizes of silicon carbide particles in diesel oil [8].

Since the onset of the impact of particle size on erosion rates, many researchers have concluded that the erosion generally increases win the increase in particle size according to the power law relationship whereby the power index for particle size varies according to the flow

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and particle characteristics. Clark [9]established the relationship between particle size and erosion rate as a power-law relationship illustrated in Equation 1.

$$\text{Erosion rate} \propto (\text{particle size})^{m} \quad (1)$$

The exponent 'm', referred to as the particle size exponent and its value is dependent on the material property, flow conditions, particle impact angle, particle size and particle distribution. The particle size exponent has then been analysed extensively and to enable researches to formulate a correlation between erosion rate and particle size depending on experimental parameters. The variation found in the reported values of the particle size exponent is due to the fact that there were various sizes of erodent particles used, different shapes of erodent particles, different type and velocity of carrier fluid and many other notable factors.

In a study of slurry properties on erosion wear of pump materials, Elkholy [10] found that the amount of wear corresponds to an increase in sand particle size. Cast iron were eroded with silica sand particles ranging from 410-560 μm at an impact angle of 30^{o} and impact velocities of 5-30 m/s for 2 minutes. Based on the power-law relationship, it was found that the relationship between particle size and erosion rate varied with an exponent of 0.616. The particle size exponent found was lower than the reported values of other researchers, partly due to the short experiment run time and due to particle degradation since the experiment was done in a closed loop.

In another similar study, James and Broad [11] found that the wear rate increased to an increase in particles size with an exponent of 0.6, 0.9 and 1.2 for velocities of 2, 4 and 6 m/s. In their study, mild steel pipe was eroded with silica sand size ranging from 15-1500 μm with a concentration of 10 % by volume for duration of 100 hours in a closed loop test rig. Figure-5 illustrates the calculated slope for each of the fluid velocity run in the experiments conducted. In all three curves, the wear rate increased proportionally to the particle size but erroneous points were obtained after a mean diameter of 150 μm for velocities of 4 and 6 m/s. The deviation from the straight line curve can be attributed to excessive particle degradation due to the lengthy duration of the experiment run. However, to reduce the effects of particle degradation on the erosion wear studies, the tests were conducted for 100 hours as the preliminary studies showed that the material degradation was not very severe for durations less than 100 hours. It was found that at higher velocities (4-6 m/s), erroneous results were reported which was attributed to excessive particle degradation [11].

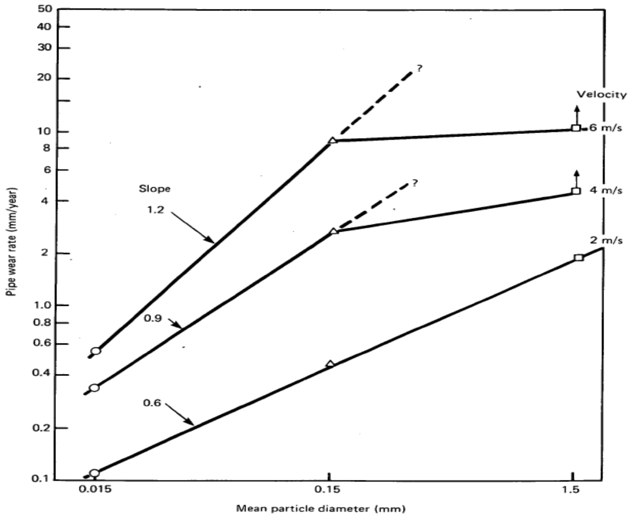

Figure-5. The particle size exponent for fluid velocities of 2,4 and 6 m/s.[11]

Gupta *et al.* [12]conducted a systematic study on the effect of copper tailing particles sized 112.5 μm and 223.5 μm on different type of target materials, namely ductile material (brass) and brittle material (mild steel) .Using a slurry pot tester with varied concentrations of erodent particles of 25 weight % and 15 weight % and velocities of 3.92, 5.49 and 8.06 m, the particle size exponent was calculated. Based on the data points from the experiments conducted, the particle size exponent for ductile material (brass) and brittle material (mild steel) were 0.291 and 0.344 respectively. In order to eliminate the effects of degradation of erodent particles which reduces the erosion rates, the authors replaced the slurry every 30 minutes throughout the experiment.

Using a jet impinging experimental set up, Stack and Pungwiwat [13] studied the impact of increasing particle sizes of alumina and silicon carbide from 250-1000 μm on the erosion rates of iron, aluminium, stainless steel, alumina and teflon target materials. The erosion rates were studied at five different fluid velocities namely 4, 6, 8, 10 and 11 m/s and impact angles ranging from 22.5^{o} to 90^{o}. For all cases, the erosion rates peaked at a certain intermediate particle size which varied for different particle and target material properties. Table-2 illustrates the particle size exponent derived for the erosion of alumina and silicon carbide on iron, aluminium, stainless steel, alumina and teflon. The particle size exponent, m was not evaluated for cases where the erosion rate did not increase in continuously with the increase in particle size. From the findings, it can be concluded that the particle size exponent, m varies according to properties of the target material and the carrier fluid velocity. Moreover, there is a strong link between particle size exponent, m and the erosion mechanism of the target material. Silicon carbide erodents resulted in a greater particle size exponent due to the greater cutting efficiency of the angular silicon carbide particles compared to the alumina particles.

