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Erosion Resistance of Surface Engineered 6000 Series Aluminium Alloy

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Abstract

Aluminium and its alloys are widely used in a wide variety of applications. Aluminium's main advantages include: lightness, high specific strength, high thermal and electrical conductivities, good formability, excellent machinability, diversity of aluminium alloys, extensive range of forms and processing options (e.g. rolling, extrusions, stampings, forgings and castings) and suitability for a diverse range of joining techniques, surface treatments and recyclability. A number of surface treatment technologies is available which produce thicker oxide coating layers that can be used to combat corrosion and wear of aluminium alloys under aggressive environments, such as in petroleum extraction environments. Coating processes for surface modification of aluminium alloys include Plasma Electrolytic Oxidation (PEO), Plasma Spray Ceramic (PSC) and Hard Anodizing (HA). In this paper, erosive wear characteristics of coatings produced using the aforesaid three processes are compared against each other and benchmarked against the uncoated aluminium substrate. This paper investigates the extent of erosion resistance, in particular impingement due to sand loading, of these coatings taking in consideration the effect of the material properties such as adhesion, ductility and roughness.

1. Introduction

Material selection in the oil and gas sector is largely influenced by aggressive environments and their impact on component degradation. Erosion phenomena involve solid particle movement in a fluid stream (gaseous or liquid) which causes material removal due to mechanical effects (wear) and chemical effects (corrosion) [1]. There is a need to improve surface resistance to withstand aggressive environments more efficiently for protecting the components from erosion damage [2].

The most common materials used currently in oil and gas sector are steels, mainly carbon and stainless steels due to their predictable corrosion behaviour, good mechanical properties and relatively low material cost [3]. However, there is still a need to modify their surfaces in order to improve erosion resistance. One method to extend the service life of metals is to use inhibitor chemicals that react with the metal surface increasing protection against erosion-corrosion. For example, chemical inhibitors were used for different types of steels including carbon steel, martensitic stainless steel and superduplex stainless steel and the resistance to erosion have been effectively increased by 50% and 45% for the carbon steel and martensite stainless steel respectively. However, the contribution of the inhibitor on the superduplex stainless steel sample was not apparent [4]. Also, different surface treatments have been applied to a variety of substrates in order to improve the erosion resistance of the components in oil sands industry. For example, it has been shown that metal matrix composites (MMCs) applied on steel using plasma transferred arc (PTA) welding, can significantly reduce wear damage [5].

Aluminium and its alloys have been widely used in various industries due to their properties such as high strength to weight ratio. Also, aluminium is a passive material which can naturally form an oxide dense layer to give corrosion protection. However, under aggressive environments, such as petroleum environments, aluminium surfaces can be subjected to many types of failure due to wear and erosion. Surface treatments techniques on aluminium can potentially enhance corrosion and wear resistance and consequently increase the lifetime of the components. The current study investigates the erosion resistance of three types of ceramic coatings deposited on 6082 aluminium alloy. These are hard anodized (HA), plasma electrolyte oxidised (PEO) and plasma sprayed ceramic (PSC) coatings.

Hard anodizing (HA) is an electrolytic passivation process in which a treated component is made the anode in an electrolytic cell. Anodization changes the microscopic structure of the metal near the surface by increasing the thickness of the natural oxide layer. Anodizing is used to increase wear and corrosion resistance, however coating produced is normally porous and subsequent sealing procedure might be required to provide adequate corrosion protection [6]. Plasma sprayed ceramic (PSC) is a coating produced by a process in which the material to be deposited is melted in the plasma jet and propelled towards a substrate. The molten droplets strike cold substrate surface with high kinetic energy where they are flattened,

solidify rapidly and form a deposit [7]. The process produces coatings with lamellar grain structure characterised by small voids, cracks and regions of incomplete bonding [8]. Such coatings are typically deposited to provide protection against high temperatures, erosion and wear and can also be used to replace worn material.

Plasma Electrolytic Oxidation (PEO) is an electrochemical surface treatment process that produces an oxide coating on light metals and their alloys [9]. The coating is produced by passing a modulated electrical current through a path of electrolyte solution and plasma discharge is formed around the component generating oxide film [10-11]. The resulting coating is well adhered to the substrate and is characterised by relatively high wear and corrosion resistance and good thermal conductivity [12-13]. Many authors have evaluated the wear behaviour of PEO coatings and it can be concluded that it improves wear resistance of aluminium substrate by 150 % - 200% [14-16]. Regarding the erosion performance of PEO coatings, Barik et al. [17] have studied their response under different kinetic energy conditions and it was found that PEO coating provides superior protection to the aluminium substrate at low energies but not enough resistance at high energy levels due to the removal of the top layer of the coating. However, Barik's study requires further research to consider different factors such as elevated temperature, different sand concentrations and different impact angles. This paper addresses some of these issues.

2. Experimental methods

2.1 Materials

The substrate material used in this paper was AA6082-T6 aluminium (Table 1). Disc specimens were cut from 25.40 mm diameter bar with a nominal thickness of 10 mm \pm 0.01 mm and fitted in the holder for erosion experiments. Three types of coatings used in this study were characterized in terms of thickness, hardness, roughness, surface uniformity and adhesion. Materials characterisation results are presented in section 3.1 and summarised in Table 4. All coatings were sourced from commercial companies.

Reference\ element (wt%)	Si	Mg	Mn	Fe	Cr	Cu	Zn	Ti	Al
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(British Standard, 1998)	0.70-1.30	0.60-1.20	0.40-1.0	0.50	0.25	0.10	0.20	0.10	Balance
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Table 1: Chemical composition of 6082 aluminium alloy.

2.2 Surface analysis

Optical and SEM images were captured for all samples to study the surface morphology, porosity and their structures using Leica microscope and Carl Zeiss SEM EVO MA15 equipment respectively. Also, the coating phase composition was determined using XRD system (PANalytical X'pert MPD). Hardness was measured using Mitutoyo MVK H2 micro-hardness tester and roughness was obtained by Veeco-Wyko NT 3300S Interferometer. After erosion experiments, profilometry analysis was carried out on the damaged surfaces using Form Talysurf 120L equipment in order to measure the surface shape, texture and to identify the depth of wear scars.

