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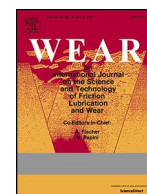
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Preliminary understanding of early-stage damage caused in high density solid particle erosion in particle accelerator piping applications

B. Suitters^{a,b,*}, E.E. Vera Cardenas^{a,c}, W. Thompson^{a,b}, R. Lewis^a, C.J. Densham^b, D. Wilcox^b

^a University of Sheffield, School of Mechanical, Aerospace and Civil Engineering, Sheffield, UK

^b Rutherford Appleton Laboratory, Science and Technology Facilities Council, Didcot, UK

^c Tecnológico Nacional de México/Instituto Tecnológico de Pachuca, División de Estudios de Posgrado e Investigación, Pachuca, Hidalgo, Mexico

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ABSTRACT

For future particle accelerator designs, granular target media are being considered to increase subatomic particle yield. Tungsten particles are of particular interest, but erosive wear has been identified as a key engineering issue. This work assessed the early-stage surface response of different surfaces to impingement by a tungsten erodent. Tests were conducted to compare the performance of three potential target container materials at different impingement angles: stainless steel 316, titanium grade 5 (Ti-6Al-4V), and Inconel 718. Particle velocity in the erosion test-rig was within the design range for a granular target. Impingement angles between 10° and 60° were used. 300 g of tungsten was applied at approximately 20 g/s to ensure that initial wear features could be analysed. Roughness was used to assess surface response to particle impacts, and statistical measures of fit were used to suggest dominant surface properties. The surfaces were measured using an optical profilometer, and inspected using SEM. It was found that roughness reached a maximum between impact angles of 30° and 45° for all materials. Stainless steel 316 and Ti-6Al-4V surfaces were roughened similarly, while Inconel 718 was consistently less roughened showing it may have the best potential, but longer-term wear tests are required to verify this.

1. Introduction

Subatomic particles are often studied by accelerating them to high energies and colliding them with a target material. This is achieved in “particle accelerators” designed to accelerate and direct protons to form beam pulses which are intercepted by the target [1]. Conventional targets are solid monoliths with external cooling. The target undergoes massive thermal shock on each pulse, causing high temperature cycling and subsequent fatigue, limiting the possible beam power. However, increasing beam power generates more particles for study, increasing the yield of results for the physics experiment [2]. For higher beam powers, work is ongoing to investigate novel technologies, such as liquid metal or granular targets for application to a Muon Collider, one of the options considered for the next global high energy physics experiment following the Large Hadron Collider [3]. A flowing target medium allows for external cooling, reducing target temperatures by exposing new material to each pulse. Liquid targets are simpler to construct than granular targets, but cavitation and corrosion can damage the

supporting plant [4]. Granular solids allow the use of conventional target materials [2]. The target container provides the structural integrity of the target and allows for connection of cooling plant, instrumentation and other equipment [5]. Target container materials are chosen due to their radiation damage resistance, strength, and radiochemistry. Due to radiation levels, maintenance operations often take weeks. Minimising downtime is desirable, so target integrity must be maintained [6].

The UK based Science and Technology Facilities Council (STFC) granular target uses a tungsten target material, fluidised by helium gas. The target is housed within an electromagnet to direct the outgoing particles. This is a large, costly part which must be protected from damage by the target container [7]. Erosion from the tungsten impinging on the target container at speeds of between 10 and 30 m/s has been shown to be a concern in previous tests by STFC [3].

At 19 g/cc [8], tungsten is beyond the range of confident experimental data for solid particle erosion, which has typically focused on sand and sand-like particles. Examination of literature on fusion reactor

* Corresponding author. Rutherford Appleton Laboratory, Science and Technology Facilities Council, Didcot, UK.

E-mail address: ben.suitters@stfc.ac.uk (B. Suitters).

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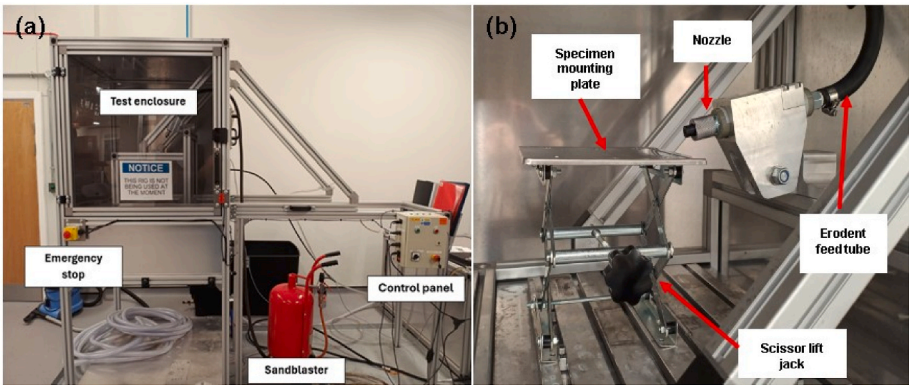


Fig. 1. (a) HiPER Rig; (b) Nozzle set up inside test enclosure.

Table 1

Matrix of Test specimen designations and test parameters.

Impact Angle (°)	60	45	30	10	60	60
Particle Shape	Ang.	Ang.	Ang.	Ang.	Sph.	Ang.
Particle Size (μm)	50-75	50-75	50-75	50-75	60.2	75-106
Counterface	Ti-6Al-4V	Ti1	Ti2	Ti3	Ti4	Ti8
Material & Test Designations	SS316	SS1	SS2	SS3	SS4	-
	Inconel 718	Inc1	Inc2	Inc3	Inc4	-

applications reveals work on impact of tungsten “dust” (a misleading term as the particles were 50-100 μm in diameter) [9,10]. While interesting, the impact velocities of several hundred to thousands of m/s put

the results out of scope for the particle accelerator application being studied here. The impact angle was also 90°. Tests have assessed the impact of particle hardness which has included higher density particles, but not at the level of tungsten. Higher hardness particles tend to give higher erosive wear rates [11], although testing is not always done with

Table 2

Vickers hardness of specimens.

Material	Hv0.5	Std. Deviation	Average Diagonal (μm)	Hv1	Std. Deviation	Average Diagonal (μm)
Ti-6Al-4V	434.5	39.4	46.3	402.4	34.0	68.0
SS316	172.3	1.7	73.4	171.3	2.5	104.1
Inc. 718	338.3	12.5	52.4	312.3	4.8	77.1

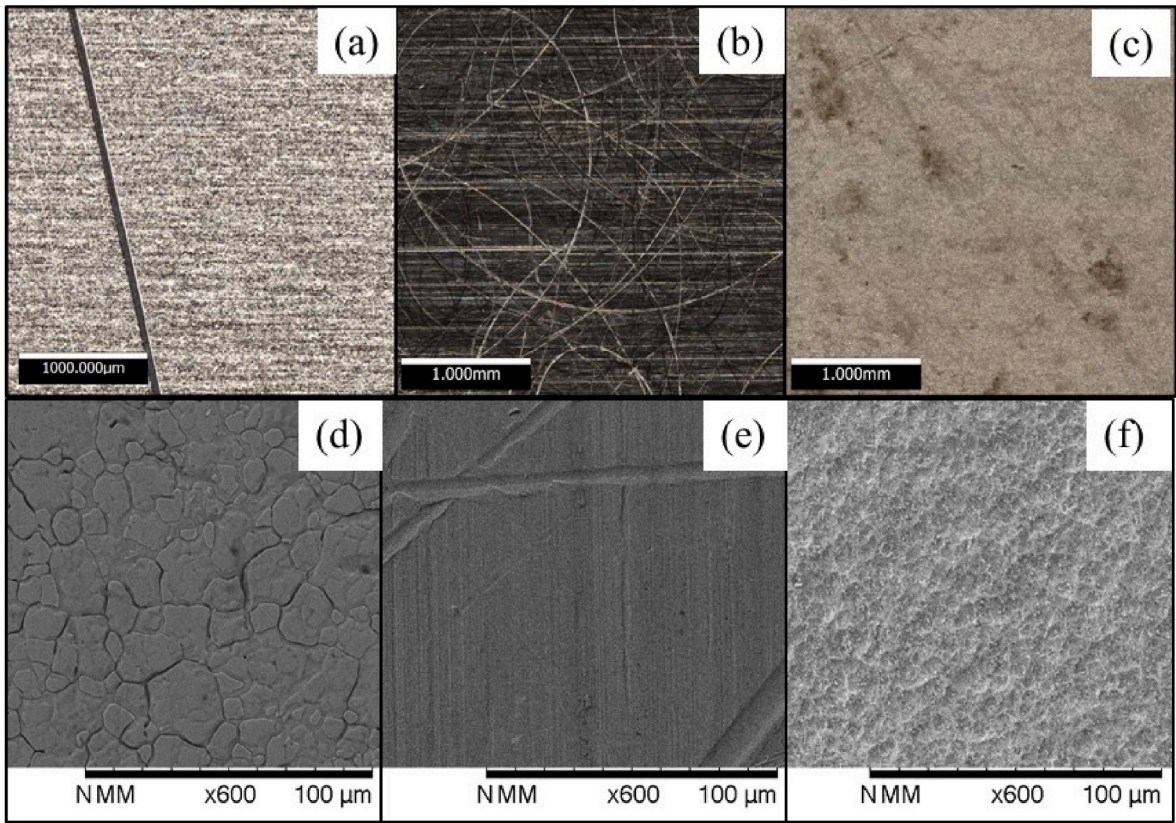


Fig. 2. Specimen surface images from profilometer: (a) SS316; (b) Inconel 718; (c) Ti-6Al-4V; SEM images of specimen surfaces: (d) SS316; (e) Inconel 718; (f) Ti-6Al-4V.

Table 3

Scratch hardness results for test materials.

Material	Scratch Hardness (GPa)	Mean Width (μm)	Std Deviation (μm)
Ti-6Al-4V	5.72	66.7	4.37
SS316	2.36	103.8	2.59
Inconel 718	3.85	81.3	3.22

particles of the same shape. More angular particles have been shown to give higher wear as they cut more effectively on impact, particularly at more shallow impact angles [12,13].

