High Temperature Erosion Resistance of Coatings for Gas Turbine

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ABSTRACT

An experimental investigation was conducted to study the ash particle rebound characteristics and the associated erosion behavior of superalloys and aluminide coatings subjected to gas-particle flows at elevated temperatures. A three-component LDV system was used to measure the restitution parameters of 15 micron mean diameter coal ash particles impacting some widely used superalloys and coatings at different angles. The presented results show the variation of the particle restitution ratio with the impingement angle for the coated and uncoated superalloys. The erosion behaviors of INCO-738, MAR-246 and X40 superalloys and protective coatings C, N, RT22 and RT22B have also been investigated experimentally at high temperatures using a specially designed erosion tunnel. The erosion results show the effect of velocity, temperature and the impact angle on the erosion rate (weight loss per unit weight of particle). Based on the experimental results of the particle mass effect on both weight losses and erosion rates, the coating lives have been estimated for different particle concentrations.

INTRODUCTION

The major problem confronting developers of coal-burning boilers, fluidized beds and turbines is the serious erosion of the system components by the suspension of fly ash in the hot combustion gases. A permanent loss of performance is associated with the surface erosion, which is caused by particle surface impacts. The performance loss depends upon the location and the condition of the deteriorated surfaces. These are critical to the aerodynamic performance of turbine blades which are particularly sensitive to the blade leading, the trailing edge configuration and the condition of the blade suction surface. Computer codes are used to model the particle dynamics in turbomachinery flow fields through the various blade rows, and to determine the particle impact conditions with the various surfaces, which affect their erosion. The codes, however, require empirical equations for particle restitution characteristics (Tabakoff et al., 1986 and Tabakoff and Hamed, 1987) to represent the effect of particle surface interaction on the particle trajectories and the resulting surface erosion.

Nickel and cobalt base superalloy blades and vanes are widely used in the hot section of gas turbines. Protective coatings have been used, to enhance superalloy resistance to hot erosion-corrosion. The most widely used coatings are those based on the NiAl (on nickel base superalloys) and CoAl (on cobalt base superalloys) formed by interaction of superalloy surfaces with aluminum. To improve the resistance to hot erosion-corrosion, aluminide coatings are modified to contain elements such as chromium, platinum, rhodium and silicon. The objective of this research work is to investigate the basic erosion processes and fluid mechanics associated with the material degradation in the components of various coal conversion and utilization systems. This is accomplished through a study of the rebound characteristics of particles impinging various surfaces and through the measurement of erosion rates of materials and coatings exposed to high temperature gas-particle flows. The overall goal is to develop a quantitative model, which will facilitate the prediction of erosion in systems operating in particulate environments.

EXPERIMENTAL SET-UP

The experimental set-up consists of the following: a) the erosion wind tunnel, b) the LDV system and c) the data acquisition system.

a) Erosion Wind Tunnel

The high temperature erosion test facility was designed to provide erosion and rebound data in the range of operating temperatures experienced in compressors and turbines. In addition to the high temperature, the facility properly simulates all the erosion parameters which were determined to be important from aerodynamics point of view. These parameters include particle velocity, angle of impact, particle size, particle concentration, and sample...
The particles are fed into a secondary air source and size. Close attention was given to the aerodynamic effects to insure that important parameters, such as the angle of impact, are not masked or altered.

A schematic of the erosion test facility is shown in Fig. 1. It consists of the following components: particle feeder (A), main air supply pipe (B), combustor (C), particle preheater (D), particle injector (E), acceleration tunnel (F), test section (G), and exhaust tank (H).

The equipment functions as follows: A measured amount of abrasive grit of a given mixture of constituents is placed into the particle feeder (A). The particles are fed into a secondary air source and blown up to the particle preheater (D), and then to the injector (E), where they mix with the main air supply (B), which is heated by the combustor (C). The particles are then accelerated by the high-velocity air in a constant-area steam-cooled duct (F) and impact the specimen in the test section (G). The particulate flow is then mixed with the coolant and dumped in the exhaust tank. Figure 1 shows that the tunnel geometry is uninterrupted from the acceleration tunnel into the test section. In this manner the particle laden flow is channeled over the specimen and the aerodynamics of the fluid passing over the sample are preserved.