2.3 Erosion experiments

Figure 1 shows the erosion rig with instruments and tools used in the experiments. The reservoir was filled with 70 litres of tap water, its composition is shown in Table 2. Water was circulated through the system according to the flow direction shown in the figure. The rig was equipped with thermostat to monitor water temperature by controlling heating coils immersed in water. Water carrying sand particles was impinging the sample surface through two 4 mm nozzles. Each sample was fixed at a distance of 20 mm from the nozzle where the water was ejected at a speed of 10 m/s.

Parameter	Value
Conductivity	2500 μ S/cm
pH	6.5 – 9.5
Chloride	250 mg/l
Sulphate	250 mg/l
Sodium	200 mg/l
Nitrate	50 mg/l
Nitrite	0.5 mg/l
Ammonium	0.5 mg/l
Aluminium	200 μ g/l
Iron	200 μ g/l
Manganese	50 μ g/l
Copper	2 mg/l

Table 2: Tap water composition.

[Source: Yorkshire Water, Leeds HL Bramley/Headingley 2004 (1802003)]

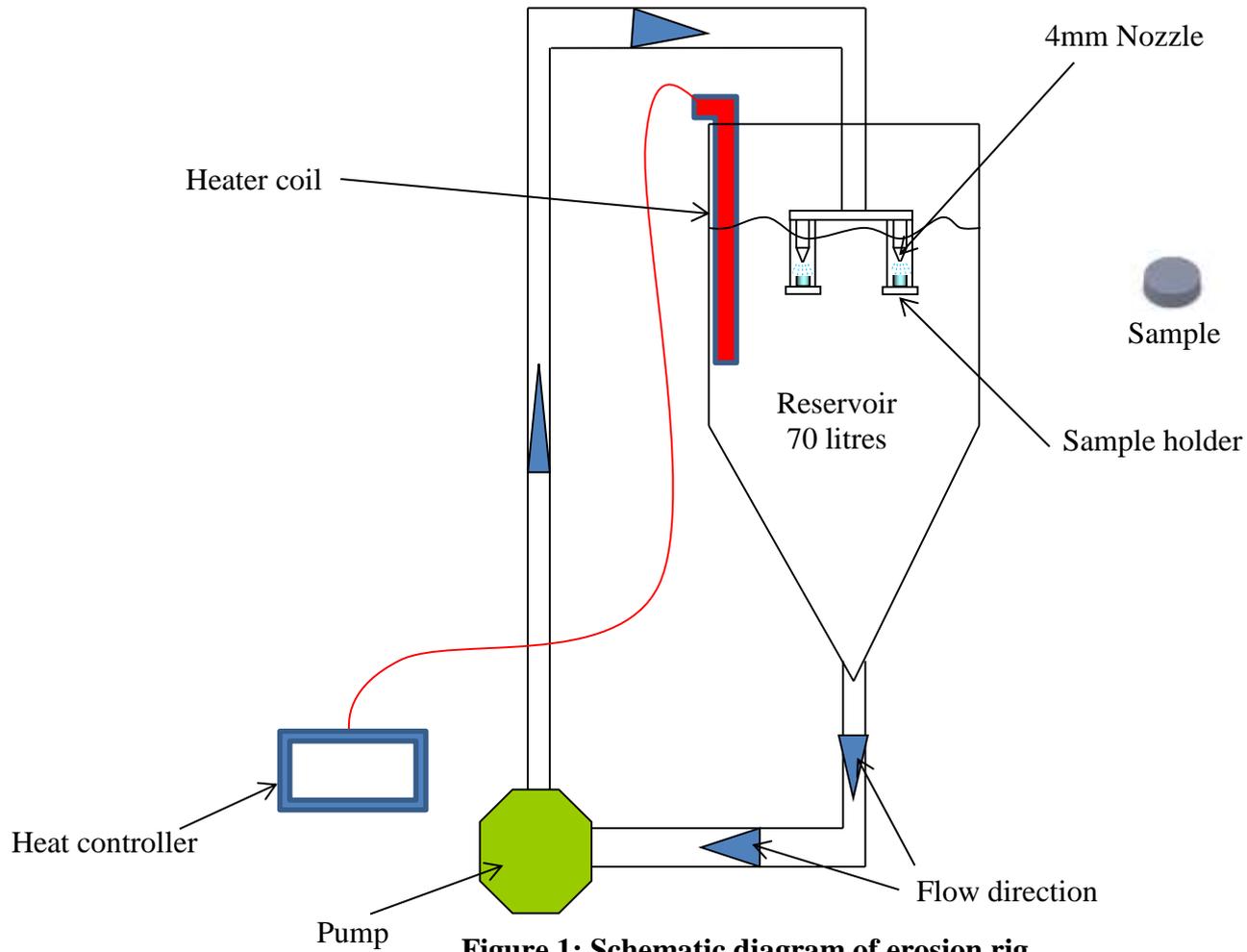


Figure 1: Schematic diagram of erosion rig.

Sand used in the experiments was a silica sand (Congleton HST 60) and Figure 2 shows an SEM image of sand particles with an average diameter between 200 μm and 250 μm .

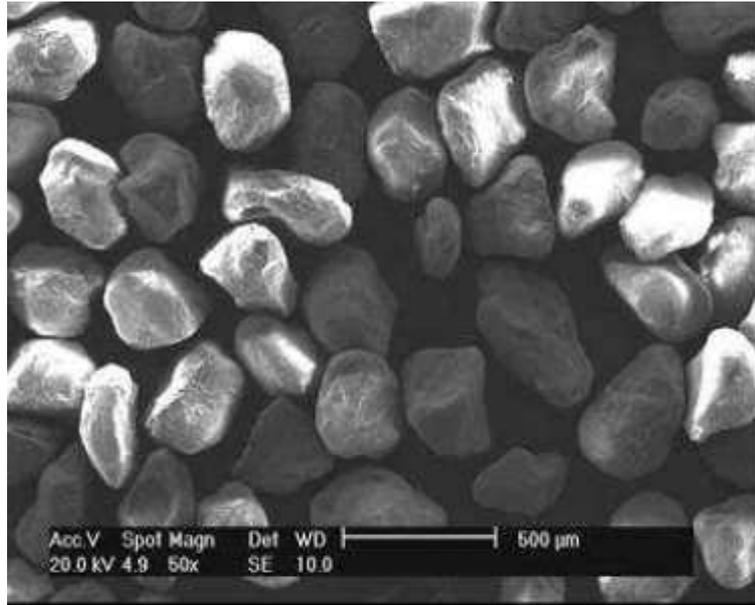


Figure 2: SEM image of sand particles.

