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COBALT COATING IN HIGH TEMPERATURE AIRCRAFT ENGINE APPLICATIONS

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1. Abstract

Cobalt coatings are used to increase the life of aircraft engine parts by decreasing friction and wear. One coating in particular Tribaloy T-800 does well meeting both objectives at high temperatures up to 704° Celsius. The alloy make up of Tribaloy T-800 results in a intermetallic Laves phase in a much softer matrix. This makes for a very good wear resistant coating. The application process for Tribaloy T-800 is very important and this is why High Velocity Oxy-Fuel (HVOF) is used to coat a large majority of aircraft engine parts. The HVOF process uses high temperatures and pressures to create a dense low porous coating. The underlying material is also very important in the adhesion of Tribaloy T-800 and the example used in this paper has Inconel 783 compressor and combustor parts. Tribaloy T-800 has the coefficient of friction .04 and Inconel has the coefficient of friction .25, which were calculated using equation 1b. These friction coefficients show that Tribaloy decreases friction significantly on a comparison basis.

2. Introduction

Within an aircraft engine there are a large number of instances when two metals wear against each other in high temperature atmospheres. One recent example is between a part in the compressor module and a part in the combustor module. A leaf seal is used to block air from escaping the flow path and allow relative motion between the two modules. Both mating parts are thermally sprayed with a cobalt-based coating (Tribaloy T-800) to reduce wear. This paper will look at the use of thermally sprayed cobalt-based coatings to resist wear at elevated temperatures.

3. Discussion

There is a large demand to constantly create more efficient aircraft engines to reduce emissions and increase fuel economy. With more efficient aircraft engines come higher internal pressures and temperatures throughout the entire engine. The components within an aircraft engine have to be developed to carry out their primary function, so materials are chosen based on the components objective. For instance, the non-rotating or stationary compressor case needs to grow thermally along the same path as the rotating compressor blades, so the clearances can be controlled to optimize the performance of the engine. The material of the stationary compressor case is chosen to increase performance and last under the high temperatures that can reach over 538° Celsius, so the consideration of any tribological behavior will not determine the material of the aircraft engine part. Since the component's material is not chosen based on friction and wear issues a tribological coating is used to increase the life of the part.

The coating should be chosen based on some requirement stages and rules as described in Coatings Tribology by Kenneth Holmberg and Allan Matthews [1, 315-324]:

Stage 1: Application and design study
Stage 2: Component specification
Stage 3: Functional tribological requirements
Stage 4: Functional coating requirements
Stage 5: Non-functional requirements
Stage 6: Economic and procurement requirements
Stage 7: Coating process characteristics
Stage 8: Coating material characteristics
Stage 9: Specific coating material and process characteristics
Rule 1: Contact stresses
Rule 2: Sliding

Rule 3: Surface Fatigue

Rule 4: Fretting

Rule 5: Abrasion

Rule 6: Impact

Rule 7: Chemical dissolution

One of the largest issues in selecting a coating and the preceding analysis is that once the part is coated it is non-isotropic, which means that the material properties vary with depth.

With these requirements and rules considered Tribaloy coatings are typically used in aircraft engine parts because they have a high melting point of 1288° Celsius and high max operating temperature of 704° Celsius [2, 160]. The particular coating selected for the interaction between the aircraft engine compressor and combustor is a Tribaloy coating T-800. The T-800 coating has a base of cobalt (Co) and contains molybdenum (Mo), chromium (Cr) and silicon (Si). The composition of the hard facing coating used is very important in the creation of a high performing wear resistant surface at elevated temperatures.

The Tribaloy T-800 alloy combination results in a hard intermetallic Laves phase in a much softer matrix. The intermetallic Laves phase is a $MgZn_2$ type Laves phase, a closely packed hexagonal (hpc) compound of Co, Mo, and Si as Co_3Mo_2Si and/or CoMoSi [7, 302-303]. The Laves phase is responsible for creating the excellent wear resistant of the material. The Laves phase also is the main contributor to the high melting point of Tribaloy T-800 alloy at 1288° Celsius. The addition of Cr to the overall composition creates the tough/soft matrix of eutectic. This matrix helps contradict the brittleness of the intermetallic Laves phase, therefore extending the life of the coating under high wear conditions. An important consideration when examining wear coatings is the composition created at the interface with the substrate material.