A detailed description of the wind tunnel and the particle feeder is given by Tabakoff and Wakeman (1979).

![Diagram of Erosion Test Facility](image-url)

FIG. 1. SCHEMATIC OF EROSION TEST FACILITY

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b) LDV System

The LDV system used in the measurements of the particle restitution characteristics and described in detail by Tabakoff et al. (1986) and Tabakoff and Hamed (1987). It consists of the laser tube, the optics, the frequency shifters and the photomultipliers. The light source is a five Watt argon-ion Spectra Physics, model 164-09 laser tube. The laser beam leaving the tube is separated in the dispersion prism into components with different wavelengths. Three beams with the highest intensities are used to measure the three velocity components. The beams with green (0.5145 μm) and blue (0.488 μm) colors are sent through an optical train in the axial direction. The third beam with purple color (0.4765 μm) passes through a second optical train whose transmitting optics are inclined at 30° from the axial direction. Each beam is polarized through a polarization rotator and split into two equal intensity components in the beam splitter. After passing through the focusing lenses, the two beams of color cross and produce a set of fringes. Six beams cross at one common measuring volume producing three sets of fringes, one for each color. The orientation of the perpendicular bisectors of the three sets of fringes gives the coordinate system for the three-dimensional velocity measurements. The dimensions of the fringe pattern in the measurement volume are a function of the LDV optics. TSI model 9189 beam expanders were used to increase the spatial resolution, improve the single-to-noise ratio, and reduce the measurement volume diameter 3.75 times. The focal length of the transmitting lenses is 480 mm and the crossing angle for the 1.5 mm diameter beam is 9.82 degrees. Two separate beam collimators, one on the blue-green optical train and the other on the purple optical train, were installed before the beam splitters for precise control of the probe volume characterization. In particular, it was possible to ensure that the focused beams intersected at their beam waists to avoid frequency broadening effects and maximize signal quality. The scattered light from the particles in the measuring volume is collected in the off-axis backward scatter mode. Frequency shifters were used on all the three beams to sense the flow direction and reduce fringe bias errors. The analog data from the photomultipliers in the receiving optics are used to measure the three velocity components. The signals from frequency shifters are transferred to three separate signal processors.

c) Data Acquisition System

The data acquisition system consists of three signal processors, an external circuit and a personal computer with the associated hardware and software. While the data acquisition is software driven, the data timing is controlled by an external circuit. The LDV signals coming from the photomultipliers are processed in the three TSI 1990 counter type signal processors. The processed data are collected by an IBM PC/AT compatible computer for further calculations and data storage. The control of the data transfer and the synchronization of data coming from three different channels are performed by the external circuit.

The logic for the data acquisition system is as follows: The frequency of the internal oscillator clock in the CTM-05 counter-timer is specified initially through the interactive software. This clock generates a square wave at the selected frequency and the period of the wave determines the coincidence window for the data coming from the processor connected to the three LDV channels. During the data collection, the external circuit is...
activated in order to detect the arrival of data ready signals. Whenever the external circuit receives a data ready pulse, it sends a data inhibit signal to the associated processor, preventing it from acquiring new data. When all the three data ready signals arrive within the specified coincidence limit, the circuit holds the data at the output buffers of the processors, and instructs the computer to transfer them into a file through the digital input port. The external circuit is then reset through the digital output port of CTM-05, the processors are reactivated and the procedure is repeated until a specified number of samples is collected.