Two sand loadings (200 mg/l & 1000mg/l) and two temperatures (20 °C & 70 °C) have been selected as the main experimental variables to represent conditions relevant to oil production sector applications [18]. Also, two impingement angles of 30° and 90° were selected since it is expected that maximum erosion rates can be achieved at those angles for ductile and brittle materials respectively [19-20]. The weight loss measurements were recorded after 2, 5, 8 and 10 hours experiments. The erosion test conditions are summarized in Table 3.

Test Condition	Jet velocity (m/s)	Sand size (μm)	Impingement angle	Temperature (°C)	Sand concentration (mg/l)	Test duration (hours)
A	10	250	90° (&30°)	20	200	2, 5, 8 & 10
B	10	250	90° (&30°)	20	1000	2, 5, 8 & 10
C	10	250	90°	70	200	2, 5, 8 & 10
D	10	250	90°	70	1000	2, 5, 8 & 10

Table 3: Erosion test conditions.

3. Results and discussion

3.1 Materials characterisation results

Figure 3 reveals the surface morphology of the materials using SEM technique. It can be seen that aluminium substrate (Figure 3 (a)) has some parallel lines which is due to scratches generated during sample preparation and small white spots shown on the surface that indicate the silicon phases. The surface morphology of PEO sample is characterised by macro-particles which resulted from the spark discharges during the layer growth (Figure 3(b)).

Hard anodized coating has many white spots which indicate the existence of micro-porosity on the surface as shown in Figure 3 (c). Plasma spray coating (Figure 3(d)) has high porosity and many white regions which indicate the presence of titanium dioxide as revealed in EDX experiments. The chemical composition and phases detected for all materials are summarized in Table 4.

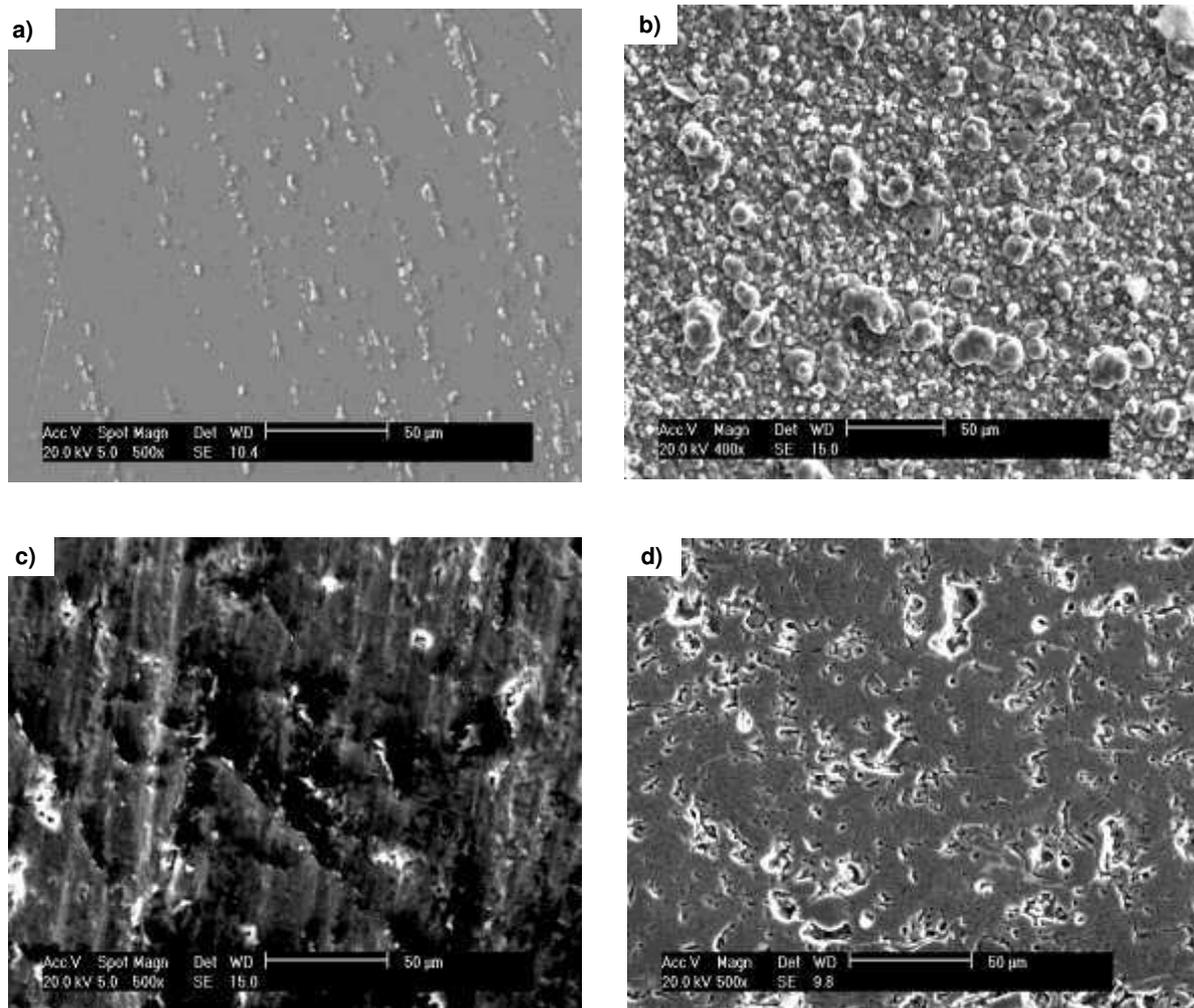


Figure 3: Surface morphology SEM images: a) Al, b) PEO, c) HA and d) PSC.