To understand the relationship between erosion rate and particle size, experiments were conducted using particles which are in a particular size range since it's difficult to obtain all equivalent sized particles [14]. These findings were later used to develop the particle size exponent according to the power law as described in Equation 1.

Table-2. Particle size exponent for the erosion of alumina and silicon carbide on iron, aluminium, stainless steel, alumina and Teflon [13].

Erodent	Velocity (m/s)	Particle size exponent, m				
		Iron	**Aluminium**	**Stainless steel**	**Alumina**	**Teflon**
Alumina	6	-	-	-	1.52	-
	8	-	-	-	1.63	-
	10	-	-	-	1.74	-
	11	-	-	-	1.78	-
Silicon carbide	4	2.40	3.11	0.91	1.73	1.05
	6	1.91	2.15	0.60	2.26	0.73

Gandhi and Borse[15] attempted to study the effect of sand particle size and sand particle size distribution on the erosion rate of cast iron in water as the flow medium. The main aim of their research is to distinguish the effects of finer particles which are present in multi sized sand water slurry. Six different water-sand slurries with different particle size distribution were tested at a concentration of 20% by weight, velocity of 3.62 m/s and impact angles of 30^{o} and 75^{o}. As illustrated in Figure-6, their findings suggest that the addition of finer particles (less than 75 µm) reduces the erosion wear. This phenomenon could be due to the formation of a thin protective layer over the target material by the fine particles which reduces the impact velocity of larger particles before it strikes and erodes the surface of the target material. In addition, as the reported by other researchers, fine particles possess insufficient kinetic energy to create craters on the surface of the target material during its impact [4, 5] [16].

Cutting and deformation are two mechanisms which takes place during the erosion process. Researchers have found that the cutting mechanism is largely influenced by the particle velocity parallel to the surface of the target material and the deformation mechanism is mainly attributed to the particle velocity normal to the surface of the target material [9, 17, 18].

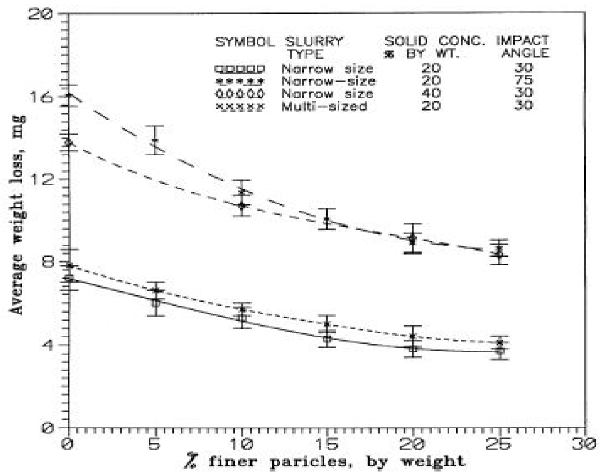

Figure-6. The effects of finer particles (less than 75 µm) on the weight loss of cast iron [15].

In addition, the power law relationship which describes the relationship between erosion rate and particle size could be refined according to the individual contributions from the cutting and deformation mechanisms. In an attempt to study the effects of particle size on erosion rate due to the cutting mechanism, Gandhi *et al.* [19] modified the setup of a slurry pot tester and found that the erosion rate for parallel flow increases with the increase in the particle diameter for all flow velocity and slurry concentration. The findings from their experimental studies using a slurry pot tester is illustrated in Figure-7. They used zinc tailing materials sized from 75-1180 µm to erode a brass pieces at impact velocities ranging from 3.2-8.18 m/s concentrations in water ranging from 20-40 % by weight. One of the key findings from their study is that the cutting mechanism is not strongly dependent on particle size compared to a strong dependence on flow velocity. This shows that the power law relationship which describes the relationship between erosion rates and particle diameter is valid for the range of

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flow and particle characteristics which was chosen by the respective researchers.

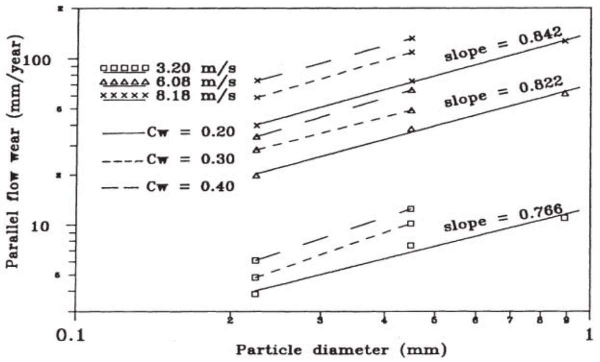

Figure-7. The effect of particle diameter on the parallel flow wear [19].

In a parametric dependence of erosion rates of Aluminium in a sand-water slurry flow, Patil *et al.* [20] found that the erosion rate increases in a linear manner with the increase in particle size for all the impact angles tested. In their experiment, sand particles with mean sizes of 225, 505 and 855 µm at a concentration of 20% by weight in water was used to erode aluminium samples. The experiments were conducted at six different impact angles between 0^o till 90^o at a flow velocity of 3.68 m/s. As illustrated in Figure 8[20], it is evident that the erosion rate increases with the increase in particle size for all the tested impact angles. In addition, the rate of increase in erosion rate is low for impact angles less than 45^o and higher for impact angles more than 45^o. The highest erosion rate increment was found for an impact angle of 90^o. This gives rise to the need to conduct more studies of erosion rates at critical equipment such as 90^o elbows which is susceptible to sudden change in momentum as a result of change in flow direction.