TEST CONDITIONS AND TESTED MATERIALS

It is well known that particle velocity, particle impingement angle, particle characteristics and material sample temperature strongly influence the erosion rate. These parameters were varied in the present test program for the different tested materials listed in Tables 1 and 2. The properties of the superalloys can be found in Aerospace Structural Metals Handbook (1963) and Alloy Digest (1969). The particle velocity was controlled by varying the tunnel air flow. The particle impingement angle was set by rotating the specimen relative to the flow stream direction. The sample temperature was varied by heating the flow stream which heats the sample to the desired temperature. The experimental measurements were obtained for fly ash particles with impact velocities ranging between 600 and 1200 fps (366 m/s) at temperatures ranging from ambient to 1500°F (815.5°C). Table 1 lists fly ash particle chemical composition. Flat rectangular specimens were used in the tests. The specimens for erosion test were 1 inch (0.0254 m) long, 0.25 inch (0.00635 m) thick and 0.5 inch (0.0127 m) wide, while the rebound test specimens were 0.25 inch (0.00635 m) wide. The maximum specimen blockage was on the order of 10%. Test data were accumulated by setting the particle impingement angle at 15, 30, 45, 60 and 90 degrees for each of the different test temperatures and particle velocities.

Table 1 - Tested Superalloys

<table>
<thead>
<tr>
<th>Superalloy</th>
<th>Chemical Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>INC0 IN-738</td>
<td>16 Cr, 8.5 Co, 3.4 Al, 3.4 Ti, 2.6 W, 1.75 Mo, 1.75 Ta, 0.9 Cb, balance Ni</td>
</tr>
<tr>
<td>MAR-M246</td>
<td>10 Co, 10 W, 9 Cr, 5.5 Al, 2.4 Mo, 1.5 Ta, 1.5 Ti, balance Ni</td>
</tr>
<tr>
<td>X40</td>
<td>25 Cr, 10 Ni, 7.5 W, balance Co</td>
</tr>
</tbody>
</table>

Table 2 - The Tested Coatings

<table>
<thead>
<tr>
<th>Coating</th>
<th>Treatment</th>
<th>Substrate</th>
<th>Thickness (mils)</th>
<th>Heat Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Aluminized</td>
<td>X40*</td>
<td>3</td>
<td>--</td>
</tr>
<tr>
<td>N</td>
<td>Aluminized</td>
<td>M246**</td>
<td>3</td>
<td>--</td>
</tr>
<tr>
<td>RT22</td>
<td>Platinum Aluminized</td>
<td>M246</td>
<td>5</td>
<td>yes</td>
</tr>
<tr>
<td>RT22B</td>
<td>Rhodium/Platinum Aluminized</td>
<td>M246</td>
<td>3</td>
<td>yes</td>
</tr>
</tbody>
</table>

**X40**: Cobalt based X40 Superalloy.

**M246**: Nickel based MAR-M246 Superalloy.

RESTITUTION TEST RESULTS

The rebound dynamics of particles can be described in a statistical sense only. This becomes obvious when one examines the number of geometric situations that might occur at impact. After an incubation period, the target material will become pitted with craters, and in fact after a slightly longer period, a regular ripple pattern will form on the eroded surfaces. Thus, the local impact angle between the small particles and the eroded surface may deviate considerably from the geometric average. Also, the individual impact angle and velocity of a particle depend on its size. Furthermore, the particles themselves are irregular in shape, some with sharp corners. As the particle approaches the specimen, the orientation of the particle is, for the most part, random. Thus, some particles will impact on a flat surface and do very little work on the target material. Others will impact with a corner oriented in a manner similar to that of a cutting tool and will remove material from the surface.

The restitution coefficient or restitution ratio is a measure of the kinetic energy loss upon impact of two objects. Since the erosion is dependent on the eroded particle kinetic energy loss upon impacting the target, the restitution ratio will give a good indication of the type of the particle-material interaction. An erosive impact occurs when the contaminant particle is much harder than the target material. Therefore, the restitution ratio will be a measure of the distortion of the target material rather than distortion of the eroding particle.

Grant and Tabakoff (1975) were the first to investigate thoroughly the rebound characteristics of high speed eroding particles. The study was carried out on annealed 2024 aluminum alloy. The data were described using histograms to illustrate their statistical distribution. It was concluded that the restitution ratio \( V_{T2}/V_{T1} \), which is directly related to the kinetic energy loss during an impact, does not give sufficient information in regard to erosion. With this in mind, the restitution ratio was broken down into a normal velocity restitution ratio \( V_{N2}/V_{N1} \) (the normal component of the particle velocity after impact divided by the normal component of the particle velocity before impact), and a tangential velocity restitution ratio \( V_{T2}/V_{T1} \) (the tangential component of the particle velocity after impact divided by the...
tangential component of the particle velocity before impact) as shown in Fig. 2. The previous measurements at various incidence angles and flow velocities indicate that these ratios are mainly dependent upon the impingement angle for a given particle material combination (Grant and Tabakoff, 1975).