Aside from the influence of particle properties, erosion rates vary greatly with small variations in operating parameters, such as temperature or impingement angle, and counterface properties [14]. Erosion varies with impingement angle of the particle stream in one of two ways, depending on the material. Brittle materials erode most severely at normal impingement angles, due to the fracture-based material removal mechanism. Ductile materials exhibit the worst erosion effects at low impingement angles, around 10° – 20° away from the surface [15–18], where material loss is largely by cutting. Both brittle and ductile

counterface materials exhibit similar wear trends during a test. In the first instance there is a so called “zero-wear” region [19]. Ductile materials are initially indented or cut which just involves deformation or flow of material. The shoulders formed around these features once further impacted are eventually removed and material loss starts to occur. Brittle materials are initially cracked by impacts, but these cracks take some time to grow and interconnect and create spalls.

Materials under consideration for particle accelerator applications include stainless steel 316, Ti-6Al-4V and Inconel 718. Stainless steels are known to erode by ductile means, with worn surfaces exhibiting plastically extruded flakes and smeared wear features [20,21]. Ti-6Al-4V is a common aerospace alloy. Its high strength and radiation resistance make it useful for accelerator applications [2]. Titanium erodes by cutting at low angles, while at high angles ploughing is combined with indentation [22–25]. Inconel superalloys (used as an erosion resistant material for turbines and aerospace applications) are less well researched than stainless steel, but the limited work available shows that they have similar behaviour to steel, but with lower damage rates [26]. Some studies on the performance of this nickel alloy on erosive wear indicates that hardness reduces the energy transferred from

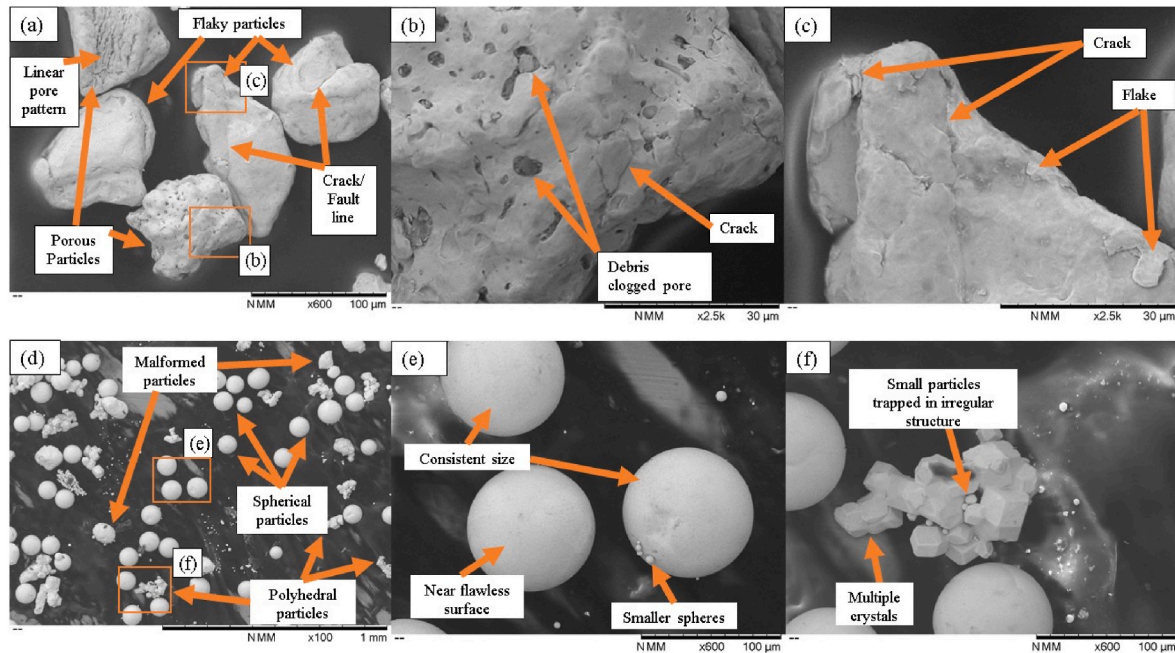


Fig. 3. (a)–(c) SEM Image of Angular Particles ((b) and (c) are enlarged); ((d)–(f) SEM Image of Spherical Particles ((e) and (f) are enlarged).

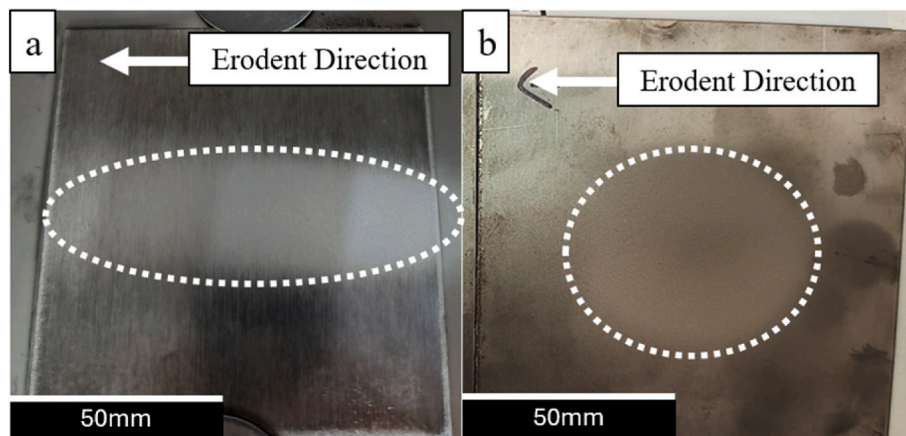


Fig. 4. Erosion Scars from Tests on: (a) Inconel 718 at 10° (Inc4) and (b) Titanium at 60° Impingement Angle Tests (Ti1).

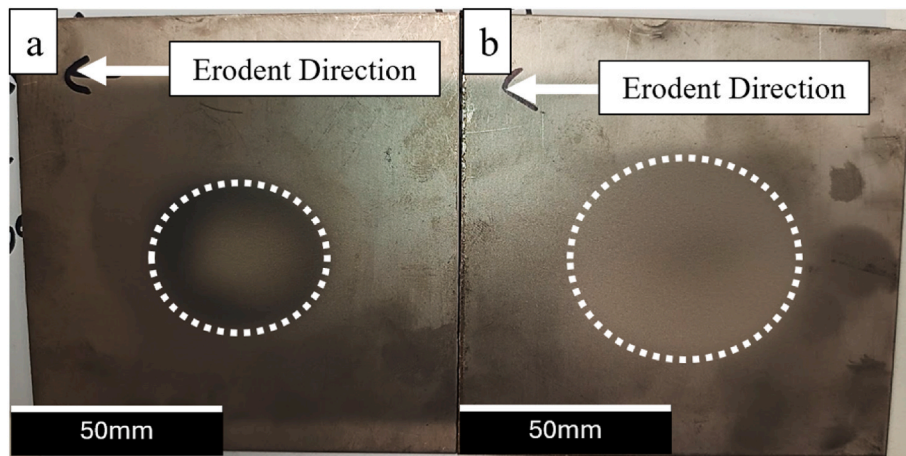


Fig. 5. Ti-6AL-4V 60° Erosion Test Wear Scar Size from: (a) Spherical Particles (Ti8) and (b) Angular Particles (Ti1).

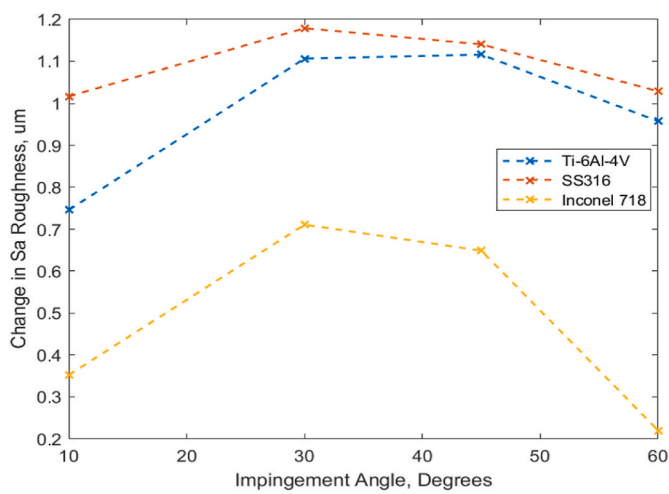


Fig. 6. Average Surface Roughness Values for All Counterface Materials and Impact Angles After Erosion Tests (for angular particles).

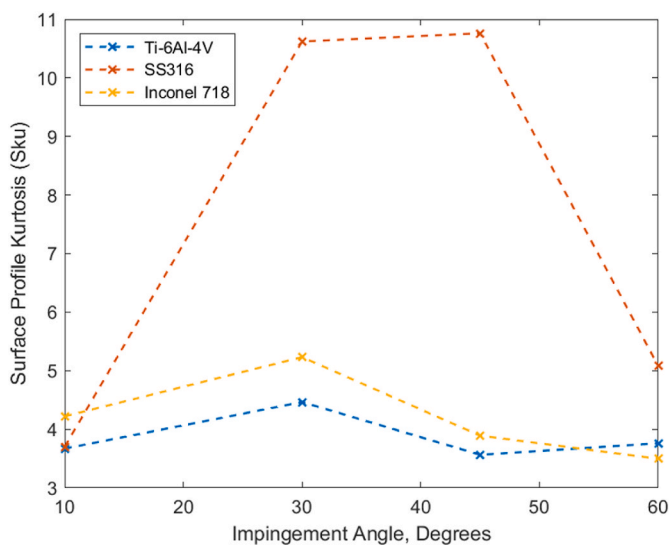


Fig. 7. Kurtosis of Worn Surface Profiles for Different Impingement Angles (angular particles).