Coating Type	Nominal Thickness (μm)	Hardness ($H_{\text{Knoop}, 25\text{g}}$)	Roughness R_a (μm)	General Features
PEO (Plasma Electrolytic Oxidation)	34.2 ± 4.0	1575 ± 391	0.07 [polished] 1.66 [unpolished]	<ul style="list-style-type: none"> • Uniform thickness; • Good edge retention; • uniform coating/substrate interface; • Two distinct regions: inner dense & outer porous; • Some porosity; • Elements (EDX): O: 49.2%, Al: 48.59%, Mg: 0.80%, Si: 0.71%, Mn: 0.70%; • Phases (XRD): Al, $\alpha\text{-Al}_2\text{O}_3$, $\gamma\text{-Al}_2\text{O}_3$.
HA (Hard Anodising)	41.0 ± 1.0	533 ± 129	1.52	<ul style="list-style-type: none"> • Variable coating thickness on the sharp edges; • Columnar cracks extending down to the substrate; • Two distinct regions: inner dense & outer porous; • Coating structure with voids; • Elements (EDX): O: 51.19%, Al: 42.08% , S: 5.63%, Cr: 0.55%, Si: 0.55%; • Phases (XRD): Al.
PSC (Plasma Spray Ceramic)	242.1 ± 5.0	790 ± 162	3.15	<ul style="list-style-type: none"> • Variation in coating thickness; • Three distinct regions: inner & outer porous layers and denser intermediate layer; • High porosity; • Elements (EDX): O: 44.23%, Fe: 23.11%, Al: 16.27%, Ti: 0.75%, Si: 14.32%, Mg: 1.32%; • Phases (XRD): $\alpha\text{-Al}_2\text{O}_3$, $\gamma\text{-Al}_2\text{O}_3$.

Table 4: Summary of materials properties. General features of coatings characterised based on SEM images cross-sections and XRD analysis.

3.2 Reproducibility of the results

Two-hour tests were carried out twice on all materials to establish repeatability of the results at low and high sand loadings as shown in Figure 4 and Figure 5 respectively. It has been found that the weight loss difference was in the range of 15% for low sand loading experiments and below 5% for high sand loading experiments for the aluminium substrate. However, the maximum weight loss difference for the ceramic coatings was found to be 26% for the PSC coating at low sand loading and 9% for high sand loading tests. Moreover, a linear relationship of a weight loss as a function of test duration has been found for all tested coatings as shown in section 3.4.

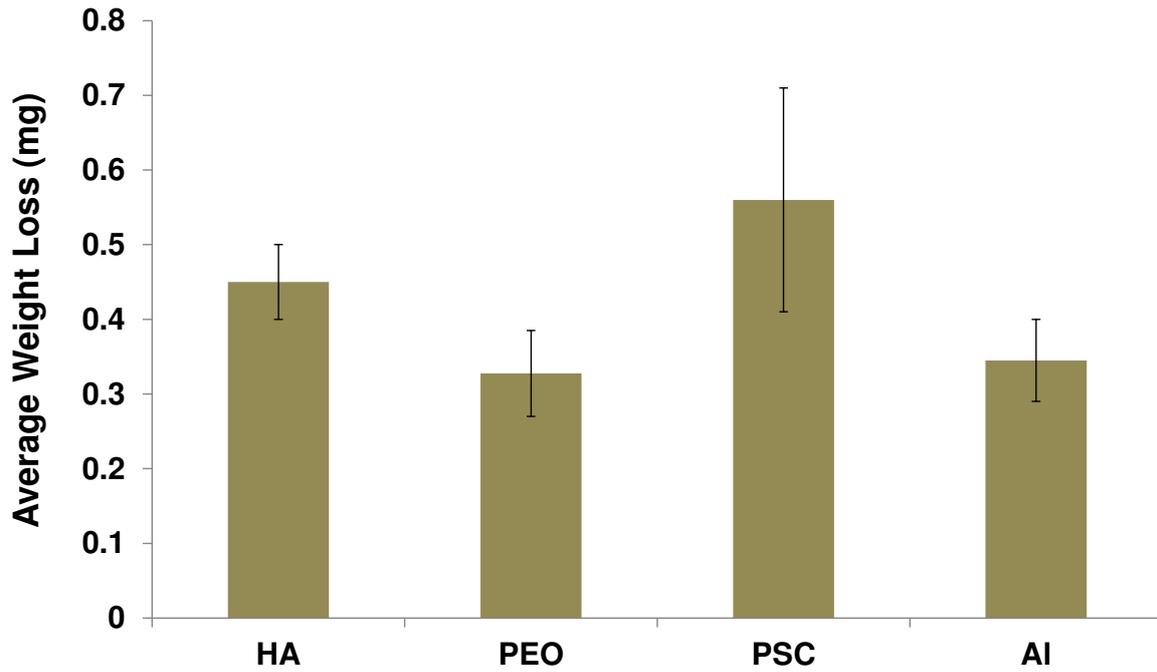


Figure 4: Reproducibility of weight loss data at sand loading of 200 mg/l.

