Review: Volcanic ash and its influence on aircraft engine components
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Abstract

Volcanic ash damages aircraft engine components, thus having a significant impact on engine performance, flight safety and maintenance costs. This paper discusses the properties of volcanic ash and their influence on engine components, as well as some potential protective coatings that may mitigate the impact of volcanic ash.

Keywords: volcanic ash; CMAS; aircraft engine; damage; coating; review.

1. Introduction

In April 2010, European airspace was closed for six days due to the ashes generated from the eruption of Iceland’s Eyjafjallajökull volcano. Because of the risks posed by volcanic ash (VA) to aircraft engines, thousands of flights were cancelled and millions of passengers left stranded. The International Air Transport Association (IATA) estimated that the disruptions had cost airlines nearly $2 billion [1]. The incident was reported to have affected 29 percent of global aviation and 1.2 million passengers a day. In the past 20 years, more than 100 commercial airplanes encountered VA, with several of them severely damaged and some nearly completely lost.

Volcanic ash damages engine components and thus can lead to engine failures. The effects of VA are manifested in at least three significant ways [2]. First, the erosion of compressor blades by VA particles results in their shape...
change consequently reduces the efficiency of the blade airfoil as well as its aerodynamic capability to maintain airflow, eventually leading to an engine stall. Second, plugging of the cooling channels in the combustor liners and in hollow turbine airfoils reduces or even stops the cooling airflow, causing components overheating and premature failure. Third, accumulation of ash on nozzle guide vanes leads to a reduction in the airflow area, making the compressor work harder and, in extreme cases, resulting in engine stall.

At light or moderate levels of exposure, VA can deposit on the surface of combustor liners, nozzle guide vanes and turbine blades, gradually degrading these hot section components by attacking surface coatings, leading to component failure over an extended period of time. This is perceived as a long-term failure mode, different from those when exposed to heavy doses of VA. The mechanisms by which molten VA attacks thermal barrier coatings (TBCs) that protect hot section components are somewhat similar to those responsible for calcium-magnesium-alumina-silicates (CMAS) attacks.

Overall, the exposure of aircraft engines to volcanic ash can has a significant impact on engine performance, flight safety and maintenance costs. This paper reviews the properties of VA and their influence on aircraft engine components. Potential protective coatings that could be applied to mitigate the detrimental effects of VA will also be discussed.

2. The properties of volcanic ash

Volcanic ash (Fig. 1), composed of small jagged pieces of rocks, minerals and glass with the size of less than 2 mm in diameter, is formed during explosive volcanic eruptions [3-5]. Very small ash particles can be less than 0.001 mm across. Explosive eruptions occur when the gases dissolved in molten rocks (magma) expand and escape violently into the air, and also when water is heated by magma and abruptly flashes into steam. The force of the escaping gas violently shatters solid rocks. The expanding gas also shreds magma and blasts it into the air, where it solidifies into fragments of volcanic rock and glass. Once in the air, wind can blow the tiny ash particles tens to thousands of kilometers away from the volcano. VA may soften and melt at temperatures above 1000°C.

The predominant component of volcanic rocks is silica (SiO$_2$) [6]. TiO$_2$, Al$_2$O$_3$, FeO/Fe$_2$O$_3$, MnO, MgO, CaO, Na$_2$O, K$_2$O, and P$_2$O$_5$ may also exist in the rocks (Fig. 2). Molten volcanic rocks with a relatively low silica concentration have low resistance to flow (Fig. 2), which produce a limited amount of ash during volcanic eruptions (Fig. 3a), whereas those with a relatively high silica concentration have high resistance to flow, thus creating a huge amount of ash (Fig. 3b). The typical composition of the VA generated from the Eyjafjallajökull 2010 eruptions is listed in Table 1 [7].