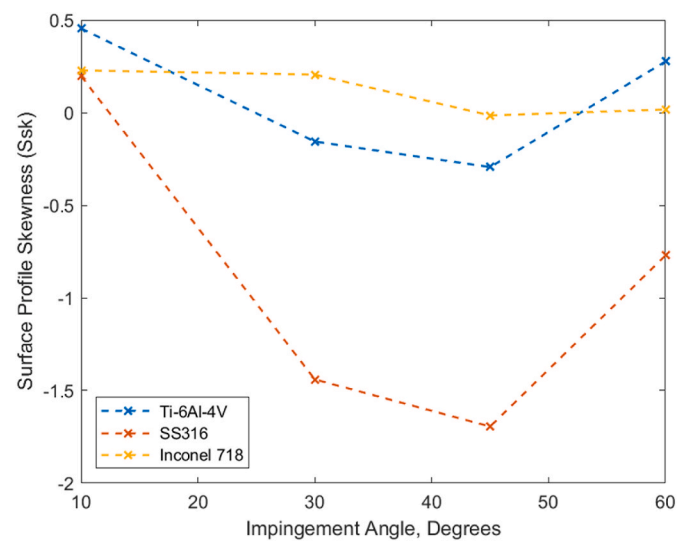


Fig. 8. Skewness of Surface Profiles at Different Impingement Angles (angular particles).

Table 4

Post-test profile distribution parameters for different erodents.

Parameter	50-75 μm Angular	75-106 μm Angular	60.2 μm Spherical
Sa (μm)	0.784	0.622	1.035
Ssk	0.276	0.766	0.779
Sku	3.760	4.501	3.701

materials ability to absorb this energy without fracture. However, high hardness may reduce the materials ability to deform plastically and therefore, its toughness may decrease [27]. This has been predicted theoretically by Hutchings [28]. A comparative study of the erosion of these materials with a dense erodent will generate new data at particle densities outside measured ranges. If tungsten erodents behave similarly to common particles, we should expect more ductile materials to erode with ploughing and cutting mechanisms.

A variety of analysis techniques have been shown to be effective measures of erosion. For advanced erosion, mass loss is used to quantify the rate of material removed per mass of erodent. In early stages of erosive wear, as mentioned above, the mass loss may be very low compared to the counterface mass, and may even increase due to particle embedment and therefore it is a poor measure of the erosion [29,

the particle into the material, and toughness is indicative of the

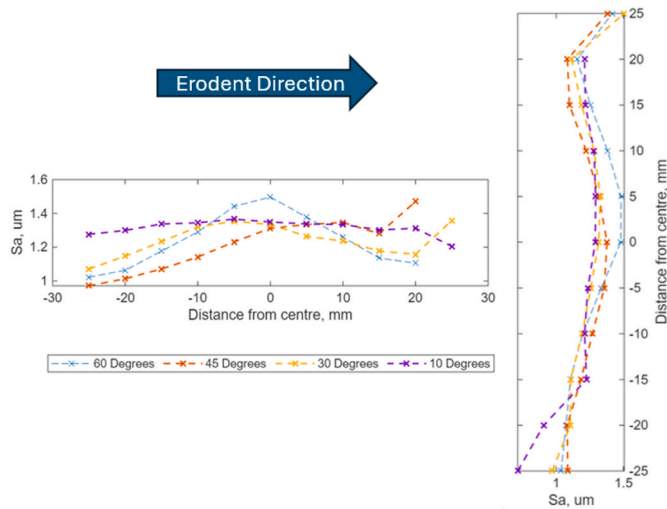


Fig. 9. Roughness Distribution Across Wear Scars for SS316 at Different Impingement Angles (angular particles).

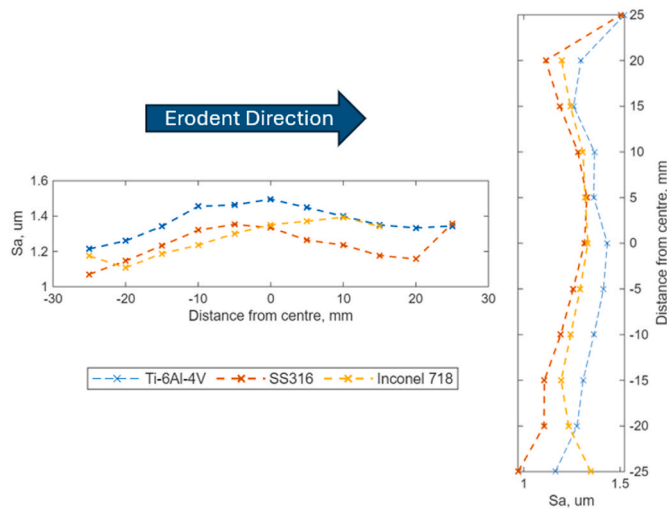


Fig. 10. Roughness Distribution for Different Materials Eroded at 30° (angular particles).

30]. Profilometry of the surface can capture wear features and different roughness parameters R_a , R_q , S_a , S_q etc. This can then be used, along with microscopy imaging to assess the erosion mechanisms. This approach has been used successfully for single particle impacts of sand on titanium alloy [22]. Roughness evolution, while a useful tool when looking at early-stage damage, is a poor metric for long term erosion rate; however, the distribution can suggest dominant mechanisms [31, 32]. An optical profilometer can also compute skewness (S_{sk}) and kurtosis (S_{ku}) for surface profiles, which can be informative when the roughness levels are high. These metrics test how well a gaussian distribution fits the data indicating spikiness and degree of peaks and valleys respectively [33].

The aim of this paper was to evaluate initial damage effects of high-density solid particle impacts on materials used in particle accelerator applications. Understanding early-stage damage mechanisms of erosion is essential to developing granular targets.

2. Experimental details

2.1. Test apparatus

The HiPER rig, used for the work, was originally designed to conduct liquid impingement erosion testing [34]. To enable solid particle erosion testing, a commercial sandblaster device was added (Fig. 1). The rig is capable of varied impingement angle by adjusting the nozzle position, and varied particle speed by varying the air pressure driving the particles. The sandblaster set-up is connected to a compressed air supply by a solenoid valve connected to the test cell interlocks, and a floor to the test cell is in place to collect erodent and any wear debris.

The particle velocity was measured using a time-of-flight measurement between rotating discs [35,36]. The particle velocity used for the tests was 22 m/s, which is within the design range for a particle accelerator target [3].

2.2. Test specimens

The counterface specimens used were 100 x 100 x 2 mm plates. Stainless steel 316 (SS316), Inconel 718 and Ti-6Al-4V were tested in the as-received condition. It was decided to not polish or otherwise prepare the samples for two reasons. First, it would be difficult to determine the response of the surface to polishing. Also, the damage to the surface by polishing could result in crack formation at the surface, especially for more brittle materials [37]. Second, in the industrial application it would be difficult to polish the entire piping system.

Two types of tungsten particle were used, angular and spherical. The angular particles were graded using sieves to obtain two sizes, 50-75 μm and 75-106 μm. Also, TEKNA W-90 spherical tungsten particles with a median diameter of 60.2 μm were used. The 10th percentile (D10) diameter was 45.6 μm, and 90th percentile (D90) diameter was 85.5 μm. The angular erodent was used for the bulk of the tests, as this is lower cost and would therefore be preferable in operation if reliable. Both types of erosion media were inspected using SEM techniques. Outcomes are shown in Section 3.3. It should be noted that each erodent was reused. Post test analysis on the particles post impact showed no changes in form which is not unexpected over so few impacts.

2.2.1. Roughness measurement

The surfaces were inspected before and after testing using an optical 3D profilometer (Alicona Infinite Focus SL). This involved taking a 3-dimensional profile of the surface, then sampling the height of the surface to calculate an area roughness. Post-test loose tungsten was removed from the surface using an air puff.

The algorithm filters the measured surface profile to remove waviness-the large-scale surface deviations which would not be caused by erosion. The roughness parameter chosen was S_a , the areal roughness expressed as the arithmetic mean of the deviation in absolute surface height across the relevant area (see Equation (1)) [38].

$$S_a = \frac{1}{A} \int |Z(x,y)| dA \quad (1)$$

A rougher surface will have a larger S_a value. Any change in S_a measured after an erosion test will signify damage to the surface. Initial surface assessments are outlined in Section 3.1.

Surface measurements were made using a 500 nm vertical resolution and a 5 μm horizontal resolution, resulting in a 1.992 μm sampling distance. High magnification images were also taken. The roughness of each surface was measured across the length and width of the scar, then of 5 mm x 5 mm square samples at 5 mm intervals across the centre in both directions. The roughness of each square sample was used to plot the roughness distribution across the wear scar.

Images approximately 60 mm by 7 mm in each direction were taken across the wear scars. The wavelength cut-off filter was set to 10 mm for the large samples. The smaller 5 mm x 5 mm samples used a 1 mm cut-