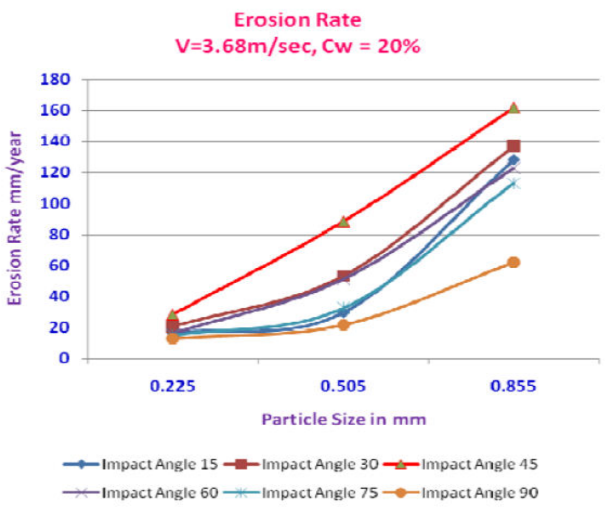

Figure-8. The effect of particle size on erosion wear at different impact angles [20].

Razzaque *et al.* [16] studied the effect of sand particle size on erosion of metal specimens at different sand particle concentrations. Sylhet sand was sieved to get a three ranges of sand particles sizes namely, less than 250 µm (A), 250-590 µm (B) and 590-1100 µm (C). On the other hand, the sand concentration in water was varied between 10, 15 and 20% by weight. Using a slurry pot tester, carbon steel 1015 was eroded at a velocity and impact angle of 3.3 m/s and 90^o respectively. As illustrated in Figure-9 [16], it is evident that the erosion rate increases with particle size for all three concentrations studied. In addition, higher increments of erosion rates were observed for larger sand particles. Besides having lesser impact energies than larger particles, the smaller particles tend to lose some of its impact energy before striking the surface of the target material due the hindrance of finer particles present in the slurry.

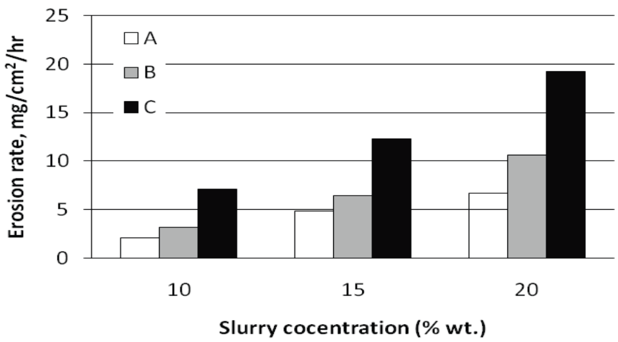

Figure-9. The erosion rates for erodent grade A, B and C and various concentrations [16].

2.2 Particle shape

Many researches have concluded that particle shape has a significant contribution towards the magnitude of solid particle erosion behaviour [5, 6, 21-31]. The influence of particle shapes has to be well understood to enable better understanding of the solid particle erosion process. In one of the earliest studies on the influence of particle shape on erosion rates, Hutchings *et al.* [21] found that different impact process may occur when erodents are of different shapes even if other particle and flow properties remained constant. Hutchings and Winter [32] classified erosion impacts based on the angle between the leading face of the erodent and the surface of the target material. Figure-10 illustrates the observed deformation mechanism for different particle shapes [21]. Figure-10 (a) and (b) illustrates the cutting and ploughing deformation respectively for angular particles. On the other hand, Figure-10 (c) illustrates the ploughing deformation for sphere particles.

Brown *et al.* [5] conducted a series of experiment to study erosion rates of 210 µm sized spherical silica and angular quartz particles on aluminium alloy 1100 at a velocity of 122 m/s and an impact angle of 90^o using a gas blast rig set up. From their experimental findings, the weight loss measurements of the material eroded by angular quartz particles were higher compared to the erosion using spherical silica particles. From Figure-1, it is

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evident that the weight change of the target material is much higher with significantly lesser quantity of angular quartz particles compared to spherical silica particles. Moreover, the SEM analysis suggests that the only additional mechanism which was present in the angular particle erosion compared to the spherical particle erosion was the cutting action. The cutting action and the comparatively larger fragmentation effect during angular particle erosion resulted in a much higher erosion rate. However, the reliability of the findings is questionable since the composition, hardness and density of silica and quartz particles are significantly different. This is because, at similar impact velocity, the particles with higher hardness and density are expected to result in a higher erosion wear.

Besides that, Levy and Liebhard [6] also studied the effects of particle shape on mass loss of the 1018 steel using spherical glass beads and angular silicon carbide using nozzle erosion tester instead of gas blast rig. The particle sizes were varied from 250-600 µm at particle flow velocity of 20 and 60 m/s and impact angle of 30°. As illustrated in Table 3, the particle shape plays a pivotal role in mass loss of the target material. It was observed that the angular particles are more erosive compared to spherical particles at a factor of 10 for smaller particles and 40 for larger particles. However, similar to the findings of Brown *et al.* [5], the results are not representative as composition, hardness and density of the erodents used are not similar.