In this investigation, the fly ash particle rebound conditions are measured using laser doppler velocimetry for particle laden flows over some of the sample materials listed in Tables 1 and 2. The experimental results are presented in the form of total velocity ($V_2/V_1$) and the directional ($\beta_2/\beta_1$) restitution ratios. The fly ash particle size distribution covers a wide range of particle diameters. Tabakoff et al. (1983) demonstrated that the individual impact angle and impact velocity of a particle depend on its size. The average of the measured impact velocities and angles have been used in restitution parameter calculations. The average of the particle impact velocities for the present investigation was 320 fps (97.6 m/s) in all the particle restitution experiments.

Figures 3 and 4 present the results for M246 alloy with "N" coating, while Figures 5 and 6 present similar results for X40 alloy with and without "C" coating. The restitution ratios of INCO-738 alloy are shown in Figures 7 and 8. The figures present the measured variation of the restitution ratios with the impact angle up to 90° range. The restitution ratios were assumed unity at 0° angle. The curves in the Figures 3 through 8 represent the mean values of the experimentally measured restitution parameter at each impact angle. To facilitate the use of these experimental data in particle trajectory and erosion computations, empirical equations were obtained using a least square polynomial curve fit of the mean values of the restitution parameters. The solid and broken lines in Figures 3 through 8 represent the polynomial curve fits and may be expressed by the following equations:

FIG. 2 REBOUND VELOCITY AND ANGLE NOTATION

In this investigation, the fly ash particle rebound conditions are measured using laser doppler velocimetry for particle laden flows over some of the sample materials listed in Tables 1 and 2. The experimental results are presented in the form of total velocity ($V_2/V_1$) and the directional ($\beta_2/\beta_1$) restitution ratios. The fly ash particle size distribution covers a wide range of particle diameters. Tabakoff et al. (1983) demonstrated that the individual impact angle and impact velocity of a particle depend on its size. The average of the measured impact velocities and angles have been used in restitution parameter calculations. The average of the particle impact velocities for the present investigation was 320 fps (97.6 m/s) in all the particle restitution experiments.

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For M-246 Alloy

\[
\frac{\beta_2}{\beta_1} = e_N = 1.00 + 0.00601123 \beta_1 - 0.000957896 \beta_1^2
\]

\[
+ 1.77426 \times 10^{-5} \beta_1^3 - 9.94 \times 10^{-8} \beta_1^4
\]

\[
\frac{V_{T2}}{V_{T1}} = e_T = 1.00 - 0.00872424 \beta_1 - 0.000834276 \beta_1^2
\]

\[
+ 1.63771 \times 10^{-5} \beta_1^3 - 9.75683 \times 10^{-8} \beta_1^4
\]

X-40 Alloy

\[
\frac{V_{T2}}{V_{T1}} = e_T = 1.00 - 0.0110425 \beta_1 + 2.38155 \times 10^{-5} \beta_1^2
\]

\[
+ 9.38784 \times 10^{-7} \beta_1^3
\]

\[
\frac{V_{N2}}{V_{N1}} = e_N = 1.00 - 0.00393812 \beta_1 - 0.0007943 \beta_1^2
\]

\[
+ 1.66937 \times 10^{-5} \beta_1^3 - 1.01213 \times 10^{-7} \beta_1^4
\]

\[
\frac{V_2}{V_1} = e_V = 1.00 + 0.000951 \beta_1 - 0.00725 \beta_1^2
\]

\[
+ 1.43015 \times 10^{-5} \beta_1^3 - 8.34 \times 10^{-8} \beta_1^4
\]

\[
\frac{\beta_2}{\beta_1} = e_N = 1.00 + 0.001295 \beta_1 - 0.0000645 \beta_1^2
\]

\[
+ 1.55053 \times 10^{-5} \beta_1^3 - 1.008 \times 10^{-7} \beta_1^4
\]