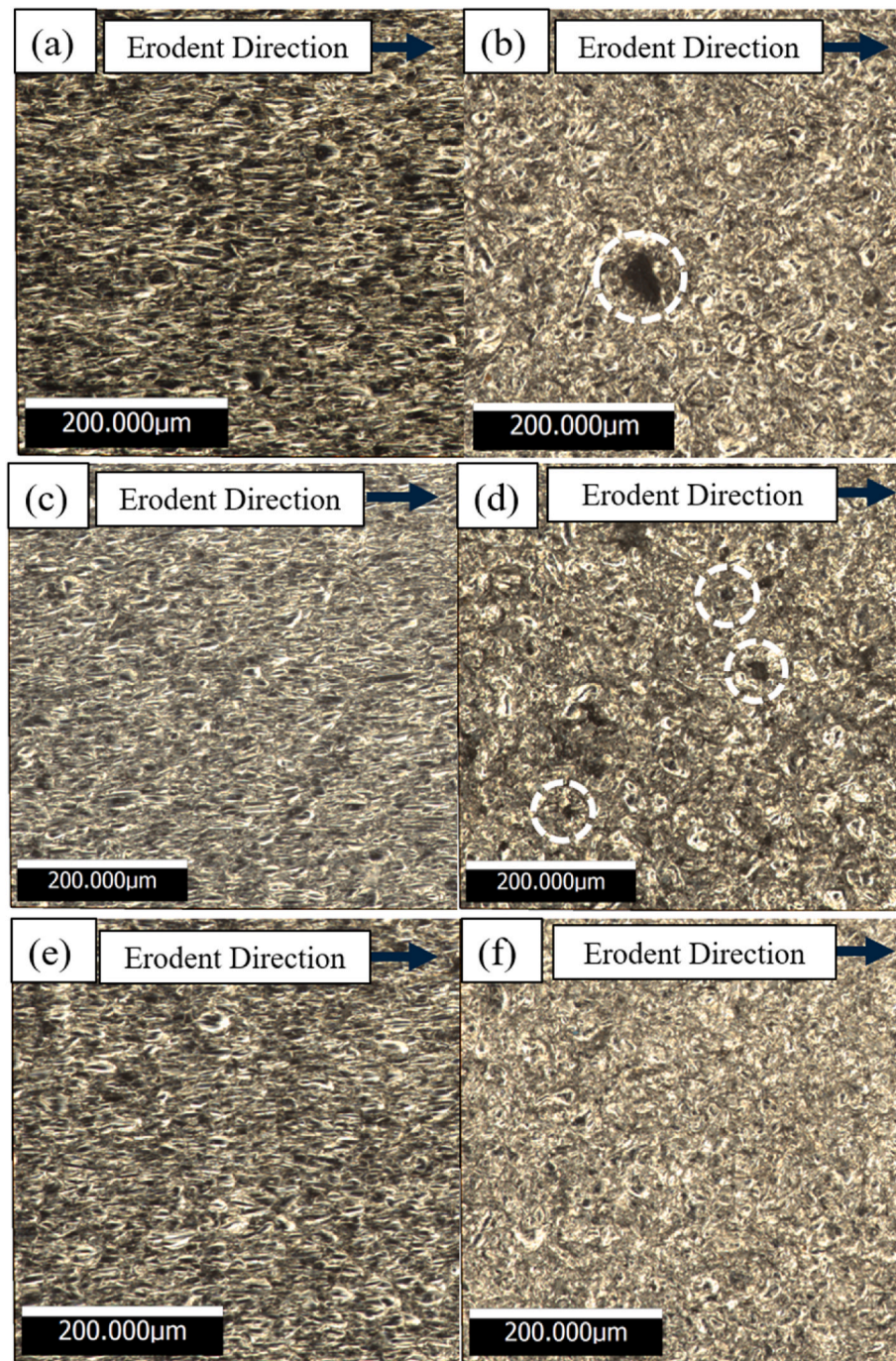


Fig. 11. Ti-6Al-4V eroded at: (a) 10° (Ti4) and (b) 60° (Ti1) (embedded tungsten circled) (angular particles). SS316 Eroded at: (c) 10° (SS4) and (d) 60° (SS1) (embedded tungsten circled) (angular particles). Inconel 718 eroded at: (e) 10° (Inc4) and (f) 60° (Inc1) (angular particles).

off wavelength.

2.2.2. Material characterisation

Two material characterisation approaches were used to assess the hardness and the resistance to abrasion of the counterface materials. Microhardness tests using a Vickers indenter at 1 kgf and 0.5 kgf and scratch hardness tests were carried out. Four indentation points were taken per material, for each load.

A scratch hardness test was selected to replicate abrasion, a closer analogue to a particle impinging along a surface at low contact angle. In accordance with ASTM G171-24, a 10 N force was applied to a 120° conical indenter, with tip radius 200 µm, using a Bruker UMT testing

machine. Three scratches were made on each material, and measurements taken of the width at three points along the length of each, using an Alicona optical profilometer, giving nine measurements per material. Hardness and scratch test data is given in Section 3.2.

2.3. Test methodology

In a test, 300 g of erodent was propelled at 6 bar air pressure to achieve a 22 m/s impact velocity. The stand-off distance between the nozzle and sample was 100 mm. Tests were conducted for four impingement angles of 10°, 30°, 45° and 60°, for each material, using 50-75 µm angular tungsten erodent. Additional tests were done using

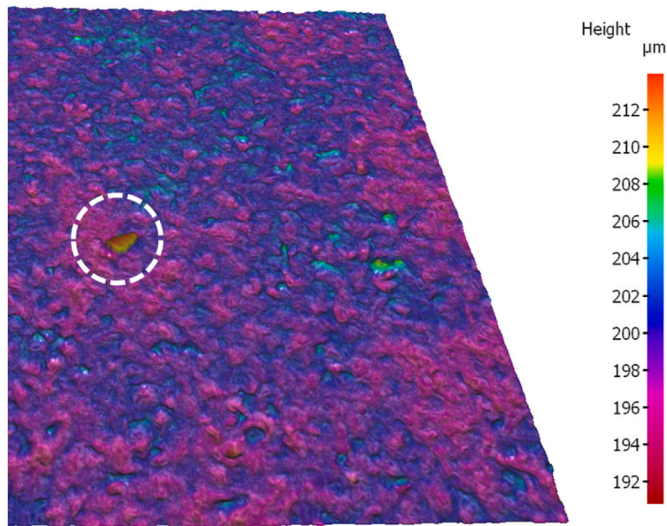


Fig. 12. Profile of Ti-6Al-4V Surface with Embedded Particle Circled (Ti1) (angular particles).

60.2 μm spherical, and 75–106 μm angular tungsten at 60° for the Ti-6Al-4V. Titanium was chosen for additional comparisons as it has seen use in high power target containers before [2] and showed promising resistance to damage from the first set of tests. Eroderent was collected after each test and reused. Samples were then labelled and taken for analysis. Test conditions are summarised in Table 1.

3. Results

3.1. Specimen initial roughness

The SS316 steel specimens (Fig. 2a) had an initial S_a roughness of 0.74 μm . The samples were generally in good condition, with some slight scratches visible on the surface which were avoided in the testing. The Inconel 718 samples (Fig. 2b) arrived with distinctive swirled scratches. These were on a smaller length scale than the scratches on the SS316 samples. The Inconel 718 surface had an initial S_a roughness of 1.02 μm . The titanium samples (Fig. 2c) were visually smooth, with patches of discoloration. The S_a roughness was 0.86 μm . While it has been shown that at high roughness (up to 20 μm R_a) erosive wear rates can differ significantly to those for a smooth surface [39], it is not anticipated that at the levels recorded for the test specimens here the differences seen will have much bearing on the wear rates. While the roughness is similar, there is a difference in texture. Using SEM techniques (Fig. 2d, e and f), the surface of the SS316 has a visible “scaly” surface structure, while the Inconel 718 surface has consistent shallow linear grooves across the surface and distinct swirled scratches. The titanium has a dimpled surface with shallow pits, each around 10 μm or smaller.

3.2. Counterface hardness

The hardness measurements showed good consistency for Inconel 718 and Ti-6Al-4V across each indentation apart from the titanium samples, which showed the largest variation. The SS316 and Inconel 718 samples varied much less. Titanium was the hardest material, followed by the Inconel 718. The SS316 was the softest material. Table 2 summarises the results.

The scratch hardness’ in Table 3 follow a similar pattern to the

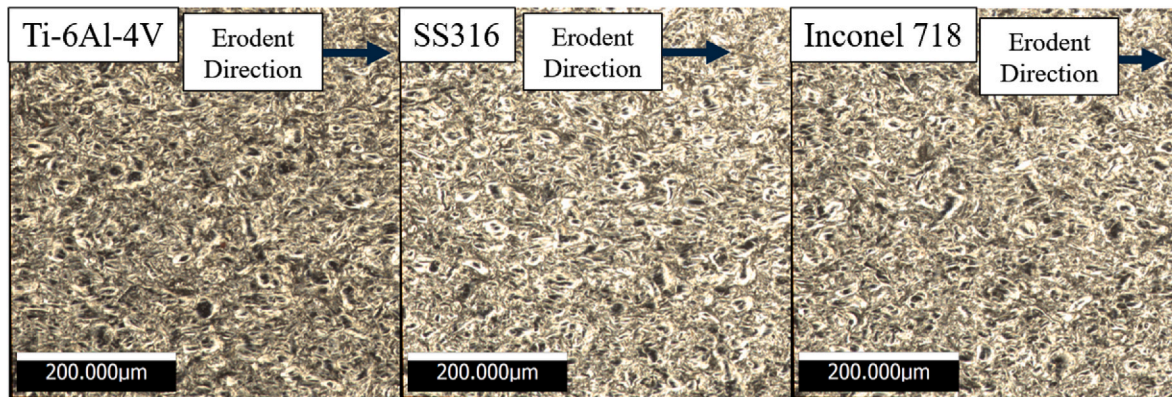


Fig. 13. Tested Counterface Materials after Erosion at 30° (tests: Ti3; SS3; Inc3) (angular particles).

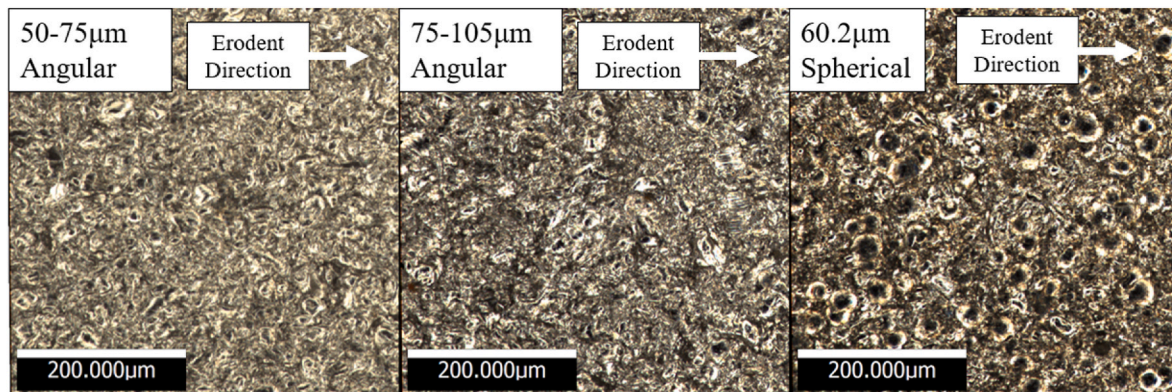


Fig. 14. Ti-6Al-4V eroded by different media at 60° (tests: Ti1; Ti9; Ti8).

