Ambient Erosion Studies of Volcanic Ash

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ABSTRACT

Increasing material restrictions are continually being imposed on commercial and military aircraft. These restrictions highlight the importance of adequate testing of material behaviour and simulated performance during pseudo real world flight conditions. Erosion due to sand, volcanic ash, and other particulates resulting from residues/aerosols in the atmosphere are considered hazardous on the structure of an aircraft and may adversely influence the lifecycle of the structure. Erosion encounters for military aircraft are more frequent due to higher cruise speeds, take-off, and severe landing conditions from unconventional runways.

The present study outlined in this paper provides a metric to gage anticipated degradation utilizing volcanic ash which is known for its very aggressive erosion properties. The insertion of technology into a new or government program with the Department of Defense includes setting performance standards and defining environmental life cycle requirements. The government standard covering sand and rain erosion is MIL-STD-810. In its current version, MIL-STD-810F outlines a six step systems engineering approach to determining and documenting the lifecycle environment of a system and the test plan to demonstrate the system robustness to meet the environment. This test standard was utilized more for guidance rather than a requirement while evaluating the erosive nature of the volcanic ash media. There are no specified test methods in MIL-STD-810F for volcanic ash, rather it mandates that standards for rain and sand erosion of airborne materials under flight conditions should be tailored for each application. Methods of characterization are measurable weight loss and average erosion depth analysis based on the duration of exposure. These results were compared against a well-known erosion media, AFRL01 to illustrate the aggressive nature of the volcanic ash media. Detailed evaluation of the volcanic ash test media was also conducted and reported.

1.0 INTRODUCTION

Since the beginning of modern aviation, erosion effects caused by sand [1], volcanic ash [2], and other particulates on aircraft during flight have been observed. The focus of this article is to provide a metric to gage the anticipated influence of erosion as an estimate of wear onto a solid structure, represented by the body of an aircraft and leading edge materials. In particular, how the impact by solid particulates can influence the characteristics of aircraft structural materials during the course of flight. This influence is dominated by exposure time to the erodent, type of erodent and impact speed of the erodent. Wear due to erosion by solid particulate impact is a phenomenon that affects many practical applications, including turbine engines, helicopter and propeller blades, high speed vehicles and aircraft, canopies and radomes [3].

Typically, aircraft encounter solid particulate erosion when the vehicle is taking off from a sand covered runway or flying at high altitudes. Volcanic ash encounters in aviation have been recognized as a major threat to the airworthiness of aircraft and in the past three decades more than a hundred commercial airplanes have been exposed to unforeseen ash cloud encounters [4]. The volcanic ash particulate with dimensions between 1 and 10 μm may be dispersed 1000 miles away from a volcano (distal volcanic ash), and since there are numerous erupting volcanoes in the world, these particles may be hazardous when entered into unexpected airspaces. Encounters with volcanic ash are often cautioned because of the risk of engine deterioration which may result in engine flame-out scenarios. Moreover, the abrasive nature of the volcanic ash stemming from its sharp and hard nature serves as a very effective erodent on the forward-facing surfaces of an aircraft and in particular on the cockpit windshield [4].

The effects of erosion are highly dependent on a number of factors such as material properties, geometrical constraints, flight/impact speed, incident angle, coating thickness, and particle size. While the aircraft and its components might be subjected to other types of wear such as corrosion wear, fatigue, fretting and other types of fracture, this study is mainly concerned with erosive wear. In erosive wear a surface is constantly subjected to an impingement by solid particulates through means of a particle steam or jet.

2.0 BACKGROUND

More than twenty-five years of continuous operation in the dusty environments of Southwest Asia have shown that degradation of gas turbine engine components due to particle ingestion is a serious threat to operations. In particular, the continuous push for higher engine operating temperatures leading to higher engine speeds have brought a new emphasis to the damage mechanisms.

The first modern aviation mishap due to encounter with volcanic ash occurred on June 24, 1982. Upon entering the volcanic ash from the Indonesian volcano Gulunggung, a Boeing 747-200 aircraft experienced an all engine flame-out at 37,000 ft [5]. The aircraft landed at Jakarta with three of the four engines restarted after the flame-out. Another unexpected encounter that resulted in erosion of the turbine blade leading edges of the NASA DC-8 Airborne Sciences airplane, flying through a diffuse ash plume, occurred on February 28, 2000 [2], where the ash cloud originated from Mt Hekla volcano in Iceland.