Volcanic eruptions inject water vapour (H$_2$O), carbon dioxide (CO$_2$), sulfur dioxide (SO$_2$), hydrochloric acid (HCl), hydrofluoric acid (HF) and ashes into the atmosphere (Fig. 4). HCl and HF will dissolve in water and fall as acid rain, whereas most SO$_2$ is slowly converted into sulphuric acid (H$_2$SO$_4$) aerosols. VA particles may absorb these aerosol droplets onto their surfaces. VA particles are hard, do not dissolve in water, and are extremely abrasive and mildly corrosive [3].
Fig 2. Major elements and flow characteristics of volcanic rocks [6].

Fig 3. (a) Basaltic lava erupts from a vent on Kilauea Volcano, Hawaii (12 September 2003), to form row of fountains and lava flows with little ash, and (b) Dacite magma erupts from the crater of Mount St. Helens (18 May 1980) to form a Plinian eruption column [3].

Table 1. Chemical composition of the volcanic ash generated from the Eyjafjallajökull 2010 eruptions [7].

| Sample        | FMWVORDHUALS | EYJAFJALLAJÖKULL | HO1510 | HO7510 | PAAS510 | GV165-4 |
|---------------|---------------|------------------|--------|--------|---------|---------|
| Major oxides  | SiO2          | FeO              | MgO    | CaO    | Na2O    | K2O     |
| (wt%)         | 47.79         | 47.72            | 57.98  | 56.76  | 59.76   | 58.24   |
|               | 12.31         | 13.21            | 9.75   | 9.93   | 9.29    | 14.89   |
|               | 0.18          | 0.18             | 0.24   | 0.24   | 0.26    | 0.74    |
|               | 8.67          | 8.91             | 2.20   | 2.15   | 2.50    | 3.17    |
|               | 10.00         | 10.07            | 5.50   | 6.11   | 4.36    | 4.70    |
|               | 3.03          | 2.95             | 5.01   | 5.04   | 5.46    | 5.18    |
|               | 0.64          | 0.62             | 1.79   | 1.85   | 1.89    | 2.02    |
|               | 3.13          | 3.01             | 1.80   | 1.88   | 1.38    | 1.50    |
|               | 0.44          | 0.43             | 0.53   | 0.43   | 0.48    | 0.48    |
|               | 158           | 155              | 447    | 425    | 489     | 449     |
|               | 328           | 292              | 85     | 76     | 124     | 66      |
|               | 107           | 108              | 144    | 137    | 192     | 161     |
|               | 203           | 198              | 490    | 441    | 498     | 481     |

Fig 4. Formation of soluble components on ash particles [3].
3. Influence of volcanic ash on engine components

Volcanic ash damages gas turbine engine components and thus can lead to premature engine failures. The major damage modes include: erosion of compressor blades, plugging of cooling channels and deposition of ash particles on turbine nozzle guide vanes [2,8].

Similar to sand, VA erodes compressor blades and, as a result, alters their shape and dimension (Fig. 5). These changes reduce the aerodynamic efficiency of the airfoils and consequently their capability to maintain effective airflow. At extreme conditions, VA erosion can lead to an engine stall, i.e. loss of airflow and thrust. Depending on the density and particle size of the ashes encountered, the damage could be more severe, from an erosion standpoint, than a sand storm.

Volcanic ash can melt when it passes through the combustor and then deposit on turbine nozzle guide vanes (Fig. 6), resulting in a reduction in the airflow area between the vane airfoils and making the compressor work harder, eventually leading to an engine stall. The exact rate of ash accumulation on nozzle guide vanes in a VA environment is unknown. It could be a function of the ash density in the atmosphere, chemical make-up of the ash particles, and the design and power setting of the operating engines.

Modern gas turbine engines use hollow turbine blades and nozzle guide vanes with internal cooling channels (Fig. 7) to withstand higher turbine inlet temperatures. When exposed to heavy doses of VA, ash particles passing through an engine will find their way into these cooling channels and plug the cooling holes (Fig. 8), resulting in reduced or total loss of cooling capabilities. This in turn can lead to overheating and premature failure of hot section components such as combustor liners, turbine blades and nozzle guide vanes. However, if an engine is exposed to moderate levels of VA, ash deposits on the surface of hot section components can gradually degrade the parts, leading to failures over an extended period of time.