"N" Coating

\[
\frac{V_{T2}}{V_{T1}} = e_T = 1.00 - 0.0124107 \beta_1 + 2.97165 \times 10^{-5} \beta_1^2
\]

\[
+ 9.35159 \times 10^{-7} \beta_1^3
\]

\[
\frac{V_{N2}}{V_{N1}} = e_N = 1.00 - 0.00275521 \beta_1 - 0.0012869 \beta_1^2
\]

\[
+ 2.72264 \times 10^{-5} \beta_1^3 - 1.604 \times 10^{-7} \beta_1^4
\]

\[
\frac{V_2}{V_1} = e_V = 1.00 + 0.0037812 \beta_1 - 0.00977626 \beta_1^2
\]

\[
+ 1.94275 \times 10^{-5} \beta_1^3 - 1.12 \times 10^{-7} \beta_1^4
\]

\[
\frac{\beta_2}{\beta_1} = e_N = 1.00 + 0.000159243 \beta_1 - 0.000723929 \beta_1^2
\]

\[
+ 1.81865 \times 10^{-5} \beta_1^3 - 1.185 \times 10^{-7} \beta_1^4
\]

"C" Coating

\[
\frac{V_{T2}}{V_{T1}} = e_T = 1.00 - 0.014949 \beta_1 + 0.00011676 \beta_1^2
\]

\[
+ 3.27 \times 10^{-7} \beta_1^3
\]
The specimen weight was recorded. The erosion rate for each successive particle increment was determined from the relation:

\[
\frac{V_{N2}}{V_{N1}} = e_N = 1.00 - 0.0096558 \beta_1 - 0.006071 \beta_1^2 + 1.61091 \times 10^{-5} \beta_1^3 - 1.048881 \beta_1^4
\]

\[
\frac{V_2}{V_1} = e_V = 1.00 - 0.0024071 \beta_1 - 0.000934 \beta_1^2 + 1.89526 \times 10^{-5} \beta_1^3 - 1.11169 \times 10^{-7} \beta_1^4
\]

\[
\frac{\beta_2}{\beta_1} = e_\beta = 1.00 - 0.001127 \beta_1 - 0.0005889 \beta_1^2 + 1.53245 \times 10^{-5} \beta_1^3 - 1.03 \times 10^{-7} \beta_1^4
\]

**Erosion Test Results for Superalloys**

**INCONEL 738 Alloy**

INCONEL 738 is a nickel based alloy. The variation of the erosion rate of this alloy with impingement angles is shown in Fig. 9 for different impact velocities (600 fps (183 m/s) to 1000 fps (305 m/s)) and temperature of 900°F (482°C). This figure indicates the ductile behavior of INCONEL 738 superalloy, with maximum erosion rate at 30° impingement angle for the three velocities.

**X-40 Superalloy**

The variation of the erosion rate of cobalt based X-40 superalloy with the impingement angle is shown in Fig. 10 for various particle velocities (600, 800 and 1000 fps (183, 244 and 366 m/s)) and temperatures of 900°F (482°C). This figure indicates the ductile erosion behavior of X-40 alloy, with maximum erosion rate at 45° particle impact angle.

The practical operating conditions of this alloy are 1500°F (815.5°C) and 1200 fps (366 m/s). Therefore, the X-40 alloy was also tested at these conditions and the results are shown in Fig. 11. The maximum erosion rate at these conditions was 3.7 mg/m² at 45° impingement angle.

**MAR-M246 Superalloy**

The erosion behavior of nickel based MAR-M246 superalloy shown in Fig. 12. The erosion rate variation with the impingement angle for different velocities (600, 800 and 1000 fps (183, 244 and 366 m/s)) and temperature of 900°F (482°C). It is clear that at these conditions MAR-M246 exhibits a ductile erosion pattern with maximum erosion rate at 30°-45°.
Fig. 13 shows the erosion rate versus the impingement angle for the M-246 material operating conditions at temperature 1500°F (815.5°C) and impact velocity 1200 fps (366 m/s). The maximum erosion rate at these conditions is 3.3 mgm/gm at 45° impact angle.