Due to the number of active volcanic incidents, volcanic ash erosion has become a growing concern with the aviation industry due to the materials highly abrasive nature, as well as, the melting effects on internal components within the hot zone of turbine engines. The engines that are utilized for military aircraft and that underwent volcanic ash ingestion are commonly taken out of service earlier than expected due to rapid erosion degradation along with other issues that accompany this type of ingestion media, such as molten glass build-up in the hot zones. These concerns have garnered much attention within the aviation community leading to the active testing that is currently being conducted to look at the effects of volcanic ash in an attempt to predict turbine engine life in this harsh environmental condition.

The results are often varied due to the inconsistent composition of the volcanic media. Volcanic ash composition and media properties vary from region to region with respect to composition of minerals, the particle sizes and size distributions, and the softening and melting points during heating much like that of sand. To build on that concept and add to the complexity of this media, no two eruptions from the same location share identical elemental consistencies. With these variations in testing media, it is expected that component wear will indeed vary to a degree and show differing results. Outside of the variations in test media, there are additional variables that could impact component testing resulting in further differences in outcomes. One cause could be that testing procedures do not accurately represent the actual volcanic ash ingestion as it happens in real world operations. Another possible cause is that the type of volcanic ash used during the testing may not actually represent the behaviour of all ashes ingested in real world operations, as previously explained. It is likely that testing improvements in both areas are warranted. Currently, there is not a standardized or manufactured volcanic ash that can be utilized as a universal representative media at this time. Thus results of testing can be expected to differ to some degree.

The aviation industry relies on robust, sustainable gas turbine engines in a large number of their vehicles. Volcanic ash ingestion degrades the service life of the engine parts, thereby decreasing the maintenance inspection intervals and the overall life of the engine. A decrease in engine life ultimately results in an increase in costs burden.

3.0 EXPERIMENTAL

A series of dust erosion experiments were conducted at the Coatings, Corrosion, and Erosion Laboratory (CCEL) operated by AFRL/RXSS of the USAF located on-site at Wright Patterson Air Force Base (WPAFB), Ohio. A typical erosion test was setup to compare the erosion resistance of three aerospace materials to an unfamiliar erosion media, Mt. Mazama crushed pumice (volcanic ash, and AFRL01 using MIL-STD-3033 as a reference point to illustrate the very aggressive nature of volcanic ash. AFRL01 is the erosion media called for in MIL-STD-3033 to evaluate the erosion resistance of military helicopter rotor blades. AFRL01 is a synthetic mineral quartz sand formed by the fracture of quartz pebbles. Shattering quartz pebbles is the source of the high degree of sharpness that makes this sand uniquely suited for the standard. The mechanics of shattering versus crushing produce more sharp edges/corners. The particle/sand shall be evenly distributed across the range size of 240 to 550 microns in diameter in the as-sieved condition [6]. The Mt. Mazama volcanic ash was air-classified (separated) to a size range of 38 to 50 microns in diameter.

For direct comparison, the samples that were investigated in this erosion test where of the same physical size. Substrate materials investigated are 1) PMMA (representative of canopy materials), 2) a leading-edge material containing high solids content surface treatment for severe erosion environments; 863250 chromate epoxy primer on 2024-T3, and 3) Ti-6-4 that is utilized in modern turbine engine compressor sections. Representative test articles were mounted in an array holder (Image 1) capable of exposing up to sixteen specimens at a time which was rastered back and forth, as well as, up and down in front of a nozzle where the volcanic ash was entrained in air under pressure and expelled at a pre-calibrated velocity using a laser Doppler anemometer (LDA).