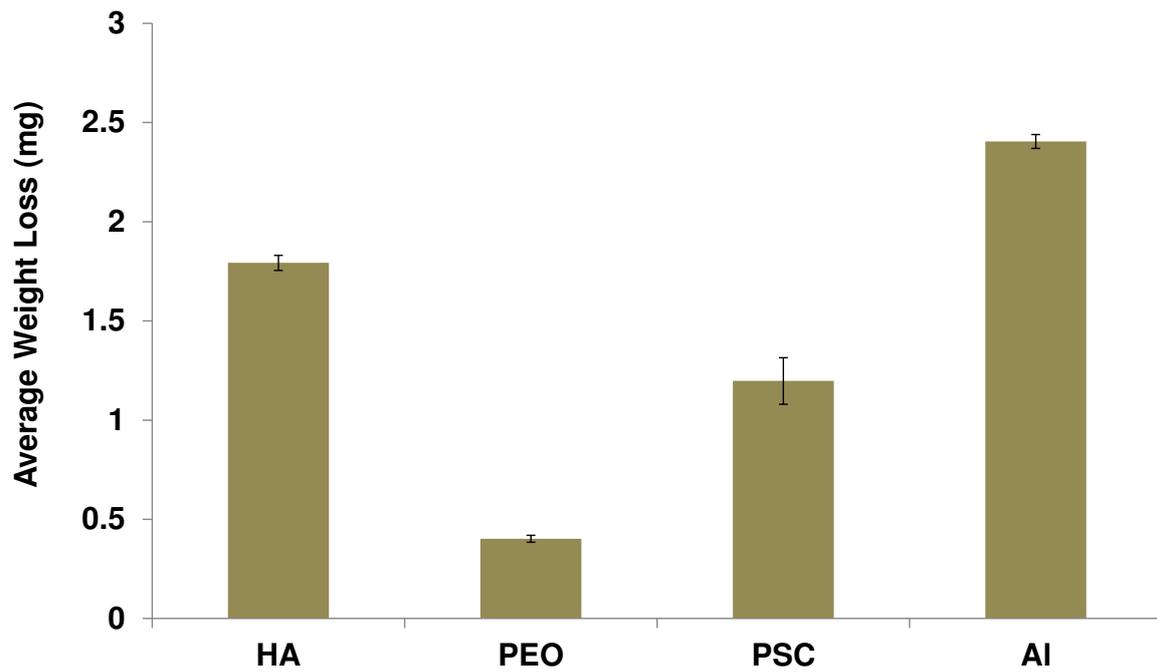


Figure 5: Reproducibility of weight loss data at sand loading of 1000 mg/l.

3.3 Effect of sand loading and temperature

Figure 6 and 7 show the total weight loss of the materials for ten hour experiments under two sand loadings at two different temperatures. A consistent increase in the wear rates has been observed with increasing sand loading for all materials as expected. Generally, PSC coating

exhibits the poorest erosion resistance in most tests conditions while PEO has the lowest weight loss. Additionally to room temperature experiments at 20 °C, high temperature tests at 70 °C were performed to investigate the effect of elevated temperature on erosion resistance of tested materials (Figure 7). The erosion rates observed at elevated temperature tests are higher than at room temperature test for all coated samples and aluminium substrate, however it is shown that PEO coating had the best erosion performance.

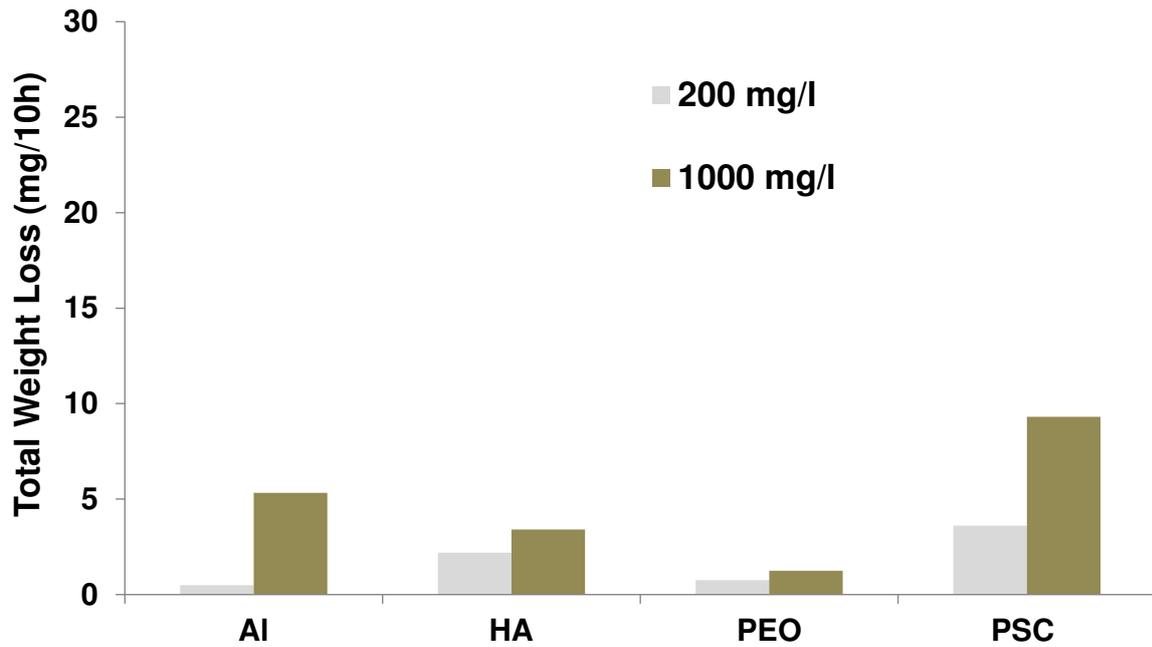


Figure 6: Effect of sand loading and temperature; test duration = 10 hours; impinging angle = 90°; temperature = 20 °C.