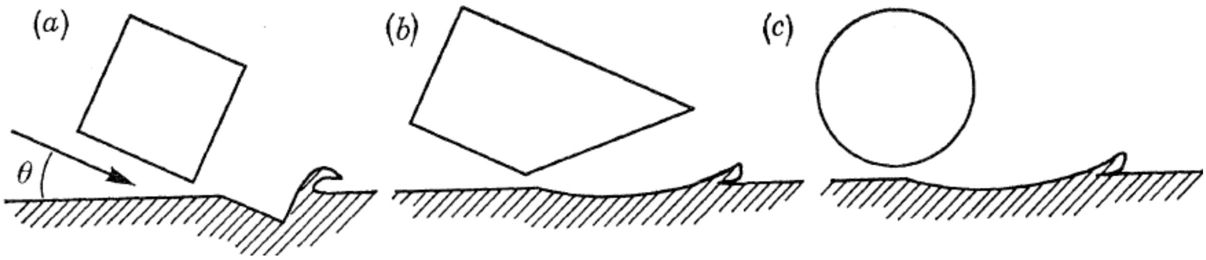

Figure-10. The various deformation models proposed by Hutchings *et al.* [21] for angular and spherical particles.

Table-3. Effects of particle shape on the mass loss of 1018 steel material [6].

Particle size (µm)	**Feed rate** (g/min)	**Mass loss** (mg)			
		20 m/s		**60 m/s**	
		Spherical glass beads	**Angular silicon carbide**	**Spherical glass beads**	**Angular silicon carbide**
250-355	6.0	0.2	1.6	3.8	28.0
250-355	0.6	0.2	2.0	4.5	32.7
495-600	6.0	0.1	-	1.2	-
495-600	2.5	-	2.0	-	42.4

Rao *et al.* [22] conducted a comparative study on the effect of erodent shape on the erosion of rate of three ductile materials, namely aluminium alloy, copper and 1045 steel using bore gun and sand blasting apparatus. Spherical and crushed glass beads size ranging from 20-30 µm were used as the erodents which was flown in gas flow at a velocity of 140 m/s. The weight loss measurements of the target material were taken by dividing the weight loss values with the respective target material densities. The cumulative weight loss of all three target materials for crushed glass particles were higher than the spherical glass beads. In addition, the SEM analysis suggest that the damage patterns from the crushed glass erosion was of "cutting wear" and the damage patterns observed from the spherical glass beads were "deformation wear". The analysis using the same material type and size ensures that the effect of particle hardness and size can be eliminated from contributing to the particle erosion process when studying the effects of particle shape alone.

The advancement in the research pertaining the effects of particle shape on erosion wear was continued by Bahadur and Badruddin [23]. In their research, the particles were characterized according to width to length ratio (W/L) and perimeter squared to area ratio (P^2/A). The SEM analysis showed that the silicon dioxide particles were more regular and circular in shape comparted to the silicon carbide and aluminium oxide particles. Using a sand blast test rig, 18Ni (250) maraging steel was eroded with silicon carbide, aluminium oxide and silicon dioxide particles with sizes ranging from 5-142 µm travelling in air at a velocity of 42 m/s. Based on their findings, the erosion rate increases with the decrease in the W/L ratio and increase in the P^2/A ratio of silicon carbide, aluminium oxide and silicon dioxide particles. Similar to the previous findings [5, 6], they observed that the ploughing mechanism was the dominant mechanism of erosion for spherical particles and cutting mechanism was the dominant mechanism for angular particles. In this study, the velocity of air was not constant for the three particles which was studied, whereby 42 m/s was used for silicon carbide and silicon dioxide and 65 m/s was used for the aluminium oxide particles. In addition, the reliability of the results in terms of the accuracy in comparing the erosion wear may not be accurate since the composition, hardness and density of all three particles used were different.

To further develop the findings of Bahadur and Badruddin [23], Palasamudram and Bahadur [24] proposed the term angularity parameter, A_n which characterizes the particles in terms of sharpness by considering the probability of the corners of a particle to come in contact with the surface of the target material. Using the similar experimental set up and parameters [23] except for a higher flow temperature (500 ^{o}C) and lower fluid velocity (5 m/s), they found that erosion rates increased with an increase in A_n whilst maintain a constant particle size. In addition, the SEM analysis on the target material shows a smoother surface when eroded by rounded silicon dioxide particles compared to a rugged surface when eroded by sharper silicon carbide and aluminium oxide particles. The accuracy of the findings would be more representative if particles of the same composition, hardness and density was used.

In a similar study using silicon carbide and silicon oxide as erodents, Roy *et al.* [25] conducted a series of experiments to study the effects of particle shape on the erosion of copper and its alloys. Using a gas erosion test rig, angular silicon carbide and spherical silicon oxide particles size 200 µm were used to erode three different copper alloys at impact velocities of 38-74 m/s and impact angle of 30^o and 90^o respectively. Firstly, higher erosion rates were obtained for angular silicon carbide particles in comparison to spherical silicon oxide particles. Besides that, the erosion rate increases with an increase in particle hardness for angular particles but reduces with an increase in particle hardness for spherical particles. In addition, the erosion rate for angular particles was maximum at the impact angle of 30^o and the erosion rate for spherical particles was maximum at the impact angle of 90^o.