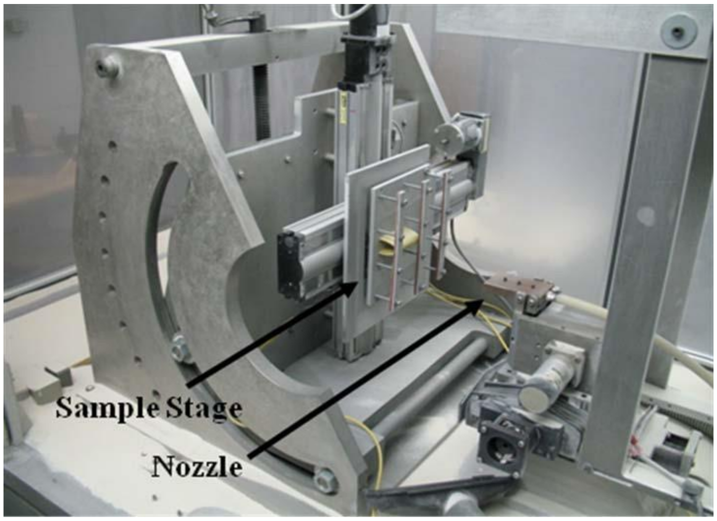

Image 1. Particle / Sand Erosion Chamber

The volcanic ash stream impacted the sample surface with an increment mass loading of 0.05 g/cm^2 with a total mass loading of 0.25 g/cm^2 at a 30-degree incident angle (Image 2) to simulate a diffuse volcanic ash cloud that may or may not be observable from a cockpit. The total mass loading was determined by dividing the total mass of particles delivered to the fixed target area and reported on a per square centimeter basis. The incident angle or impact angle in this context refers to angle suspended between the path of the incoming particle and the normal plane and not to the angle of attack of the aircraft. The particle velocity for both erosion media was 210 m/s (400 knots, 470 mph). Particle velocity was confirmed with a Dantec Laser Doppler Velocimeter. The average erosion depth analysis was conducted utilizing a Taylor Hobson Precision Surtronic 25 profilometer with an 8.00 mm scanning length to measure erodent erosion depth penetration.

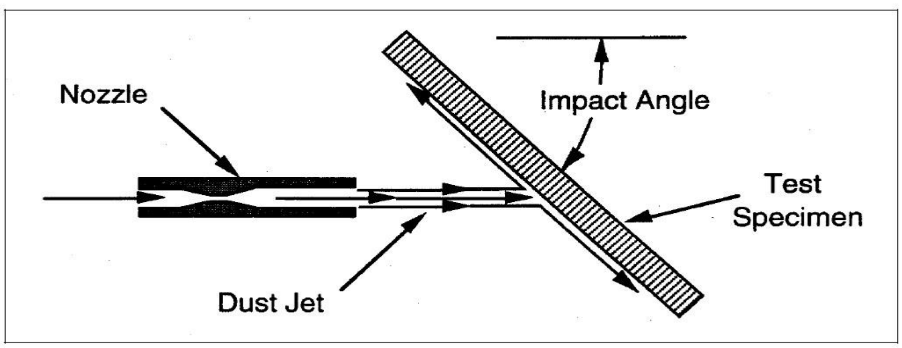

Image 2. Sand Particle Erosion Schematic

4.0 EXPERIMENTAL RESULTS

From the data collected, it can be observed in Charts 1-3 that a common trend supporting the hypothesis that volcanic ash is indeed more erosive to the selected test substrates at ambient temperatures as compared to the AFRL01 standard test media. Interestingly enough, the surface analysis profile results illustrated in Chart 4 suggests that AFRL01 creates a coarser surface profile despite less substrate mass loss across all test substrates. This is due to the larger diameter size variation of AFRL01 as compared to the volcanic ash. The variations in the surface profile of the test substrates are observed in Images 3-8 as they correlate to the erodent mass loading.

More specifically, a direct comparison of the test results after the total mass loading of 0.25 g/cm^2 test media exposure at 210 m/s with 863250 chromate epoxy primer on 2024-T3 suggest that the volcanic ash is 1.6 times, PMMA suggests that volcanic ash is 3.2 times, and Ti-6-4 suggests that volcanic ash is slightly more erosive as compared to the AFRL01 standard test media, respectively.