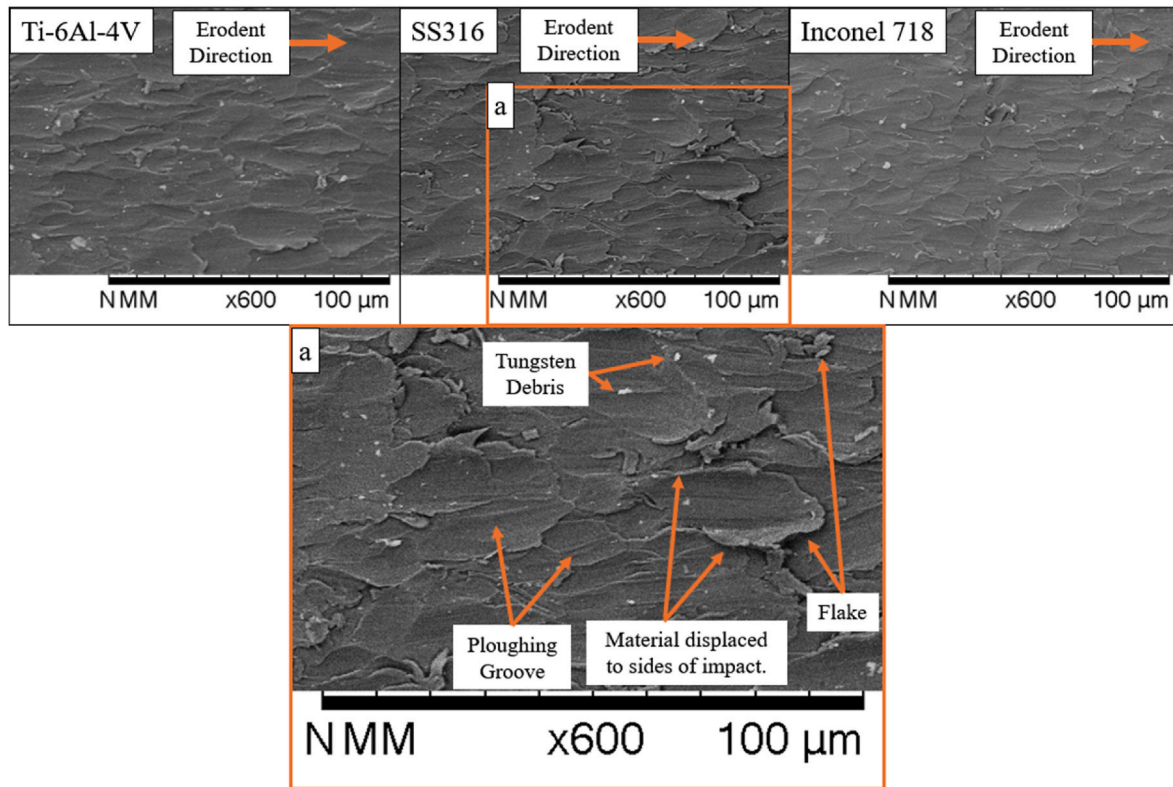


Fig. 15. SEM Images of Ti-6Al-4V, SS316 and Inconel 718 Eroded at 10°: (a) SS316 enlarged (tests: Ti4; SS4; Inc4) (angular particles).

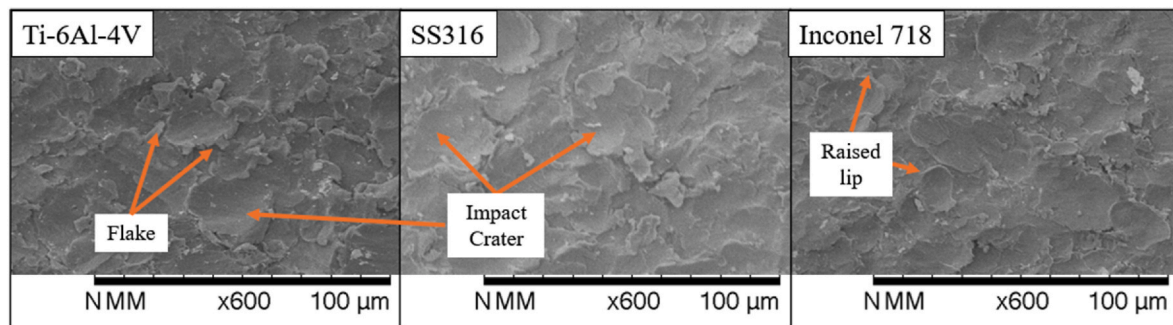


Fig. 16. SEM Images of Ti-6Al-4V, SS316 and Inconel 718 Eroded at 60° (tests: Ti1; SS1; Inc1) (angular particles).

Vickers hardness tests, with titanium being most resistant to scratching, followed by the Inconel 718 sample.

3.3. Tungsten particles inspection

The angular erodent consisted of a wide range of particle shapes at similar sizes. Two particle types were identified in Fig. 3a, porous and flaky. Porous particles had holes across the entire surface, some of which contained debris (Fig. 3b). Some particles had pores in a linear pattern across the surface. On other particles the pattern seems random. Some cracks are present on the particle surface. Flaky particles have a more solid surface with small flakes and significant cracks or fault lines across a large portion of the particle (Fig. 3c). The spherical particles had a more consistent structure (Fig. 3d). The surface of the particles was smooth, and most particles were well formed spheres (Fig. 3e). Some particles were malformed, ovoid shapes, and there is a scattered assortment of smaller polyhedral particles visible in (Fig. 3f).

3.4. Macro assessment of wear scars

The shapes of erosion scars formed by the tests were consistent across materials. As shown in Fig. 4, the 10° erosion scar extended slightly past the edge of the plates, while the steeper angles were contained within the plate. This was the case for all counterface materials, as well as the dulling of the eroded portion. There was some variation in the appearance of the surface across the scar. The outer edges of the scar appeared to have been affected less by the erosion. The centre of the scar had the greatest visual change. The velocity of the flow will be lower at the edge though and there will be fewer particles in this location.

On the specimen eroded by spherical particles, the scar was smaller, and significant discolouration was present which was not the case with the angular erodent on any counterface. The size comparison is shown in Fig. 5. The larger wear scar of the angular particles could be due to their aerodynamic instability compared to the more uniformly sized spherical particles [40]. No clear difference in the density of impacts was observed under SEM.

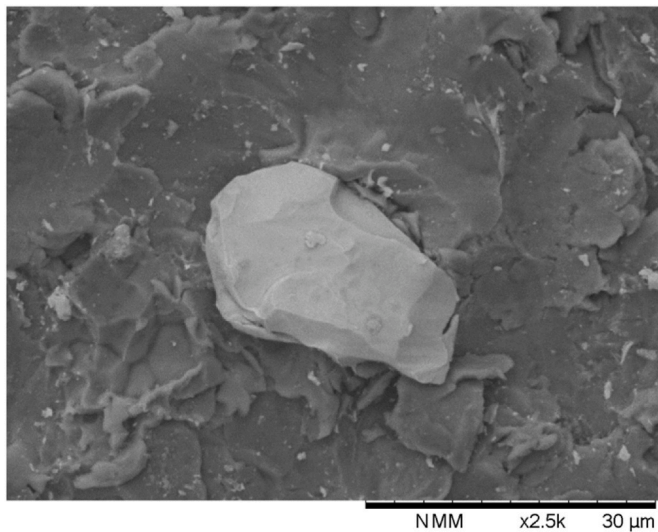


Fig. 17. SEM Image of Tungsten Particle Embedded in Titanium from 60° Erosion (test Ti1) (Angular 75–106 μm particles).

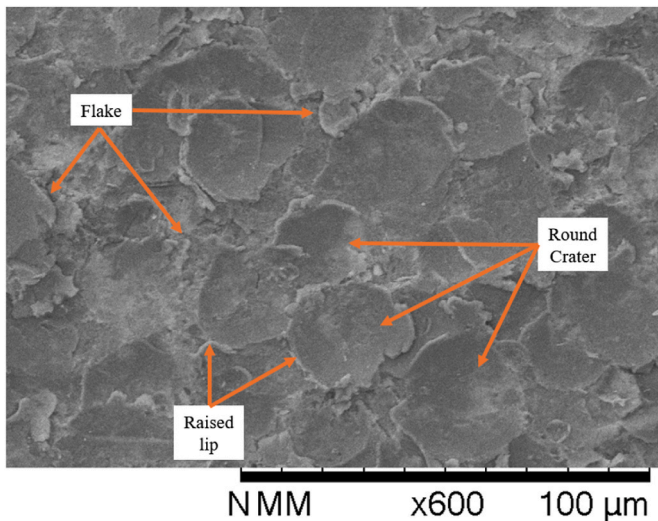


Fig. 18. SEM image of Ti-6Al-4V eroded by spherical particles at 60° (Ti8).

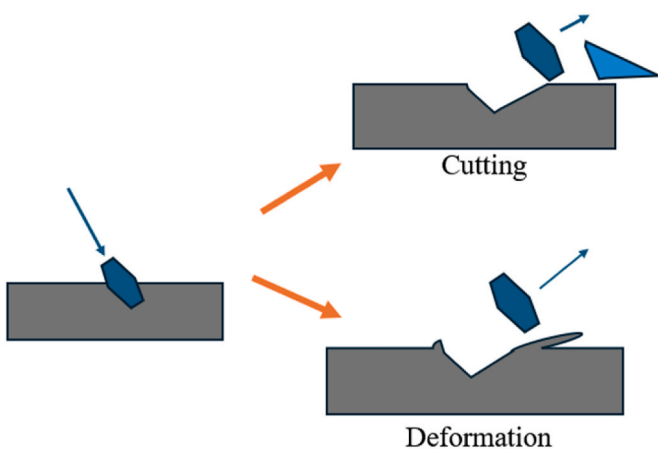


Fig. 19. Mechanisms of roughening after particle impact.

3.5. Average roughness analysis

The S_a roughness was calculated across the scar parallel to the particle travel and perpendicular, then averaged between the parallel images and the perpendicular images. There was an increase in S_a across all tests, as shown in Fig. 6. The Ti-6AL-4V exhibits a peak roughness at 45°, while the SS316 and Inconel 718 were roughest at 30°. In Inconel 718 S_a increased by just 0.729 μm at 30° while the S_a of the equivalent SS316 sample increased by 1.179 μm . This roughness behaviour follows trends obtained in other studies for roughness and wear evolution [39].