In a more recent study using silicon oxide and silicon carbide particles as erodents, M. Al-Bukhaiti *et al.* [26]studied the effect of erodent shape on erosion of AISI 5117 steel. Using a whirling-arm tester, AISI 5117 steel were eroded with silicon oxide of sizes from 90-710 µm and silicon carbide of sizes from 24-220 grit at velocity of 15 m/s in a solid water mixture of 1% weight concentration at impact angles of 30^o and 90^o.The characterized the erodent's shape according to circularity factor, ϕ which was developed by Riley in 1941 [33]. The circularity factor, ϕ is equal to unity for circular shapes and any values below unity indicates its departure from circularity. The SEM analysis on the silicon carbide and silicon oxide particles indicate that the former is angular in shape and the latter is nearly spherical in shape. The experimental findings suggest that the circularity factor and erosion rate follows a linear relationship. The increase in shape factor resulted in an increase in wear rates for silicon oxide particles and decrease in wear rates for silicon carbide particles. This trend corresponds with the previous work [23, 24] using the same type of erodents and ductile material as the target material. Since, the particle size and properties such as hardness was not similar between the two types of erodents, the trend observed cannot be attributed to particle shape alone.

In another empirical study using circularity factor as a particle shape classifier, Walker and Hambe [27] studied the effects of particle shape on the erosion rate of white iron. In their study, they used the Coriolis Tester which was reported to produce a more representative results in terms material properties [34]. Table 4 illustrates the particle size, circularity factor and the hardness of the erodents used. Taking into account for the difference in density, the erosion rates were corrected for particle relative density on a linear basis. The results show that the erosion rate increases as the circularity factor decreases following a power law relationship.

Table-4. Erodent properties used in the erosion testing of white iron [27].

Erodent	**Size range** (µm)	**Circularity factor**	**Hardness** (Hv)
Silicon carbide	600-800	0.64	3300
Alumina	600-800	0.71	2400
Sand	1200-2000	0.73	1400

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Table-5. The summary of the properties of the erodent particles used [28].

Erodent	Hardness (Hv)	Toughness (MPa $m^{0.5}$)	Density (g/cm^3)	Shape
Steel shot	286	50	7.8	Spherical
Glass beads	540	0.2-0.7	2.55	Spherical
Silica	1100	1.2	2.67	Irregular
Alumina	1800	3-3.35	3.99	Irregular
Tungsten carbide	2200	5.0	15.7	Irregular
Silicon carbide	2500	3.5-4.5	3.2	Irregular
Diamond	8000	7-11	3.5	Blocky

Feng and Ball [28] expanded the study of erosion on glass, alumina, tungsten carbide cobalt and 304 stainless steel using seven different types of erodent to gain a better understanding on the important parameters which effects the erosion mechanism. Table 5 illustrates the summary of the erodent particle properties used in their experiments. Using a gas blast rig the target materials were eroded with various erodent with different shapes, sizes ranging from 63 - 1000 µm at velocities of 33-99 m/s and impact angles of 30^o-90^o. Based on the SEM analysis conducted, several key findings pertaining erosion mechanisms as a function of particle shape were found. Firstly, irregular shaped particles resulted in the formation of lateral cracks. Besides that, the erosion rate of spherical erodents was largely influenced by particle size and velocity. In addition, particle shape and kinetic energy plays an important role in the erosion of ductile materials where else the particle size and kinetic energy plays a major role in the erosion of brittle materials. Most importantly, it was found that the toughness and hardness of the erodents has a minimal impact on erosion rates of ductile materials.

The uncertainty of using particles of different composition, hardness and density by the previous researchers [5, 6, 23, 24] was addressed by Levy and Chik [29], who conducted a series of experiments to study the effect of angular steel grit and spherical steel shot on the erosion of 1020 carbon steel. Using a nozzle erosion tester, angular steel grit and spherical steel shot with an average size of 100 µm were accelerated in air flow at velocity and impact angle of 80 m/s and 30^o respectively. From their findings, the erosion rate resulted from the impact of angular steel grit particles was four times higher than spherical steel shot particles. The findings correspond with the SEM analysis which shows that sharper craters were formed from the impact of angular steel grit and shallow rounded craters were resulted from the impact of spherical steel shot.

Desale *et al.* [35] studied the effect of particle shape on erosion wear of ductile materials. Using a slurry pot tester with water as the flow medium, AA 6063 and AISI 304L steel were eroded with quartz, alumina and silicon carbide with a nominal diameter of 550 µm at 3 m/s and impact angles varying from 15-90^o. The shape factor calculation suggested by Cox [30] resulted in a significantly high standard deviation which prompted the application of the modified shape factor approach based on the method proposed by Voort [31]. Table 6 illustrates the physical properties of the erodents and their calculated modified shape factor. The results showed that the erosion rate increase with a decrease in the modified shape factor. The effect of density of the erodents were accounted for by the inversely proportional relationship between the modified shape factor and the particle density.

Table-6. The physical properties and calculated modified shape factor of the erodents [35].