4.1 Measurable Weight Loss

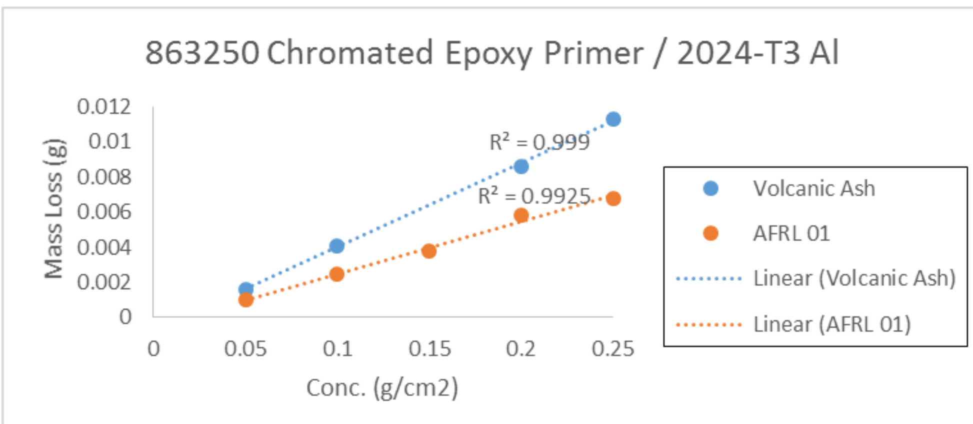

Chart 1. 863250 Chromated Epoxy Primer / 2024-T3 Al Mass Loss Comparison

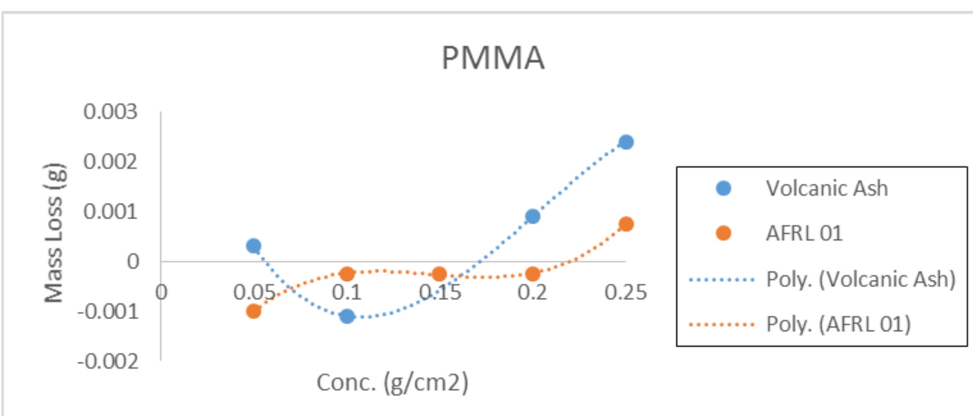

Chart 2. PMMA Mass Loss Comparison

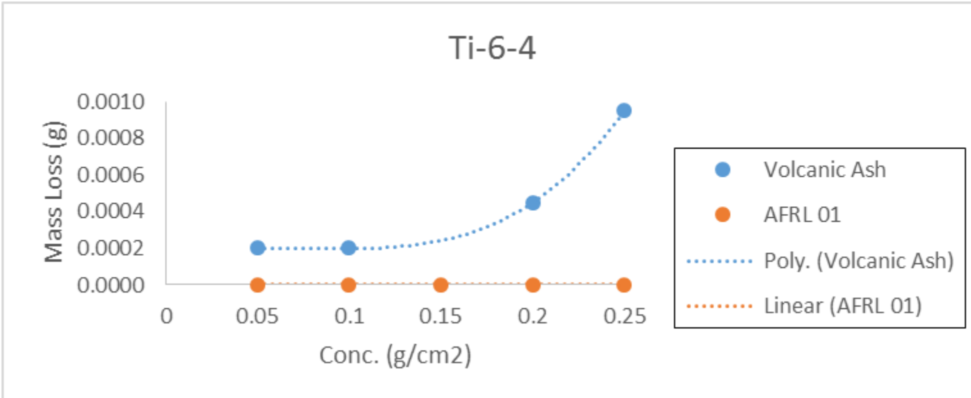

Chart 3. Ti-6-4 Mass Loss Comparison

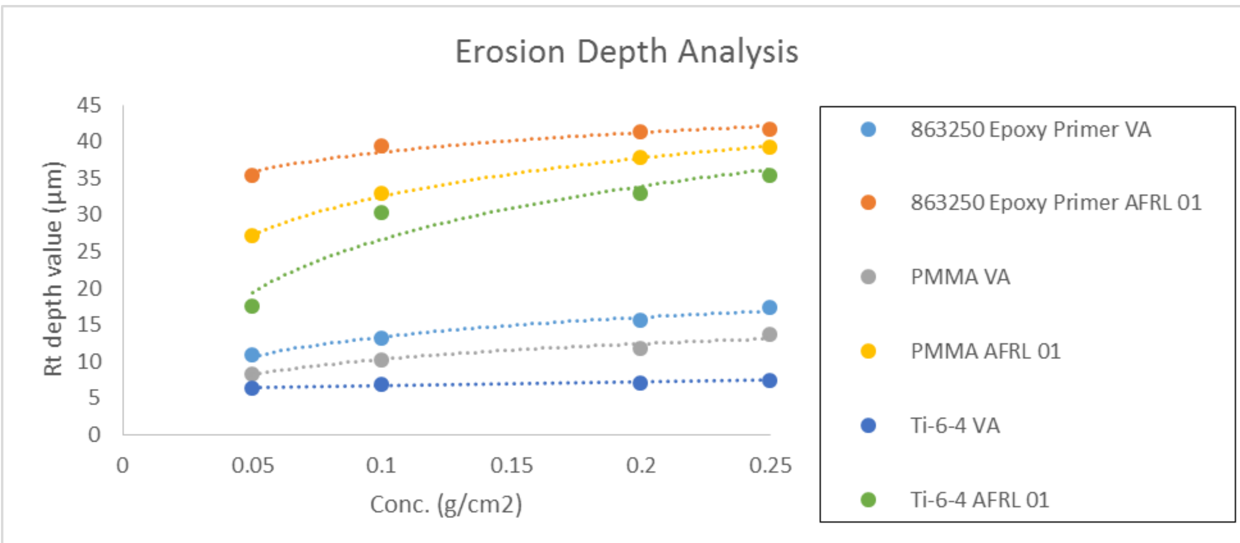

Chart 4. Erosion Depth Analysis