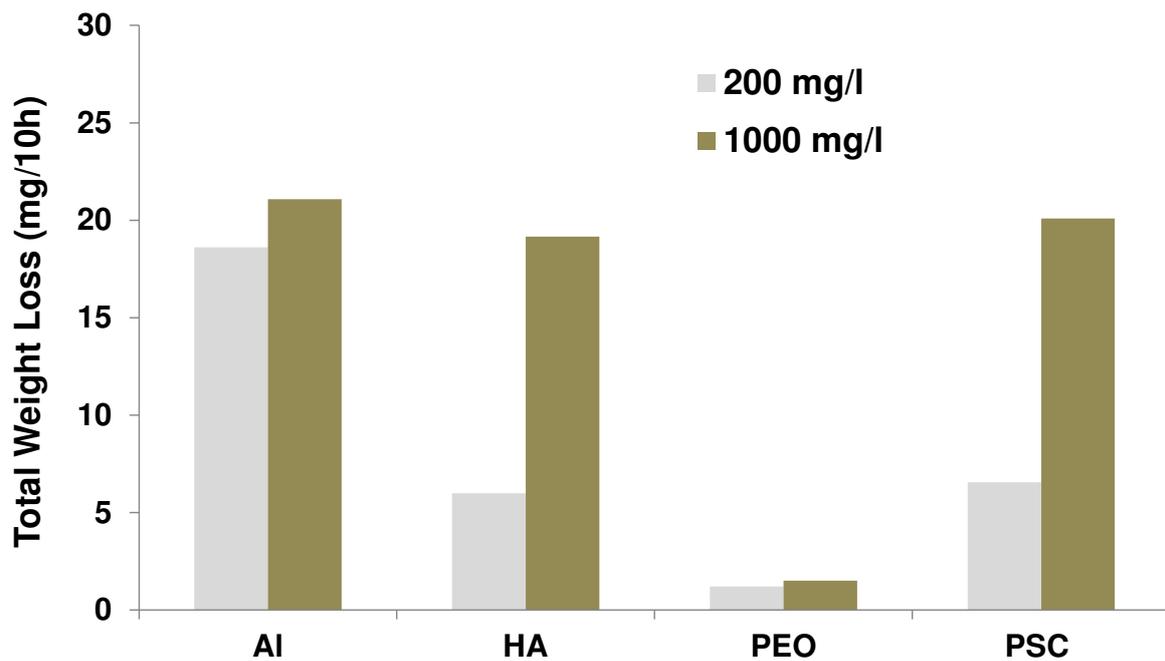


Figure 7: Effect of sand loading and temperature; test duration = 10 hours; impinging angle = 90°; temperature = 70 °C.

It has been observed that aluminium substrate has good erosion resistance at low sand loading and low temperature which indicates that the aluminium oxide film gives certain erosion protection. This film is being damaged at high sand loading resulting in considerable increase of the material loss of Al as reported by Zhang et al. [21]. Higher temperature affects erosion of the aluminium substrate more than the ceramic coatings. The erosion rate for the aluminium substrate at higher temperature increases by factor of 4 compared to room temperature tests. This phenomenon could be attributed to the thermal conductivity of the substrate, while ceramic coatings are more resistant to temperature. Also, increase of the weight loss at 70 °C test of coated samples can be explained by the viscosity effect of the fluid at high temperature [22], where the fluid velocity increases and the kinetic energy of the impacting particles will consequently increase resulting in higher erosion rates. Moreover, it is expected to have higher degradation due to corrosion at high temperature tests which will increase the weight loss. Good erosion resistance of PEO coating under all test conditions can be explained by coating uniformity, good adhesion to the substrate and low porosity level. Also, the existence of the dense aluminium oxide ($\alpha\text{-Al}_2\text{O}_3$) improves the material mechanical properties by giving it high hardness which increases the level of protection against erosion.

3.4 Wear mechanism

Damage mechanism can be dominated by brittle or ductile material response under erosion conditions. Ductile materials have localized plastic deformation while brittle materials can be removed due to chipping effects and cracking. Surface morphology of a ductile material will be modified due to impact of the solid particles at localized areas eventually leading to fracture after reaching critical strain hardening [23]. In contrast, brittle materials cannot absorb loading generated by impinging particles (no plastic deformation) and large amount of material can be removed by brittle fracture and debris formation. The erosion rates will also increase with higher porosity of materials [24].

In addition to 90° impingent angle experiments, the samples were also tested at 30° to study the impact of lower impingement angle on the wear loss and surface damage mechanism. Figure 8 shows a comparison between the weight loss due to erosion at two different angles after ten hours for all materials. There is a significant difference in the erosion performance for all materials with changing impingent angle. It is noticed that the effect of changing the angle from 90° to 30° resulted in nearly 50% increase in the wear loss of both Al and HA, while it caused decrease of wear rates for PEO and PSC coatings.

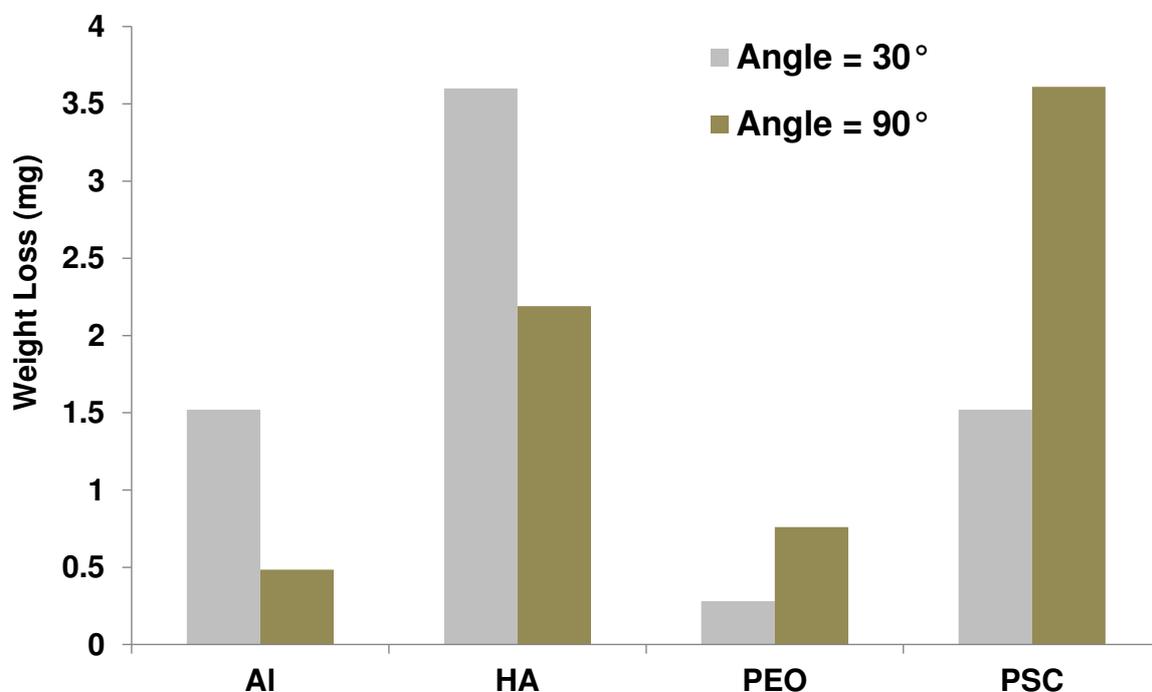


Figure 8: Effect of impact angle at 1000 mg/l; test duration = 10 hours; temperature = 20 °C.