Erodent	Hardness (Hv)	Density (kg/m^3)	Modified shape factor	Shape
Quartz	1100	2650	0.7007	Blocky
Alumina	1800	3940	0.3425	Angular
Silicon carbide	2500	3220	0.4425	Angular

The effects of particle shape on erosion is gas and liquid flows taking into consideration of viscosity was studied by Okita *et al.* [36]. The target material selected for this study was aluminium 6061-T6 and 316 stainless steel, where else the erodents used was California 60 mesh sand (300 µm), Oklahoma #1 sand (150 µm), silica flour (20 µm) and glass beads (50-350 µm). For the liquid testing, a submerged jet geometry with liquid viscosities of 1, 10, 25 and 50 cP was used. On the other hand, for the gas testing, a nozzle erosion tester was employed. For the liquid testing, it was found that the shape of the erodent does not significantly affect the erosion rate trend as the fluid viscosity changes. This could be due to the fact that the target material was immersed under liquid and the kinetic energy of the erodents at impact point was drastically reduced due to friction and drag force.

However, for the gas testing, the shape of the erodent plays a significant role in the erosion wear of the target material.

In an attempt to understand the mechanism of material removal due to single solid particle impact, Oka and Nagahashi [37] conducted a series of experiments using a gas gun unit. Aluminium, iron and cast iron were eroded by spherical tungsten carbide ball and angular silicon carbide particle of 3000 µm in diameter travelling at velocities ranging from 50-200 m/s in air and impact angle varying from 20^{o}-90^{o}. From the SEM observations, shows that material removal at impact angles from 20^{o}-40^{o} was evident for angular silicon carbide particles but was not noticeable for rounded tungsten carbide ball. It can be deduced that the cutting action which is associated with the erosion ear of angular particles is largely dependent on the impact angle.

The majority of the studies on particle erosion were performed on ductile materials. Focusing on brittle materials, Ćurković *et al.* [38] studied the effects of hardness and shape of erodents on the erosion of alumina ceramic. Alumina ceramic was eroded with silicon carbide and silicon dioxide sized 350 µm and 600 µm respectively travelling at 25.4 m/s at impact angles ranging from 30^{o} to 90^{o}. Based on the mass loss analysis, they found that the angular silicon carbide erodents resulted in greater wear compared to the more rounded silicon dioxide erodents. In addition, the SEM analysis shows that the more angular and harder silicon carbide erodents resulted in higher surface roughness of the target material. However, the silicon carbide particle has a hardness number 2.4 times higher than the silicon dioxide particle. Hence, the higher erosion rates could be attributed to the angular shape and also the higher hardness number of the silicon carbide erodents.

Although there are many studies which shows that the erodent shape plays a pivotal role in the erosion rate, there has been no clear method to precisely describe the angularity of the erodents. In order to standardize particle angularity, Stachowiak 39] in his study represented particle angularity by numerical parameters namely,' spike parameter-linear fit'(SP) and 'spike parameter-quadratic fit'(SPQ).SP was calculated by constructing triangles around the boundary of the erodents and SPQ was calculated by fitting quadratic segments to the protruding sections of the erodents. In addition, experiments were conducted using a pin-on-disk machine to calculate erosion wear as a function of SP and SPQ. Alumina and brass coupons were eroded with 7 erodents namely glass beads, silica sand, garnet, diamond, silicon carbide, quartz and crushed alumina with respective calculated SP and SPQ. The results show that SP and SPQ exhibits a linear relationship with erosion rates for all the erodents tested. This research allows particle shape to be qualitatively analysed using numerical parameters to predict the contribution of particle shape towards the erosion wear process.

2.3 Particle hardness

In addition to particle size and shape, the particle hardness also has a significant influence on the solid particle erosion. In one of the earliest investigations in the field of solid particle erosion, Tsai *et al*. [3]conducted a series of experiments to study the effects of particle hardness on erosive wear quantitatively. Coal and silicon carbide particles sized 24 µm and 150 µm with an average hardness of 3.8 HM and 9.5 HM respectively were added to kerosene to form slurry with concentrations of 30% and 50% by weight. The slurry was circulated at two different velocities, namely 20 and 40 ft/s for 2 hours prior taking the weight loss measurements of the target material. The erosion rates from using silicon carbide particles of higher average hardness were higher compared to coal particles. However, this finding cannot be attributed to the effect of hardness alone since the silicon carbide particles were much bigger than the coal particles used. This would result in a greater impact force since the silicon carbide particles would be travelling at higher kinetic energies.

Wada and Watanabe [40] attempted to study the dependence of erosion wear on erodent hardness of brittle materials using the ratio of target material hardness to erodent hardness (H_P/H_T). Tables 7 and 8 illustrates the properties of erodents and target material used in their experiment. All the erodents except iron were of sizes between #20 and #32 grit and almost similar irregularity. However, the iron particleswere0.8, in diameter and angular in shape. The tests were conducted using a stationary impact test using air at a velocity of 300 m/s as the carrier fluid. They concluded that the erosion rate depends greatly on the ratio of H_P/H_T. It was found that the erosion rate decreases as the ratio of H_P/H_T decreases since particles are not able to penetrate the surface of the target material and to form lateral cracks. In addition, for the ratio H_P/H_T of above unity, the target material exhibits plastic deformation by radial and lateral crack formation. Although the particles tested were of different hardness, the particle sizes of the various erodents were not similar. Hence, the erosion rates could have been influence by particle size and hardness collectively.

Table-7. Properties of the erodent particles used in the experiment [40].