Only the left-to-right images were used to compare kurtosis and skewness, as the pe images taken perpendicular to particle travel included unworn sections of the samples which would misrepresent the worn surface. As shown in Fig. 7, the Ti-6AL-4V and Inconel 718 surface heights had kurtosis close to 3 throughout the range, with a small increase in kurtosis for the 30° impingement angle. This means that sharp portions and indented portions co-exist. The SS316 samples showed large variation in kurtosis throughout the range of angles tested. The maximum kurtosis was 10.76, which indicates a highly spiked surface at moderate angles.

The skewness of the surfaces shows that valleys are more dominant for 30° and 45° impingement angles. Fig. 8 demonstrates that SS316 is most strongly dominated by valleys, while the Inconel 718 shows little variation in skewness for any impingement angle. The closeness of kurtosis and skewness in surface height for Ti-6AL-4V and Inconel 718 to those for a Gaussian distribution (kurtosis of 3, skewness of 0). This suggests a less spiked, more uniform surface than for the SS316.

The spherical erodent roughened the Ti-6AL-4V surface more than the 50–75 μm angular erodent. The larger angular erodent increased the roughness by the least. All Ti-6AL-4V surface profiles are slightly positively skewed when eroded at 60°, with the larger erodent generating a more skewed profile. The kurtosis is highest for the larger angular erodent, suggesting a more irregular surface. Table 4 shows the profile distribution parameters for the different erodent tested with Ti-6AL-4V.

3.6. Roughness distribution analysis

To assess the distribution of damage across each image, smaller samples 3 mm $\times$ 3 mm were taken. In these measurements, the cut-off wavelength for the waviness filter was 1 mm, versus the 10 mm used in the whole image analysis. The distribution of surface roughness across the wear scar is close to even in both directions across the wear scars at shallow impingement angles. As the impingement angle increases, the roughness distributions gain a central peak. SS316 showed this most clearly in Fig. 9. Comparing materials, a similar pattern to the whole scar roughness is shown in Fig. 10. Ti-6AL-4V and SS316 show similar changes in roughness from erosion, whilst the roughness of the Inconel 718 surface is less affected. At shallower angles, all materials have more uniform roughness along the length of the scar parallel to erodent direction compared to that at steep angles.

3.7. Higher resolution analysis of surfaces

The profilometer was used to take high magnification profiles of the surfaces for angular particles. At shallow angles, the surface has significant left-to-right impressions visible. All materials appear somewhat similar. At low angles, all surfaces had teardrop shaped indents (Fig. 11a, c and e), while at high angle the indents are more random in shape. Tungsten was embedded in the Ti-6AL-4V (Fig. 11b) and SS316 (Fig. 11d) samples at high angles, while embedment is barely visible in the Inconel 718 sample (Fig. 11f). The large particle embedded in the Ti-6AL-4V sample from 60° erosion is proud of the surface by around 20 μm , as shown in Fig. 12.

At 30°, the SS316 surface is roughened by almost the amount of the Inconel 718, while the three surfaces are visually similar in Fig. 13. The pits on the surface appear larger than in the shallower angles, implying

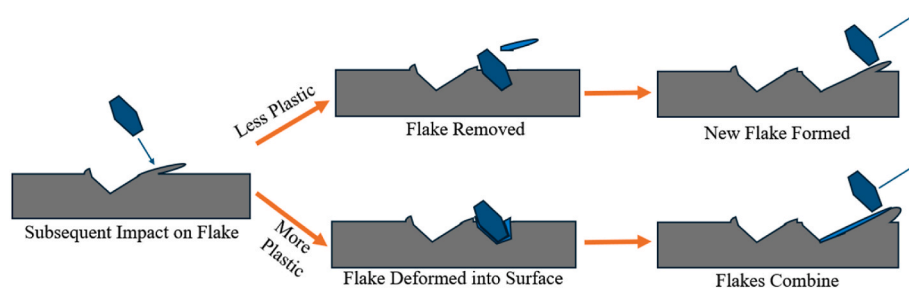


Fig. 20. Flake formation and removal from subsequent impact.

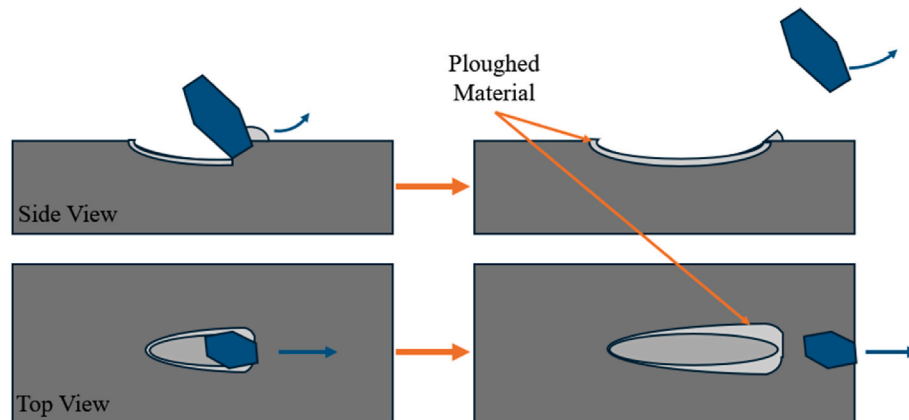


Fig. 21. Ploughing of material at low angles.

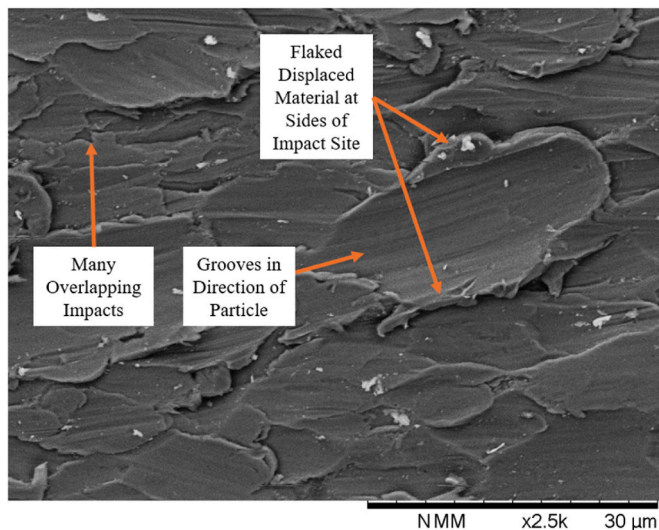


Fig. 22. SEM image of SS316 eroded at 10° (SS4).

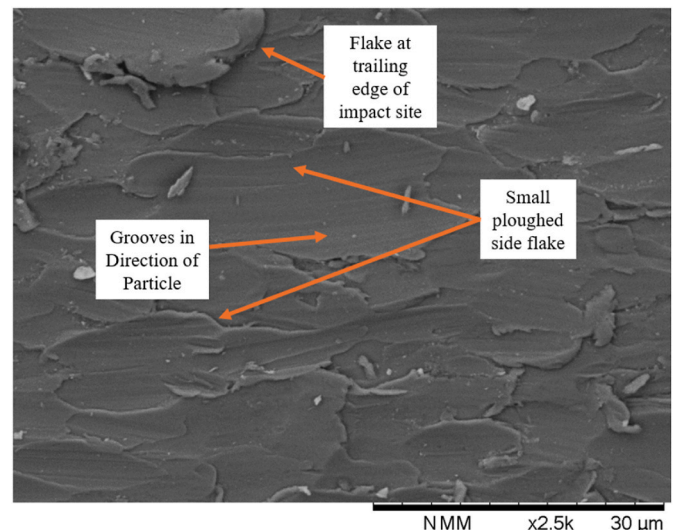


Fig. 23. SEM image of Inconel 718 eroded at 10° (Inc4).

the erodent may have penetrated deeper into the surface.

When the spherical erodent was used, the surface was pitted with more regular, circular impressions. Compared to 75–106 μm angular tungsten, the spherical pits appear larger in Fig. 14. The two angular erodents appear to have created very similar surfaces.

The surface topology was assessed after erosion using SEM. At 10° impingement angle, SEM imaging makes the difference between the three materials clear. The Inconel 718 appears smoothest, with small, sharp ridges between impact sites. The stainless surface has a large number of flakes formed on the surface, created by large plastic deformation. Fig. 15 shows the flakes in detail. As well, ploughing marks

characterised by grooves in the surface are visible, and material has been displaced to the sides of the impact sites. The Ti-6Al-4V surface shares characteristics with both the SS316 and Inconel 718 surfaces. The damage to this surface is less severe than the stainless surface, but noticeable flakes are visible, unlike with Inconel 718.

At 60° impingement angle, the SS316 and Ti-6Al-4V titanium surfaces gave more severe damage than the Inconel 718 sample. For all surfaces, raised lips are visible on all sides of impact craters in Fig. 16. Flake formation can also be seen, particularly in the Ti-6Al-4V and SS316 surfaces. The Inconel 718 surface shows some flake formation and appears more deformed than in the shallow angle case but is less

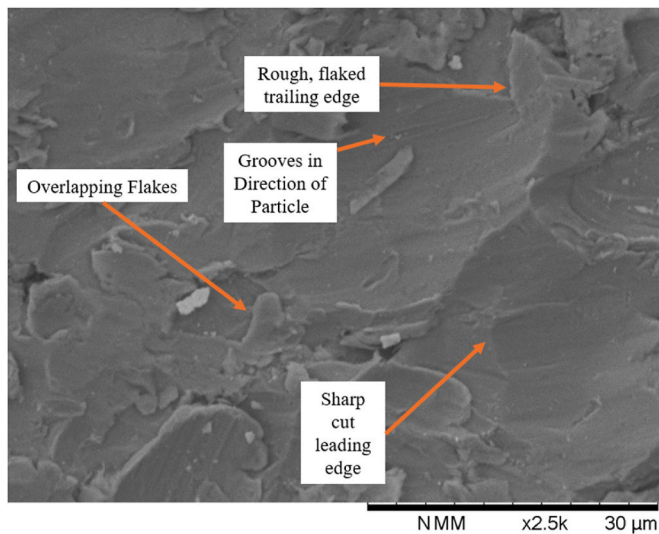


Fig. 24. SEM image of SS316 eroded at 30° (SS3).