Erosion Test Results for Coatings

"C" Coatings
The "C" coating is a cobalt based aluminide that was applied to the cobalt based X-40 superalloy. The "C" coating erosion characteristics are shown in Fig. 14. The erosion rate variation with the impingement angle shows a ductile erosion pattern with maximum erosion at 60° impingement angle for the coated sample, at 1500°F (815.5°C) and 1200 fps (366 m/s). The erosion rate results of Fig. 14 indicate that this coating provides a significant erosion protection, compared to the substrate X40 shown in Fig. 11.

"N"-Coatings
The "N"-coating is a nickel base aluminide that was applied to nickel base M-246 superalloy. The erosion rate variation with the impingement angle for N-coating is shown in Fig. 15 for temperature 1500°F (815.5°C) and impact velocity of 1200 fps (366 m/s). Inspection of this figure reveals that this material exhibits a ductile erosion pattern, with maximum erosion at 45°.
RT22 Coating

This coating is a platinum aluminide that was applied to nickel based MAR-M-246 superalloy. Figure 16 shows that the erosion rate curve follows the familiar form of ductile erosion with a peak at 30 degrees. Comparing Figs. 16 and 15, one can conclude that the platinum content in the aluminide coating enhances the erosion resistance. The erosion rate is reduced to less than half the erosion rate of the "N" aluminide coating. In addition, the angle at which maximum erosion occurs decreases to 30°.

Comparison of Maximum Erosion Rates

Figure 18 presents the maximum erosion rates (at 1500°F (815.5°C), 1200 fps (366 m/s)) of the superalloys and coatings investigated. The results in this figure indicate that protective coatings enhance greatly the superalloy resistance to hot erosion. The aluminide coated sample erosion rates ("C" and "N" coatings) are less than one-third the erosion rates of the base materials (M246 and X-40). The platinum aluminide coating (RT22) offer the best performance with a more than ten times reduction in the erosion rate compared to the base material (M246). Comparing the maximum erosion rate of aluminide coatings ("N" and "C"), and platinum aluminide coating (RT22) indicates that platinum content enhances the erosion resistance of the aluminide coatings. The RT22 coating has the minimum erosion rate, less than one-half the erosion rate of "N" coating and one order of magnitude less than the erosion rate of the base material (M246).
Cumulative test results were obtained of the particle dose effect on both weight loss and erosion rate. Although the concentration of the particles in the test tunnel, PPM (based on weight), is kept low enough to avoid particle interactions, it is still much higher than in practical applications. Therefore, the actual coating life in terms of time is much longer than determined in the erosion wind tunnel. However, the relationship between the coating life and the mass of impacting particles as determined in the erosion tunnel will hold true in practical applications. Using these data, we have calculated the coating lives of nickel based coatings and cobalt based coatings for different particle concentrations. The computations were performed for the maximum erosion rates at 1500°F (815.5°C) temperature and 1200 fps (366 m/s). Figure 19 presents the estimated coating life versus particle concentration (ppm). It is clear from this figure that the coating life is strongly dependent on the particle concentration (ppm), and decreases rapidly as the particle concentration increases. According to this study, the RT22 coating has the longest life (Fig. 19). This is attributed to the fact that it has the best erosion resistance (Fig. 18) and thicker coating.

CONCLUSIONS

From the experimental investigation conducted to study the ash particle rebound characteristic, it was found that the \( V_2/V_1 \) and \( B_2/B_1 \) parameters did not change significantly between coatings "C" and "N" in regard to the superalloys M-246, X40 and INC0738. The erosion rate for all materials investigated increased with the increase of the particle velocities and temperatures. The impingement angle corresponding to maximum erosion was not affected by increased velocities and temperatures. Comparison of maximum erosion rates at 1500°F (815.5°C) and 1200 fps (366 m/s) of the superalloys investigated showed that the aluminide coated samples "C" and "N" are less than one-third the erosion rates of the base materials (M-246 and X40). The platinum aluminide coating (RT22) offers the best erosion protection and longest life prediction for given particle concentrations.

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