Erodent particles	**Hardness** (GPa)	**Weight of particle** (mg)
Silicon carbide	29.3	0.60
Aluminum oxide	16.6	0.56
Silicon nitride	13.9	0.76
Partially Stabilized Zirconia	14.0	1.20
Magnesium aluminate	14.5	0.52
Magnesium oxide	9.0	0.60
Glass	6.0	0.36
Iron	3.7	2.0

Table-8. Properties of the target materials used in the experiment [40].

Target material	**Hardness** (GPa)
Silicon nitride	13.9
Partially Stabilized Zirconia	14.0
Silicon carbide	24.3
Glass	5.8

Shipway and Hutchings [41] also studied the role of particle hardness on the erosion of brittle materials but with equal sized erodent particles. A gas-blast erosion apparatus was used to accelerate 125-150 µm sized erodent particles in compressed air at 60 m/s and at an impact angle of 90^o. Table 9 and 10 illustrates the properties of the target material and erodent particles used in their experiments. From their findings, they concluded that generally the erosion rates increased as the ratio of particle hardness to target material (H_P/H_T) increased. In addition, similar to the findings of Wada and Watanabe [40], the erosion rates were low for conditions where H_P/H_T was less than unity. Moreover, the SEM analysis shows that the comparatively softer erodents resulted in small scale chipping where else comparatively harder erodents resulted in indentation induced fracture on the surface of the target material.

In a similar study but using ductile materials, Srinivasan and Scattergood [42] found that there is a profound change in erosion rates when the ratio of target hardness to hardness of erodent particle (H_P/H_T) approaches unity.. However, in this study, the two erodents namely aluminum oxide and silicon carbide with identical particle sizes of 405 πm were used. The particles were accelerated at 80 m/s in air flow using an air blast type erosion rig to erode sintered and commercial aluminas with varying hardness. Firstly, the erosion rate increases as the hardness of the samples reduces. In addition, higher erosion rates were observed using silicon carbide particles which has higher hardness compared to alundum particles. This corresponds with the trend observed by Wada and Watanabe [40] whereby the erosion rate increases as the ratio of target material hardness to erodent hardness (H_P/H_T) increases. Moreover, SEM analysis shows that H_P/H_T ratio above unity results in the formation of lateral cracks in brittle ceramics and lower than unity H_P/H_T ratio results the crushing and fragmentation of softer erodents upon impact on the harder target material.

Wellman and Allen [43] studied the effects of erodent hardness on the erosion rates of M94 and M94F aluminas. The hardness of the M94 and M94F aluminas were 1764 and 1789 H_V respectively. The properties of the erodents are described in Table-11. Using a compressed air erosion rig, the alumina materials were eroded using the erodents listed in Table-8 at velocity of 40 m/s and impact angle of 60^o. Analysing their results in terms of H_t/H_p (target material hardness/erodent hardness) ratio, they found that the erosion rate with silicon carbide (H_t/H_p =1.64) was the highest followed by aluminium oxide (H_t/H_p =1) and silicon oxide (H_t/H_p =0.72). As expected, the erodent with a higher hardness value resulted in higher erosion rates since the crack initiation and propagation takes place at a higher rate compared to erodents with lower hardness values while maintaining other experimental parameters constant.

Table-9. Properties of the target materials used in the experiment [41].

Target material	**Hardness** (GPa)
Soda-lime glass	6.14
Borosilicate glass	8.10
Fused silica	5.54
Partially stabilised zirconia	14.0
Alumina	12.7
Silicon carbide	30.5
Boron carbide	36.3

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Table-10. Properties of the erodent particles used in the experiments[41].

Erodent particles	**Hardness** (GPa)
Silicon	9.3
Silica	13.1
Alumina	26.5
Silicon carbide	33.4

Table-11. Properties of the erodent particles used in the experimental studies [43].

Erodent	**Hardness, H_V**	**Shape**	**Density** (SG)	**Size range** (πm)
Aluminium Oxide	1800	Sharp	3.99	106-125
Silicon Carbide	2500	Angular	3.21	106-125
Silicon Oxide	1100	Rounded	2.63	106-125

In another research to study the effects of erodent properties on the erosion of 1020 carbon steel, Levy and Chik [29] found that erosion rates increased as the erodent's hardness increased. Table-12 illustrates the erodent's hardness measured in Mohs' hardness and Vicker's hardness scale. Using a nozzle erosion tester, the five different particles with an average particle size ranging from 180-250 µm were accelerated in air flow at a velocity of 80 m/s and at impact angles of 30^{o}and 90^o. Their findings suggest that the erosion rates were notably low for the softest materials tested namely calcite and apatite. However, the erosion rates were found to be almost constant as the Vickers' hardness of the material reaches 700 kgf/mm and above. Although the carbide particles had Vicker's hardness, the erosion rates found were almost similar to the sand particles with Vicker's Hardness of 700 kgf/mm. The slight difference in erosion rates were attributed to the different particle shapes of the erodents studied, whereby the silicon carbide particles are much angular in shape compared to the sand and alumina particles. From the SEM analysis conducted, it was found that the calcite and apatite particles with low Vicker's hardness strength tend to break into smaller pieces when they strike the target material. The smaller pieces do not have enough kinetic energy to erode and remove the materials from the surface of the target material.

Table-12. Erodent's hardness measured in Mohs' hardness and Vicker's hardness scale [29].