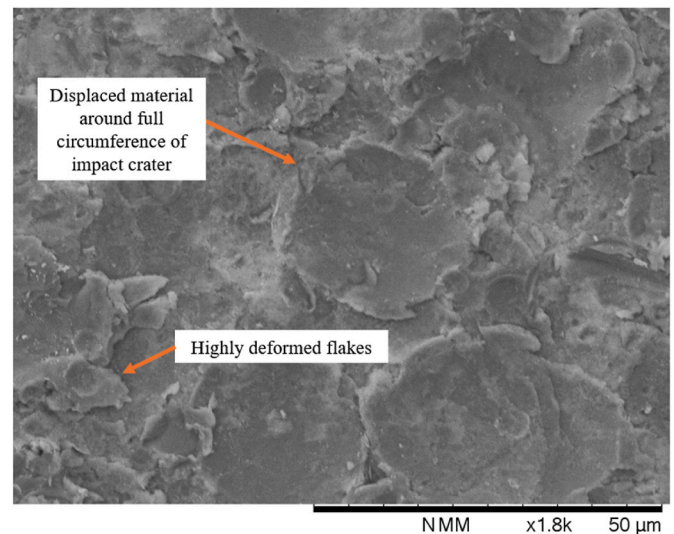


Fig. 26. SEM image of Ti-6Al-4V eroded by spherical particles at 60° (Ti8).

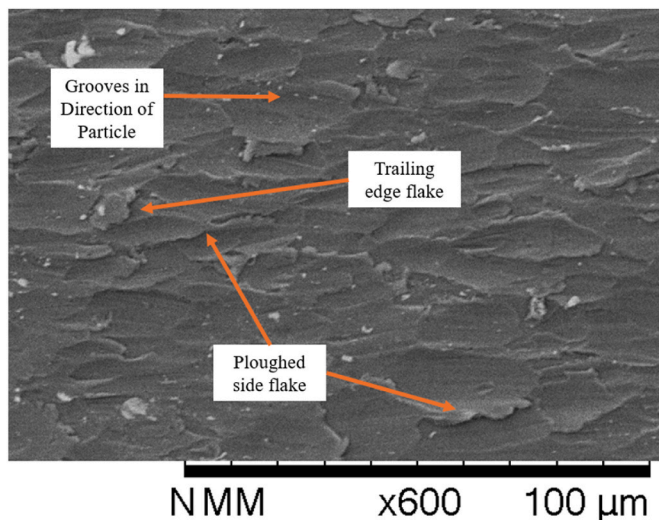


Fig. 25. SEM image of Ti-6Al-4V eroded at 10° (Ti4).

severely deformed than the other materials.

At 60°, tungsten embedment was significant for SS316 and Ti-6Al-4V, as shown in Fig. 17. At around 30 μm wide, this particle is smaller than the expected size of the angular erodent.

When spherical particles are used, distinct circular impressions are left on the surface. Using the SEM, it is clear that the impingement of spherical particles at 60° has caused material extrusion in all directions. Fig. 18 shows the extruded flakes from particle impact. These will be vulnerable to damage and then removal by further particle impacts. Each crater is more uniform in shape than those created by angular particles. The uniform rounded shape of impacts suggests little cutting has occurred, the large, extruded flakes contributing to the high roughness compared to angular erodent [13].

4. Discussion

The roughness values measured followed a similar trend to previous work on ductile materials [39] with a rise for contact angles around 30° due to the increase in cutting. Inconel 718 specimens underwent less roughening than the SS316 and Ti-6Al-4V specimens. The roughness, however, does not follow a clear trend in relation to the measured

hardness of the materials. The SS316 and Inconel 718 behave as expected. Ti-6Al-4V, as the hardest material, does not follow the trend as its roughness was as high as the SS316. While care has to be taken as high roughness does not mean more wear, it would be useful to consider why the Ti-6Al-4V was rougher than expected.

From examining the worn surfaces, it can be seen that at high angles, impacting particles indent the surface. The size of the pit should relate to the hardness of the material. At lower impact angles the particle moves through the surface, either cutting or deforming the material. The initial impact creates a raised lip, and the subsequent movement through the surface will either remove material (cutting) or generate a flake (deformation), as in Fig. 19. Hutchings describes these two processes as Type II and Type I cutting respectively [18].

If the material is cut, there will be an elongated pit with little material above the surface. If deformed, a flake will form on the trailing edge of the pit. On subsequent impacts, the flake will either be removed or deformed back into the surface. The more plastic deformation a material can withstand before fracturing, the more likely it is that the flake will be recombined into the surface, as in Fig. 20. If the flakes are removed easily, the surface roughness will be dominated by the pits and will be lower. If the flakes are not removed easily the roughness will be contributed to by both the pits and flakes and will be higher. The sharpness of the particle will affect the cutting performance, with spherical particles removing material less efficiently [13].

The harder the surface, the smaller the initial indent and shoulders should be. This means the raised lips and flakes are less likely to be impacted by subsequent particles—resulting in less material removal. For an equivalent erosion condition, a harder surface should therefore have a lower roughness. At shallower angles, the material is more likely to be ploughed to the sides by the impinging particles [18]. In this case, deformed material will be present at the sides of the erosion site, not just the trailing edge, as in Fig. 21. If material is cut, there will be little plastic deformation around the impact site.

This ploughing mechanism is visible in Fig. 22 for the SS316 at 10° impingement angle. Material has been displaced both in the particle direction and to the sides. The overlapping impact sites (evidenced by the different angles of the scars overlaying each other) are smeared together and high plastic deformation obscures individual impacts.

By comparison, the Inconel 718 surface has much less plastic deformation visible in Fig. 23. The indentation hardness and scratch hardness of Inconel 718 is much higher than for SS316 which also helps explain the smaller indentations/scratches made by the particles.

The high angle results show a similar pattern. The SS316 samples

appear to have deformed more, with cutting more prominent at 30° than at 10°, comparing Figs. 22–24. At 60°, the cutting mechanism appears less prominent than at lower angles. The kurtosis also changes significantly at this point, suggesting that a different pattern of surface profile generation may dominate for the SS316.

For the Ti-6Al-4V counterface, these mechanisms alone do not explain the high roughness. The measured hardness of the Ti-6Al-4V counterface is higher than both SS316 and Inconel 718, so we should expect the roughness to be lower, particularly at low angles where erosion approaches abrasion [18]. Compared to Inconel 718, we would expect Ti-6Al-4V to have shallower indentations due to its higher hardness. However, as in Fig. 25, the Ti-6Al-4V surface at 10° impingement angle appears similar to the SS316, with smaller flakes on the trailing edge of impacts. The accompanying roughness is similar to SS316 at high and low angles, with less roughening at 30° and 45°.

Another issue affecting the surface damage could be particle to particle interactions, before and after impact and particle cutting versus rolling. At the angles tested rebounding particles will not affect incoming particles. However, at very shallow impact angles, particles may roll rather cut. Tests of single particles loaded against a surface have shown that if there is high friction between particle and surface brought about by high adhesion of roughness leading to asperity interlocking that particles will roll rather than slide [41,42].

Hardness is known to be a poor predictor of erosion due to the high strain rate in the deformed surface [18]. While unlikely here, in longer tests with a 22 m/s impact velocity that work hardening of the surface will occur. This would have to be characterised carefully as the materials under test will harden via different mechanisms. Titanium, for example, will experience a twinning process while for stainless steel and Inconel it would be via deformation. Resistance to deformation during erosion may be better characterised using the H/E ratio which is used, for example, in gear design as a plasticity index. However, H/E values for SS316, Ti-6Al-4V and Inconel 718 are: 0.0085, 0.03 and 0.017 respectively. This still does not provide the answer.

Another factor that could influence the damage seen on the Ti-6Al-4V is softening due to temperature rise. While only a hypothesis for this work at present, temperature increases during impacts have been measured in steels in the order of 50 °C [40,43] while numerical models predict surface temperatures of several hundred degrees during the actual particle impact [43–41]. Titanium decreases in strength rapidly at high temperatures, reducing in yield strength to 620 MPa at 315 °C [43, 44] while Inconel 718 yields at 1096 MPa at 315 °C [44,45]. As Vickers hardness is linearly related to the yield strength [44,46], the material would soften. The sample eroded by spherical particles was significantly discoloured after testing. This is likely an oxidation reaction at the surface, which occurs faster for high temperatures and for thin sections. The surface in Fig. 26 has more thin flakes than that eroded by angular particles, supporting this hypothesis.

5. Conclusions

The tests showed that solid particle erosion could be generated by the HiPER rig using a range of tungsten particles on three metallic counterfaces. The early-stage erosion damage generated is a good starting point for considering particle accelerator design changes. However, a more comprehensive study considering temperature effects as well as the mechanical interactions is needed. The developed test method showed that early stage roughening due to erosion varies with impingement angle, and that the relationship is stronger with softer material. Features of the roughened surfaces were investigated using SEM techniques, and mechanisms proposed based on literature. The tests showed that quasi-static hardness tests had no strong relation to roughening from erosion. Early investigation into erodent topology showed that spherical erodent generated a rougher surface with less particle embedment than angular erodent for high impingement angle, while a larger angular erodent generated a smoother surface. Particle

embedment was found in the surfaces of SS316 and Ti-6Al-4V for high impingement angles with angular erodent. Inconel 718 showed very little particle embedment. Inconel 718's surface roughness was less severely affected by erosion than SS316 and Ti-6Al-4V, suggesting it has merit as a piping material for particle accelerators.

For future work, in combination with more robust methods of wear quantification, such as precise mass or volume loss measurements, longer testing would allow for wear rate estimation. Longer tests would also allow for comparison of surface roughness to wear. Completing tests with more impingement angles would also allow for confident identification of the peak in roughness.

Particle analysis would be worthwhile to understand erodent effects more fully. Studies of the fracture and contamination of particles by wear debris would be relevant to the industrial application as the particles would be recirculated through the system. Contamination would affect the performance of the target, and particle fracture could change the aerodynamic effects of the gas stream on the particles. Better data would allow for design rules to be created to justify decisions for future particle accelerators.