4.2 Test substrate images

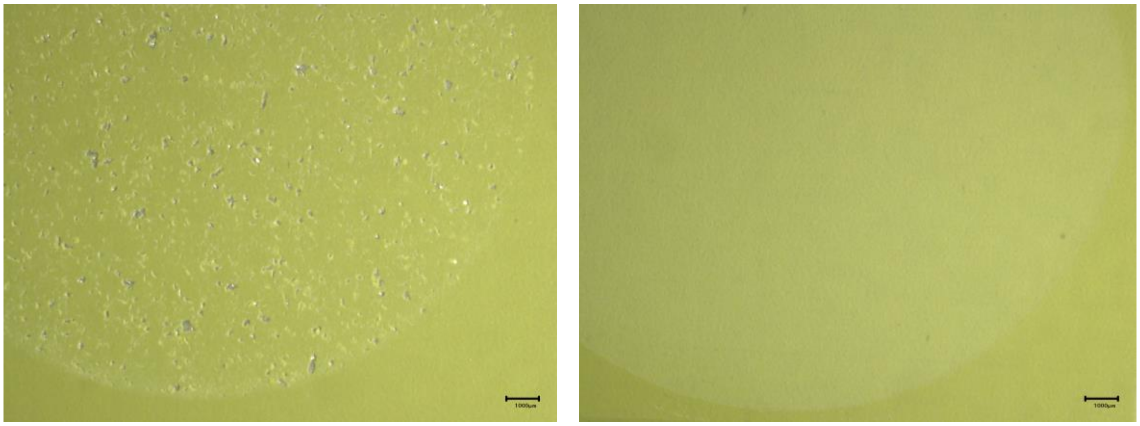

Image 3. 863250 Chromated Epoxy Primer / 2024-T3 Al surface profile comparison AFRL01 (left) and VA (right) at mass loading of 0.05 g/cm^2

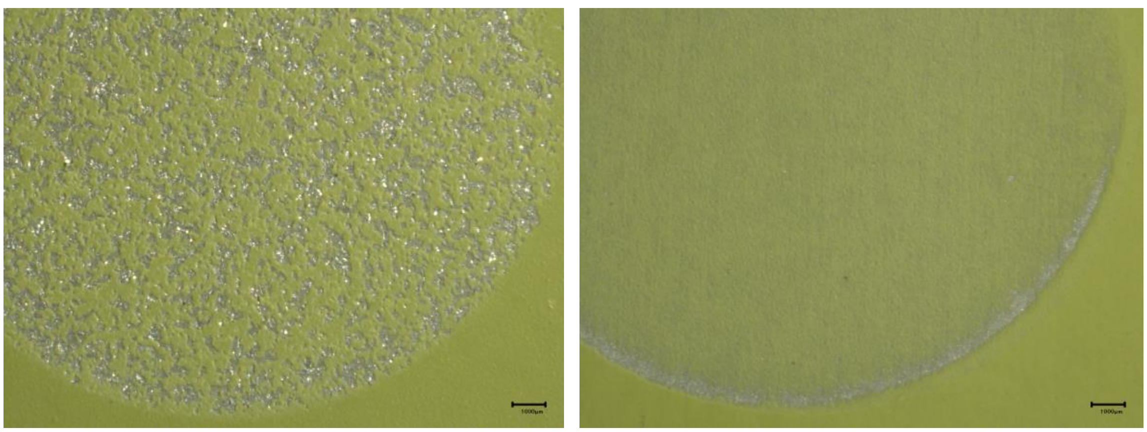

Image 4. 863250 Chromated Epoxy Primer / 2024-T3 Al surface profile comparison AFRL01 (left) and VA (right) at mass loading of 0.25 g/cm^2