Fig. 5. (a) 16th stage compressor blades after dust exposure, (b) 9th stage compressor blades after multiple surges. Pratt & Whitney engines [9].

Fig. 6. F-101 high pressure turbine (HPT) vane row after exposure to volcanic ash [9].
In modern aircraft engines, hot section components such as combustor liners, turbine blades and nozzle guide vanes are often protected by TBCs, composed of a yttria-stabilized-zirconia (YSZ) ceramic topcoat and a metallic bond coat deposited on the superalloy substrate [10]. The YSZ topcoat provides heat insulation to the components, whereas the metallic bond coat provides adhesion between the YSZ topcoat and the superalloy substrate as well as oxidation and hot corrosion protections. The YSZ is usually produced by either electron-beam physical vapour deposition (EB-PVD) or air plasma spraying (APS) [10]. The attack of VA on TBCs is attracting increasing attentions from engine original equipment manufacturers (OEMs), airlines, military fleet operators, coating developers and research organizations. Previous work has shown that the mixed oxides, CaO-MgO-Al₂O₃-SiO₂, or CMAS, have a melting point of around 1240°C. Fine CMAS particles sucked into a combustion chamber will melt and then deposit onto the downstream turbine blades and vanes, infiltrating the open void spaces in the YSZ layer of the TBCs [11]. Consequently, the YSZ will degrade both chemically and microstructurally [11-13]. Upon cooling at the end of an operation cycle, the molten CMAS freezes and the infiltrated volume of the coating becomes rigid, losing its ability to accommodate strains arising from the thermal expansion mismatch between the ceramic topcoat and the underlying metallic bond coat. As a result, the YSZ layer develops delamination cracks that lead to progressive exfoliation with concomitant loss of insulation efficiency and accelerated degradation of the underneath metallic bond coat [13].

![Fig 7.](image1)

Fig 7. (a) A high pressure turbine (HPT) stage 1 blade [10], (b) rotor blade cooling [8].

![Fig 8.](image2)

Fig 8. Plugged cooling holes in a CFM56-2 engine [8].

A recent investigation on the reactions between EB-PVD YSZ and artificial volcanic ash (AVA) [14] has shown that the AVA on the YSZ surface becomes denser at 1000°C and penetrates the YSZ’s inter-columnar gaps, whereas the majority of the AVA infiltrates the inter-columnar pores of the YSZ ceramic layer at higher temperatures (Fig. 9). The characteristic feather-arm morphology of the EB-PVD YSZ is not affected by infiltration up to 1100°C (Fig. 10), and moreover no significant reactions or newly formed phases were present. At 1200°C, the feather-arm...
structure of the YSZ shows significant degradation (Fig. 11a) due to grain growth and pore coalescence. The inter-columnar pores are either completely infiltrated by AVA-derived glass or, in other locations, the glass forms isolated pockets. In addition, along with Fe$_2$O$_3$-rich and plagioclase (SiO$_2$-Al$_2$O$_3$-CaO-Na$_2$O) solid solutions, the formation of ZrSiO$_4$ was also observed in AVA/EB-PVD YSZ diffusion couples (Fig. 11b), probably due to the progressive dissolution of Y$_2$O$_3$ from YSZ by AVA until ZrSiO$_4$ nucleates and grows at the interface between the Y$_2$O$_3$-enriched amorphous phase and the residual ZrO$_2$. The reaction between ZrO$_2$ and SiO$_2$ is very slow at 1200°C [15,16]. Typically, ZrSiO$_4$ is located on top of the inter-columnar gaps bridging individual YSZ columns. Filling of the feather-arm pores by ZrSiO$_4$ was also frequently observed [14].