Ductile materials experience high erosion rates around 20° to 30°, while the erosion peak for brittle materials is at 90° [20]. It has been observed that the aluminium substrate experienced more weight loss at low impact angle test (30°) than the normal impact angle. At normal angle impingements, only normal stress will affect the impacted surface causing damage to the oxide film, however this film will not be completely removed providing certain limit of erosion resistance [21]. At low angle impingements, a combination of shear stress and normal stress occurs and oxide film becomes thinner and eventually is removed under shear stress loading.

Slurry jet tests done by Zhang et al. [25] on alumina ceramics (AD998 and AD92) and mild steel at 16.5 m/s and 7.6 wt.% sand loading at different angles show that the maximum wear rate, for the alumina ceramics, occurs at normal angle then the rate decreases as the impact angle becomes smaller. Similar conclusion was made in [26] demonstrating that ceramic brittle materials have high wear loss at normal angles. The surface texture of PSC after tests indicated competition between ductile and brittle wear mechanisms and similar conclusion was made by Wellman et al. [27]. Also, Mishra [28] found that erosion mechanism for the plasma spray Ni-20Cr coating was dominated by ductile behaviour since platelets were formed by plastic deformation. Additionally, fracture mechanism was also observed on the eroded surface due to ploughing. Therefore, ductile materials have better erosion resistance at high impact angles whereas brittle materials have minimum erosion wear at low angles.

3.5 Effect of PEO coating surface finish

As a result of discharges occurring during the PEO process and the resulting plasma modification of the structure of the oxide layer, the surface of a coated component is relatively rough. When feasible, PEO coated components are usually polished to give a smooth and shiny finish to the surfaces. Hence, in this study we wanted to investigate the impact of polishing on PEO coatings erosion response. Figure 9 shows the erosion rate for the polished and unpolished surfaces of PEO coating at two sand loadings at room temperature. The surface roughness of the materials is expected to affect the material degradation in erosion experiments and it is clearly shown that the unpolished (rougher surface) has more weight loss than the smoother surface. The hypothesis is that the rougher surface will have lower surface integrity as a result of more valleys and higher number of peaks which can be

removed easily due to impacting particles, and as a result, the erosion rate will increase [29]. In addition, the erosion resistance for the polished PEO surface at high sand loading (1000 mg/l) is even better than the unpolished one at low sand loading (200 mg/l).

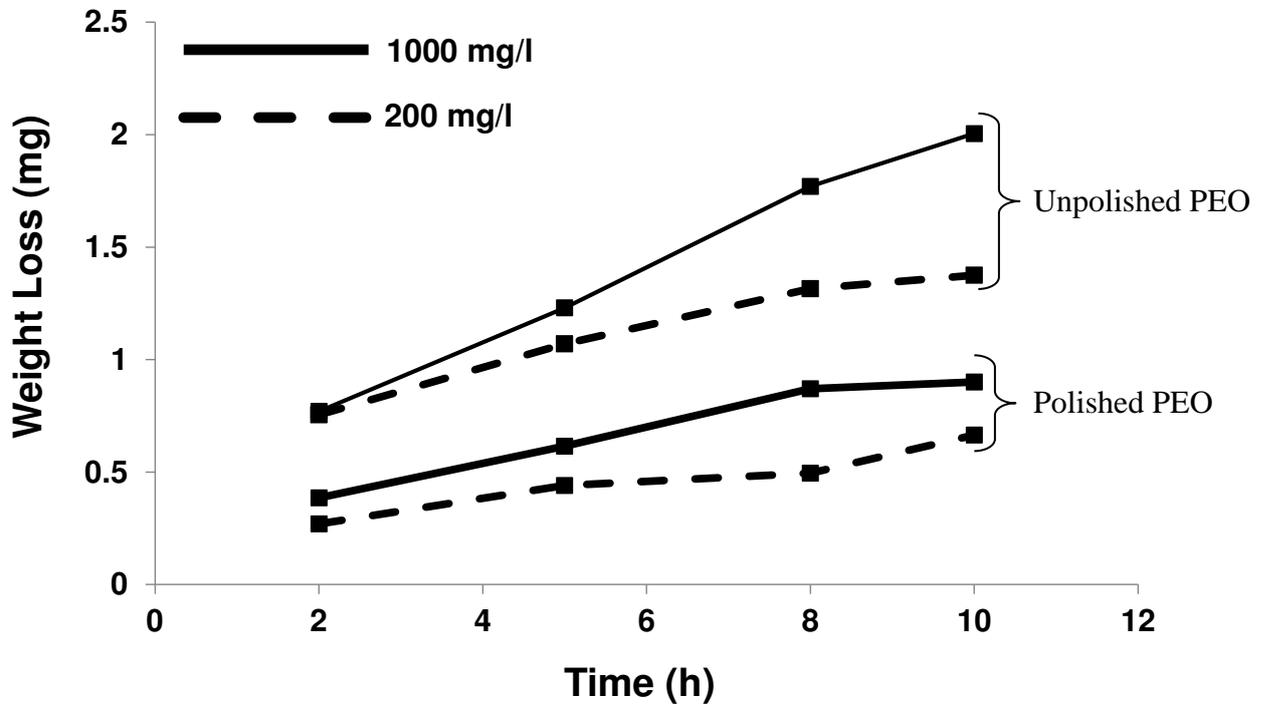


Figure 9: Relationship between roughness and erosion rate; test duration = 10 hours; angle = 90°; temperature = 20 °C. The lines have been added for visual purposes only and do not indicate trends.