CRediT authorship contribution statement

B. Suitters: Investigation, Methodology, Writing – original draft, Writing – review & editing. **E.E. Vera Cardenas:** Formal analysis, Writing – original draft, Writing – review & editing. **W. Thompson:** Writing – original draft, Writing – review & editing. **R. Lewis:** Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing. **C.J. Densham:** Conceptualization, Funding acquisition, Supervision. **D. Wilcox:** Conceptualization, Funding acquisition, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

- [1] What are particle accelerators? Accessed: December. 10, 2023. Available: <https://www.iaea.org/bulletin/what-are-particle-accelerators-0>.
- [2] K. Ammigan, et al., Novel materials and concepts for next-generation high power target applications. Proceedings of Snowmass 2022, 2022. Seattle, USA, 17–26 July, <https://lss.fnal.gov/archive/2022/conf/fermilab-conf-22-139-ad.pdf>.
- [3] T.W. Davies, O. Caretta, C.J. Densham, P. Loveridge, R. Woods, The potential of fluidised powder target technology in high power accelerator facilities. Proceedings of PAC09, 2010. Vancouver, BC, Canada, 4–8 May, 2009.

- [4] D. Winder, D. McClintock, D. Bruce, Cavitation-induced erosion in liquid metal spallation targets – a comparison between a predictive method and measured erosion damage to stainless steel target modules at the spallation neutron source, *Wear* 450–451 (2020) 203257.
- [5] D. Wilcox, L.G. Jones, Design and optimisation of the ISIS TS1 project target, *Phys.: Conf. Ser.* 1021 (1) (2018) 012058.
- [6] C. Densham, LBNF target conceptual design selection. Proceedings of NUFAC2019, 2019, Daegu, Korea, 26–31 August, 2019.
- [7] O. Caretta, et al., Response of a tungsten powder target to an incident high energy proton beam, *Phys. Rev. Spec. Top. Accel. Beams* 17 (10) (2014) 101005.
- [8] E. Oberg, F.D. Jones, H.L. Horton, H.H. Ryffel, *Machinery's Handbook*, 29th Ed., Industrial Press, South Norwalk, Connecticut, 2012.
- [9] M. De Angeli, P. Tolias, F. Suzuki-Vidal, D. Ripamonti, T. Ringrose, H. Doyle, G. Daminelli, J. Shadbolt, P. Jarvis, M. De Angeli, Normal high velocity solid dust impacts on tiles of tokamak-relevant temperature, *Nuclear Mater. Energy* 41 (2024) 101735.
- [10] P. Tolias, M. De Angeli, D. Ripamonti, S. Ratynskaia, G. Riva, G. Daminelli, M. De Angeli, Wall cratering upon high velocity normal dust impact, *Fusion Eng. Des.* 195 (2023) 113938.
- [11] H. Arabnejad, S.A. Shirazi, B.S. McLaury, H.J. Subramani, L.D. Rhyne, The effect of erodent particle hardness on the erosion of stainless steel, *Wear* 332–333 (2015) 1098–1103.
- [12] I. Finnie, Erosion of surfaces by solid particles, *Wear* 3 (1960) 87–103.
- [13] A. Levy, P. Chik, The effect of erodent composition and shape on the erosion of steel, *Wear* 89 (1983) 151–162.
- [14] R. Tarodiya, A. Levy, Surface erosion due to particle-surface interactions – a review, *Powder Technol.* 387 (2021) 527–559.
- [15] I. Finnie, Some observations on the erosion of ductile metals, *Wear* 19 (1) (1972) 81–90.
- [16] I. Finnie, A. Levy, D.H. McFadden, The Fundamental Mechanisms of the Erosive Wear of Ductile Metals by Solid Particles, U.S. Department of Energy, Berkeley, California, 1978. Available: <https://escholarship.org/content/qt3998930p/qt3998930p.pdf?t=p21o0p>.
- [17] J.G.A. Bitter, A study of erosion phenomena part I, *Wear* 6 (1) (1963) 5–21.
- [18] I.M. Hutchings, *Tribology: Friction and Wear of Engineering Materials*, fifth ed., Butterworth Heinemann, Oxford, UK, 1992.
- [19] T. Deng, Erosive wear mechanisms of materials—A review of understanding and progresses, *Materials* 18 (2025) 1615.
- [20] Lin, N., Arabnejad, H., Shirazi, S.A., McLaury, B.S., Lan, H., 201, “Experimental study of particle size, shape and particle flow rate on erosion of stainless steel”, *Powder Technol.*, Vol. 336, pp70–79.
- [21] F.A. Bikbaev, V.I. Krasnov, M.Z. Maksimenko, V.L. Berezin, I.B. Zhilinski, N. T. Otroshko, Main factors affecting gas abrasive wear of elbows in pneumatic conveying pipes, *Chem. Petrol. Eng.* 9 (1) (1973) 73–75.
- [22] C. Yan, W. Chen, Z. Zhao, Experimental study on the high-speed impact of a sand particle on Ti–6Al–4V, *Proc. Inst. Mech. Eng. Part J J. Eng. Tribol.* 234 (4) (2020) 632–646.
- [23] R. Sahoo, S. Mantry, T.K. Sahoo, S. Mishra, B.B. Jha, Effect of microstructural variation on erosion wear behavior of Ti-6Al-4V alloy, *Tribol. Trans.* 56 (4) (2013) 555–560.
- [24] N.A. Kazarinov, A.D. Evstifeev, Y.V. Petrov, S.A. Atroshenko, R.R. Valiev, The effect of grain refinement on solid particle erosion of grade 5 Ti alloy, *J. Mater. Eng. Perform.* 27 (6) (2018) 3054–3059.
- [25] R. Sahoo, B.B. Jha, T.K. Sahoo, S. Mantry, Effect of volume fraction of primary alpha phase on solid particle erosion behavior of Ti-6Al-4V alloy, *Tribol. Trans.* 58 (6) (2015) 1105–1118.
- [26] M. Kaplan, A study of erosion wear behaviour of Inconel-718 nickel-based superalloy at different impingement angles, *J. Mater. Manufacturing* 2 (2023) 10–19.
- [27] K.G. Thiruganasambantham, S. Natarajan, Degradation through erosion: mechanistic studies on IN-718 superalloy under hot air jet conditions, *J. Mater. Eng. Perform.* 24 (2015) 2605–2613.
- [28] I.M. Hutchings, A model for the erosion of metals by spherical particles at normal incidence, *Wear* 70 (1981) 269–281.
- [29] A. Evstifeev, N. Kazarinov, Y. Petrov, L. Witek, A. Bednarsz, Experimental and theoretical analysis of solid particle erosion of a steel compressor blade based on incubation time concept, *Eng. Fail. Anal.* 87 (2018) 15–21.
- [30] V. Hadavi, N.H. Arani, M. Papini, Numerical and experimental investigations of particle embedment during the incubation period in the solid particle erosion of ductile materials, *Tribol. Int.* 129 (2019) 38–45.
- [31] G.A. Novelletto Ricardo, M. Sommerfeld, Experimental evaluation of surface roughness variation of ductile materials due to solid particle erosion, *Adv. Powder Technol.* 31 (9) (2020) 3790–3816.
- [32] Haj Mohammad Jafar, R., Spelt, J.K., Papini, M., “Surface roughness and erosion rate of abrasive jet micro-machined channels: experiments and analytical model”, *Wear*, Vol. 303, No. 1–2, pp138–145.
- [33] Surface roughness measurement—parameters | evident, Accessed: April. 30, 2024. Available: <https://www.olympus-ims.com/en/metrology/surface-roughnessmeasurement-portal/parameters/>.
- [34] P. Christoforou, *Laser Cladding for Use in Extreme Tribological Interfaces*, PhD Thesis, University of Sheffield, 2020.
- [35] M.J. Presby, Influence of Particle Velocity and Impingement Angle on Elevated Temperature Solid Particle Erosion of SiC/SiC Ceramic Matrix Composite, 2020. Nasa Technical report NASA/TM-20205003560.
- [36] M.G. Gee, I.M. Hutchings, General Approach and Procedures for Erosive Wear Testing, National Physical Laboratory, 2002. Measurement Good Practice Guide No. 56, Available: <https://eprintspublications.npl.co.uk/2544/1/mgpg56.pdf>.
- [37] B. Rowe, Towards high productivity in precision grinding, *Inventions* 3 (No.24) (2018).
- [38] BSI, Geometrical Product Specifications (GPS)- Surface Texture: Areal. Part 2: Terms, Definitions and Surface Texture Parameters, 2022. ISO Standard 25178-2: 2021.
- [39] R. Liu, Y. Pan, A. Chen, G. Bin, H. Li, Study on the influence of surface roughness on the erosion characteristics of compressor blades, *Powder Technol.* 430 (2023) 119037.
- [40] W. Zhang, K. Tainaka, S. Ahn, H. Watanabe, T. Kitagawa, Experimental and Numerical investigation of effects of particle shape and size distribution on particles' dispersion in a coaxial jet flow, *Adv. Powder Technol.* 29 (2018) 2322–2330.
- [41] S. Scherrer, S.N. Ramakrishna, V. Niggel, C.-P. Hsu, R.W. Style, N.D. Spencer, L. Isa, Characterizing sliding and rolling contacts between single particles, *Proceedings National Academy of Sci, Eng* 122 (10) (2025) e2411414122.
- [42] Inconel 718 Tech Data.” Accessed: April. 28, 2024. Available: <https://www.hightempmetals.com/techdata/hitemplinconel718data.php>.
- [43] Y.I. Oka, M. Matsumura, T. Kawabata, Relationship between surface hardness and erosion damage caused by solid particle impact, *Wear* 162–164 (1993) 688–695.
- [44] Ti-6Al-4V Grade 5 Datasheet.” Zapp. Accessed: Apr. 28, 2024. Available: https://www.zapp.com/fileadmin/_documents/Downloads/materials/high_performance_alloys/en/TiAl6V4-Grade5-Datasheet.pdf.
- [45] R. Melentiev, F. Fang, Investigation of erosion temperature in micro-blasting, *Wear* 420–421 (2019) 123–132.
- [46] D. Tabor, The hardness of metals, in: *Oxford Classic Texts in the Physical Sciences*, Clarendon Press; Oxford University Press, Oxford: New York, 2000.