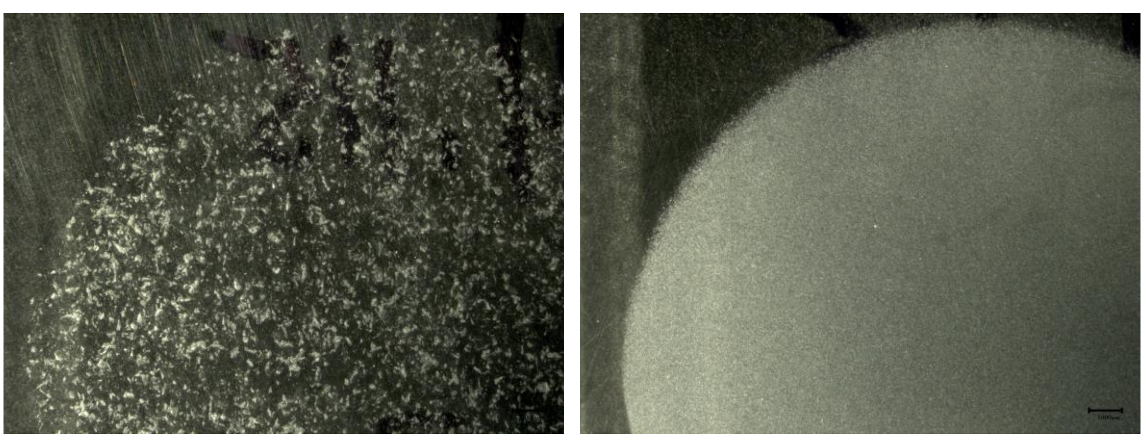

Image 5. PMMA surface profile comparison AFRL01 (left) and VA (right) at mass loading of 0.05 g/cm^2

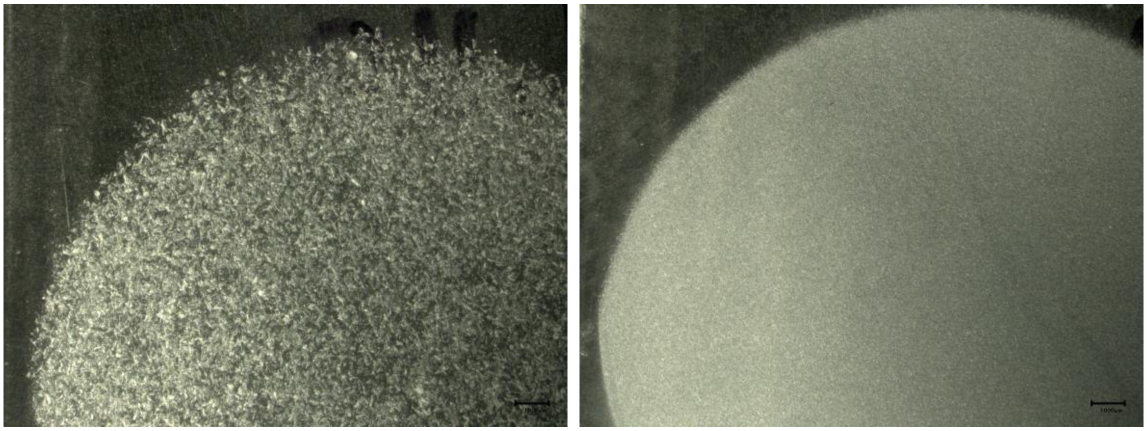

Image 6. PMMA surface profile comparison AFRL01 (left) and VA (right) at mass loading of 0.25 g/cm^2