Fig. 9. The microstructural development of the AVA/EB-PVD YSZ interface after 1 h annealing at 900°C (A), 1000°C (B), 1100°C (C), and 1200°C (D) (SE images). Infiltration levels of molten AVA in the coating are indicated by the dashed lines [14].

Fig 10. Lack of interfacial reactions between the AVA and EB-PVD YSZ, and retention of the characteristic feather-arm morphology in the coating after 1 h annealing at 900°, 1000°, and 1100°C, respectively [14].

The wetting and infiltration behaviours of AVA differ from the standard CMAS-type recession [12,13,17,18]. CMAS-type deposits were found to melt and subsequently infiltrate EB-PVD YSZ above 1230°-1240°C. Generally, the onset temperature for reactions is much lower in the case of AVA [14]. The AVA deposit exhibits softening above the glass transition temperatures rather than a well-defined melting point; therefore, infiltration occurs by viscous flowing rather than by instantaneous melt infiltration. The typical solution/re-precipitation of globular ZrO$_2$ in contact with CMAS-type melts was not observed in the case of AVA after short annealing. On the contrary, the formation of ZrSiO$_4$ was observed in CMAS-type scenarios, because the AVA environment provides sufficient saturation of SiO$_2$. A further important difference between AVA and CMAS is the presence of Fe$_2$O$_3$ and TiO$_2$ in AVA that accumulate as an Fe$_2$O$_3$-rich, hematite-type phase at the surface of the EB-PVD YSZ. This Fe$_2$O$_3$ and
TiO$_2$-rich residual deposit may act as a newly formed reactive interface for subsequent CMAS-type contaminations. CMAS-type deposits with significant amounts of Fe$_2$O$_3$ and TiO$_2$ have been found on actual engine hardware [19].

Fig 11. Interfacial reactions between AVA and EB-PVD YSZ after 1 h at 1200°C exhibits the formation of a plagioclase-type solid solution (A), a re-crystallized Fe2O3-rich solid solution (A and B) and ZrSiO4 (B). Note that the YSZ column tips are still faceted at this stage [14].

4. Mitigating the impact of volcanic ash

Although systematic investigations on the influence of volcanic ash on EB-PVD and APS TBCs are limited, it can be expected that the coatings will suffer severe degradation when exposed to molten VA [11-13,17-22]. Recent developments of new TBC systems lead to using rare-earth zirconates (REZ) as the ceramic insulation layer, primarily due to their lower thermal conductivity and higher resistance to sintering than state-of-the-art YSZ [23-27]. A recent study has revealed that gadolinium zirconate can mitigate CMAS penetration of its compliance-inducing features and the associated detrimental effects on strain tolerance of the coating [18]. In this case, the dissolution of the zirconate into the CMAS melt and the ensuing conversion of the latter into a mixture of crystalline phases can fill the flow channels and prevent further penetration. The key to the effectiveness of this mechanism is the formation of a highly stable apatite phase incorporating Ca, Gd, Si and some Zr. After early sealing of the flow channels, the reaction progresses slowly by interactions of the bulk CMAS with the column tips. Both the mechanism and the product morphology are conducive to a progressive slowing of this attack, which is beneficial for the survivability of the reaction layer under thermal cycling. Further studies lead to a CMAS resistant thermal barrier coating [28] comprising alternating layers of YSZ and a molten-silicate resistant material that may be formed from at least one of these metal oxides: La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Sc, In, Zr, Hf and Ti, or from a gadolinia-stabilized zirconia.

Another approach to mitigating CMAS attack is incorporating Al$_2$O$_3$ and TiO$_2$, in the form of a solid solution, into the YSZ using a solution-precursor plasma spray (SPPS) [29] or APS [30] process. The YSZ serves as a reservoir of Al and Ti solutes, which are incorporated into the molten CMAS glass that is in contact with the YSZ ceramic layer. An increase of Al concentration in the molten CMAS glass, as it infiltrates the YSZ, shifts the glass composition from the difficult-to-crystallize psuedo-wollastonite field to the easy-to-crystallize anorthite field. The incorporation of Ti in the glass promotes crystallization of the CMAS glass by serving as a nucleating agent. These combined effects result in a near-complete crystallization of the leading edge of the CMAS front into anorthite, essentially arresting further CMAS infiltration [30].