Particle	**Mohs' hardness**	**Vickers' hardness, HV** (kgf/mm^2)
Calcite, ($CaCO_3$)	3	115
Apatite, ($Ca_5(PO_4)_3$)	5	300
Sand, (SiO_2)	7	700
Alumina, (Al_2O_3)	9	1900
Silicon Carbide, (SiC)	>9	3000

Using a commercially available abrasive water jet apparatus, Fowler *et al*. [44] conducted a series of experiment to study the effects of particle hardness on the milling of titanium alloy (Ti6Al4V). Unlike the conventional sand particle erosion studies, the water jet technology is specifically designed to cut materials in the machining operations. Table 13 illustrates the hardness of the erodents and target material used in this experiment. The erodents with an average diameter of 180 πm were jetted in a water flow of 0.003 kg/s at an impact angle of 90^o. In all cases, it was found that the rate of material removal increased as the particle hardness increased. In addition, it was observed that the material removal rates were higher for particle hardness in the range of 200-1000 H_V and becomes less significant for particle hardness of higher than 1000 H_V. Although there is a direct relationship between particle hardness and material removal rate, the erodents were comprised of different shape factors. It was found that with a shape factor of 1.0, the material removal rate was reduced by 35% and the shape factor becomes less significant at lower value of shape factor. This research reaffirms that the shape factor and particle hardness collectively contribute to the overall erosion wear. On the other hand, Desale *et al.* [45] studied the effects of particle hardness on the erosion wear of ductile materials. Using a slurry pot tester, aluminum alloy 6063 and stainless steel 304L with hardness of 91 H_V and 210 H_V respectively was eroded with three different erodents as described in Table-14. The experiments were conducted at impact angles from 0^o to 90^o in steps of 15^o with erodent particles sized 550 πm at 10% concentration by weight in a water mixture circulated at 3 m/s. Their findings suggest that the increase in target material hardness reduces the overall material removal from the surface of the target material. As a whole, the increase in density, hardness and angularity of the erodents resulted in higher erosion rates. However, the effects of particle hardness alone on the overall erosion rate cannot be identified since the erodents used were of different density and shape which has a considerable effect on the erosion rate of ductile materials.

Table-13. Hardness values of the erodents and target material used in the experiments [44].

Erodents	Hardness (H_V) kgf/mm
Soda lime glass	500
White alumina	1800
Brown alumina	1800
Garnet	1000
Steel shot	200
Target Material	Hardness (H_V) kgf/mm
Titanium	330

Table-14. The physical properties of the erodent particles used in this experiment [45].

Erodent	**Hardness** (H_V)	**Density**	**Shape factor**
Quartz	1100	2.65	0.7007
Alumina	1800	3.94	0.3425
Silicon carbide	2500	3.22	0.4425

Table-15. Operating conditions used in the experiments [46].

Operating conditions	**Submerged apparatus**	**Air/water mist apparatus**
Jet velocity (m/s)	16.8 (liquid)	45.7 (gas)
Particle concentration (kg/kg)	1%	1%
Liquid flowrate (l/s)	0.715	0.013

Table-16. Properties of the erodent particles used in the experiment [46].

Erodent	**Density** (kg/m^3)	**Average size** (μm)	**Hardness** (VHN)
Iron Powder	7860	32	65
Calcite	2710	6	145
Barite	4300	38	173
Hematite	5260	30	600
Magnetite	5170	2	680
Silica flour	2650	24	1000
Alumina	3950	20	2000
Silicon carbide	3210	20	3000

In a more recent study Arabnejad *et al.* [46] conducted a series of tests in submerged and air/water mist apparatus to study the effects of eight different erodents with different hardness on the erosion wear of stainless steel. Tables 15 and 16 illustrates the operating condition and the properties of the erodent particles. In addition, CFD simulations and particle tracking were used to estimate the particle impact velocity. It was observed that the erosion ratio increases with the increase in particle hardness in cases where the hardness of the target material is higher than the hardness of the erodent itself. Lower erosion ratios were observed for particles with lower hardness compared to the target material as the particles may deform during the collision and the kinetic energy possessed by the particles may not be effectively transferred to the surface of the target material.

3. CONCLUSIONS

This review paper consists of the findings of previous researchers on the effects of particle properties, namely particle size, shape and hardness on the solid particle erosion rates in a chronological manner. The experimental conditions and particle parameters of each research conducted were discussed in detail. From the reviewed analysis conducted, it can be summed that the particle parameters play a pivotal role in the solid particle

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erosion rates. Generally, the increase in particle size results in an increase in erosion rates until a critical size is reached and minimal increase in erosion rate is observed if the particle size is further increased above its critical size. This trend was found to be similar for all flow conditions and target material properties. In addition, the particle shape also has a significant contribution towards the magnitude of solid particle erosion behaviour. By categorizing particle shapes into circularity factor or particle shape factor, the particle shape can be defined quantitatively which enables clear indication of its effects on the solid particle erosion process. The general trend observed was higher particle shape factor (more spherical) resulted in lower erosion rates. Lastly, the effects of particle hardness on the overall erosion rates were better analysed in terms of the ratio of particle hardness to target material (H_P/H_T). It was found that the erosion rates increased as the ratio of particle hardness to target material (H_P/H_T) increased and the erosion rates were low for conditions where H_P/H_T was less than unity.

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