3.6 Summary of coatings performance

Figure 10 shows the erosion rate for the tested materials under four test conditions outlined in each figure. PEO coating has the minimum weight loss under all test conditions compared to the other materials investigated in this study (Figure 10 (b)). This could be attributed to high hardness, high density of the coating and good adhesion between the coating and the substrate which gives the coating more resistance against the impacting particles. PSC coating has the highest linear erosion rate compared to other materials' rates which could be attributed to low adhesion where the material is removed heavily due to chipping effect and cracking. High porosity of PSC coating decreases its strength by promoting stress concentration and consequently minimising absorption of the impact loading [30]. Other materials, such as Al and HA, behave as ductile materials absorbing the particles' impacts and as a result suffer from localized plastic deformation. Moreover, the low erosion

resistance of HA compared to PEO coating could be attributed to the low hardness value of HA [29].

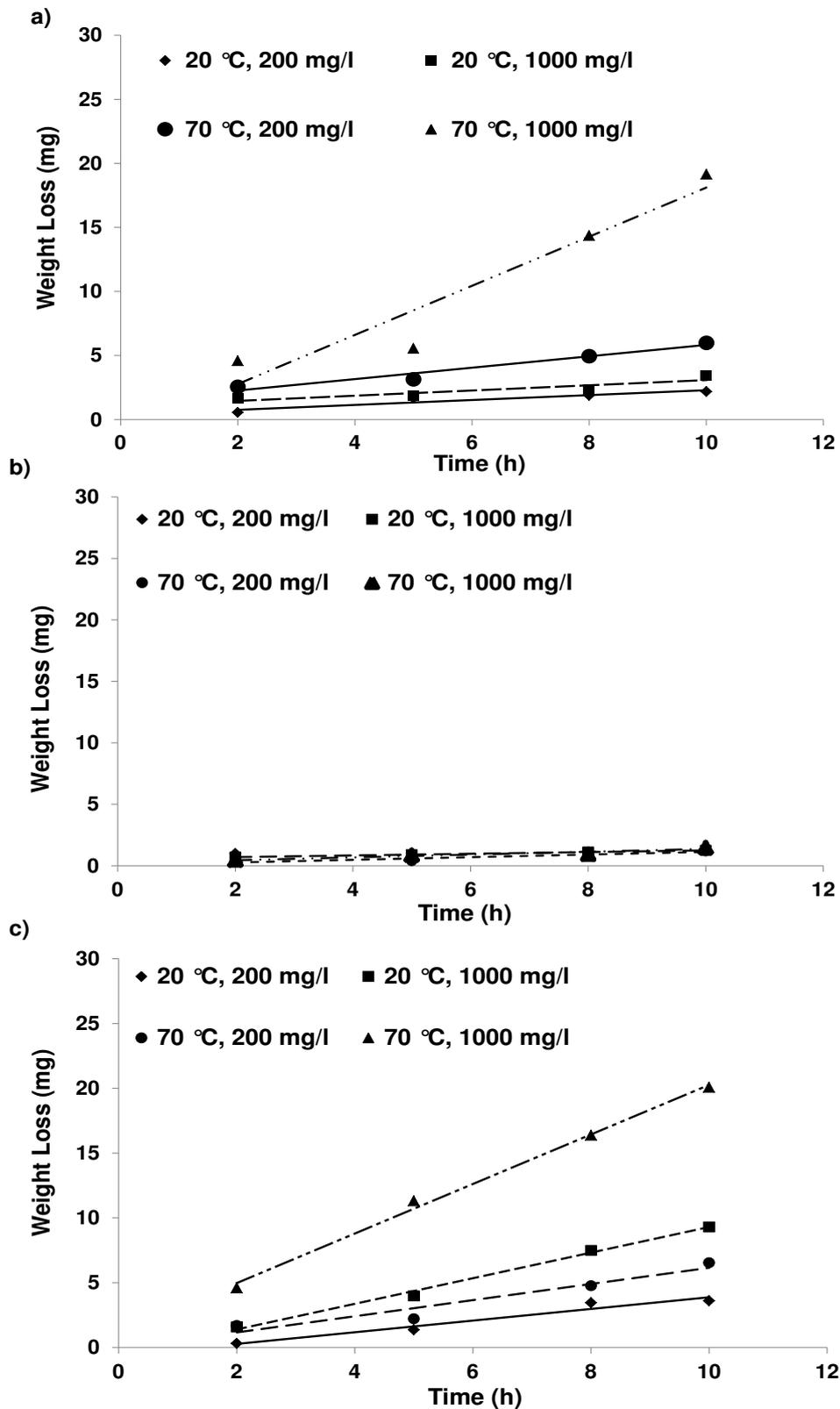


Figure 10: Erosion rate for a) HA, b) PEO and c) PSC. The lines have been added for visual purposes only and do not indicate trends.

4. Conclusions

It has been shown that the erosion performance of aluminium alloy can be highly increased using different surface treatments. PEO coating gives higher level of erosion protection comparing to HA and PSC coatings. Other findings are summarized as follows:

- PEO coatings are more dense comparing to HA and PSC coatings and show crystalline Al_2O_3 structure and higher hardness.
- Increase of test temperature from 20°C to 70°C causes significant increase of Al, HA and PSC weight loss and minimal change of weight loss of PEO.
- It has been shown that the materials which behave as ductile materials (Al and HA) have maximum wear loss at low impinging angles (around 30°) due to surface morphology modification and work hardening leading eventually to the material fracture.
- The brittle coated materials (PSC and PEO) have highest wear loss at normal angle (90°) which is in agreement with the literature.
- It has been shown that surface finish has an impact on PEO coating erosion performance; the unpolished (rougher surface) had more weight loss than the smoother surface.

5. Acknowledgements

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