The reactions between the ash generated from Eyjafjallajökull volcano and two APS-produced CMAS-resistant TBCs as well as conventional APS-YSZ have been studied [31]. It clearly shows that, after 24 hours at 1200°C in air, the silicate-based molten ash penetrates all the way to the bottom of the YSZ layer (Fig. 12), compared to a depth of only ~5% and ~17% for gadolinia-stabilized zirconia (Gd$_2$Zr$_2$O$_7$) and YSZ+Al+Ti layers, respectively. In Gd$_2$Zr$_2$O$_7$, the top region has the VA glass with some isolated grains of apatite-type phase based on Gd$_6$(SiO$_4$)$_3$O$_6$ and t-ZrO$_2$; the region just below the top layer consists of a dense mixture of grains of apatite-type phase and t-ZrO$_2$; the bottom region has only Gd$_2$Zr$_2$O$_7$ phase (pyrochlore). In YSZ+Al+Ti, the top region consists mostly of exfoliated grains of Al-depleted t-ZrO$_2$ in a glassy matrix; the region underneath reveals a mixture of t-ZrO$_2$ grains depleted in Al content, anorthite (CaAl$_2$Si$_2$O$_8$) phase and some glass; the bottom region is unreacted t-ZrO$_2$. These
microstructural features clearly show that both Gd₂Zr₂O₇ and YSZ+Al+Ti are highly resistant to the penetration of molten Eyjafjallajökull VA. The mechanisms by which molten VA (glass) attacks APS-YSZ, Gd₂Zr₂O₇ and YSZ+Al+Ti ceramic coatings are depicted schematically in Fig. 13.

Fig 12. Si elemental EDS map of three APS ceramic coatings: YSZ, Gd₂Zr₂O₇ and YSZ+Al+Ti after 24 hours at 1200°C in air, after deposited by Eyjafjallajökull volcanic ash [31].

Fig 13. Schematic cross-sections of APS TBCs with ash deposits, before and after exposure to heat. APS TBCs are polycrystalline, with pores and cracks generally running parallel to the TBC/substrate interface. (a) In 7YSZ TBC the ash melts to form a glass that penetrates pores, cracks and grain boundaries, causing 7YSZ grains to dissolve and re-precipitate as rounded ZrO₂ grains (yellow) depleted in Y. (b) In Gd₂Zr₂O₇ or YSZ+Al+Ti TBC the formation of an impervious, crystalline reaction layer consisting of rounded ZrO₂ grains, together with an apatite-type phase or anorthite, prevents further penetration of molten ash. Isolated faceted apatite-type grains in a glassy matrix above the reaction zone in (b) are observed only in the Gd₂Zr₂O₇ TBC case [31].

5. Summary

VA particles are hard, do not dissolve in water, and are extremely abrasive and mildly corrosive. VA has a composition similar to CMAS with lower glass transition temperatures. At high levels of exposure, VA can compromise engine conditions in at least three significant ways: (1) erosion of compressor blades, reducing aerodynamic efficiency of the airfoils and even causing engine stall; (2) plugging of cooling channels in turbine blades and vanes, losing/limiting the airflow cooling capacities and leading to premature failures of the components; and (3) accumulation on turbine nozzle guide vanes, resulting in a reduction of the airflow area and causing compressor overload and possible engine stall. At moderate levels of exposure, VA can deposit on the surface of combustor, nozzle guide vanes and turbine blades, gradually degrading these hot section components and leading to their failure over an extended period of time. The mechanisms by which molten VA attacks TBCs are somewhat similar to those for CMAS. Advanced TBCs that are resistant to CMAS have the potential to provide effective protection against molten volcanic ash.
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