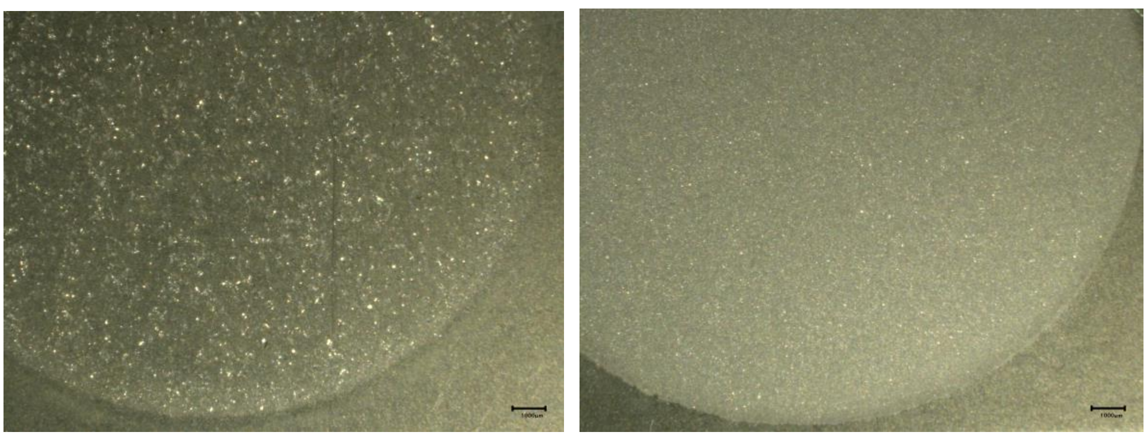

Image 7. Ti-6-4 surface profile comparison AFRL01 (left) and VA (right) at mass loading of 0.05 g/cm^2

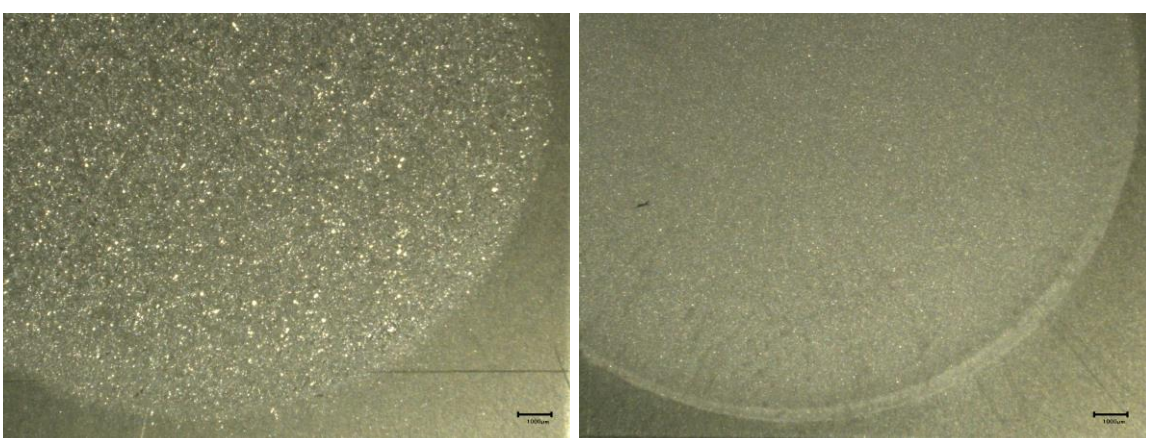

Image 8. Ti-6-4 surface profile comparison AFRL01 (left) and VA (right) at mass loading of 0.25 g/cm^2

5.0 CONCLUSION

Erosion due to sand, volcanic ash and dust resulting from residues/aerosols in the atmosphere are considered as hazardous on the structure of an aircraft and may adversely influence the lifecycle of the structure. The actual rate of erosion does differ depending on the erosive media encountered. The effects of erosion are highly dependent on a number of factors such as material properties, exposure time, geometrical constraints, flight/impact speed, incident angle, coating thickness, and particle size. A series of dust erosion experiments were conducted at the CCEL on-site at WPAFB to compare the erosion resistance of three aerospace materials to Mt. Mazama volcanic ash and AFRL01. From the data collected, it can be observed that volcanic ash is indeed more erosive in nature to the selected test substrates at ambient temperatures as compared to the AFRL01 standard test media based on the mass loads specified. From the images obtained, it can observed that the volcanic ash has a significant hazing effect on each of the selected substrates at each mass load. This is due to the smaller particle size resulting in a "polished" appearance.

6.0 REFERENCES

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