In the aircraft engine example the compressor component coated with Tribaloy T-800 is made of a Superalloy Inconel 783 (IN783). The adhesion of the coating depends greatly on the bond strength of the two materials and how they mix with each other at their interface. With IN783 mixed into Tribaloy T-800, the coating microstructure changes from blocky shaped Laves phase to a more eutectic from of the Laves phase and carbides emerge [9, 161]. A Co-Ni-Cr matrix is formed at the interface between the coating and substrate. The composition created with the mixing of the coating and substrate weakens or creates a more brittle material, so the hardfacing process should be chosen to minimize this affect.

The wear resistance of Tribaloy coatings depends greatly on the application process. The most common deposition technique used for aircraft engines is the thermal spray process. The best thermal spray technique is the High Velocity Oxy-Fuel (HVOF) method. The wear properties of thermal sprayed HVOF coatings are directly related to microstructure, which affects micro hardness and surface roughness [6, 299-301]. This means that the thermal spray method needs to be tightly controlled in order to generate the optimal surface to resist wear.

The HVOF process is an improved thermal spray method because it uses high pressures to create large velocities to move the coating particles threw the air, so the particles do not have adequate time to cool down, as shown in figure 1 [10, 53]. The temperature of the coating particles is very important because they need to be in a molten state in order to create a good bond with the substrate. The HVOF process also creates high turbulence in the combustion chamber of the gun, so the coating particles have uniform heating [10, 53]. This procedure creates greater impact energies as compared to a typical thermal spray process, which establishes a much denser and lower porous surface. The porous nature of the coating is directly proportional to the wear resistance of the coating. Once an adequate coating is produced it is important to be able to analyze and test the wear characteristics of the surface.

4. Governing Equations

The governing equations for analyzing the friction and wear of coatings according to Kenneth Holmberg and Allan Matthews [1] are:

4.1 Coefficient of friction

$$\mu = F/w \qquad (1a)$$

F = frictional force, w = normal load

$$\mu = \pi * S/w^{1/3}(3R/4E')^{2/3} \qquad (1b)$$

S = shear strength, w = normal load, R = radius of the sphere, E' = reduced modulus of elasticity

4.2 Hertzian Contact Width of Cylinders

$$b^2 = 4wR(1-\nu^2)/\pi*E \tag{2}$$

b = half contact width, w = normal load, R = radius of cylinder, ν = poisson's ratio, E = elastic modulus

4.3 Wear volume

$$V = K'(w*s/H) \tag{3}$$

V = worn volume, w = normal load, s = distance moved, H = harness, K' = constant

4.4 Wear rate

$$K = V/w*s \tag{4}$$

K = wear rate ($10^{-6}mm^3/Nm$), V = worn volume, w = normal load, s = distance moved

5. Analysis

Equation 2 is based on Hertzian elastic contact theory and assumes that cylinders are in contact. The problem can be idealized into one cylinder contacting a flat plate, which can be used to analyze the aircraft engine contact example stated earlier. Figure 2 represents the simplified geometry found between the compressor and combustor. The half contact width was calculated using equation 2 with inputs from table 1 for Tribaloy T-800 and table 2 for Inconel 783. With the contact width calculated the applied normal load was found by multiplying the delta pressure, circumferential distance, and 2 times the contact width. The results from tables 1 and 2 show that the half contact width and applied normal load are higher for Inconel 783 then Tribaloy T-800, which are used to calculate the coefficient of friction and friction force. Equation 1b is also based on Hertzian theory and is used to calculate the sliding coefficient of friction for a sphere sliding on a plate. This equation was used only to compare the friction coefficients of Tribaloy T-800 and Inconel 783, so it could be seen why the parts needed coating. The results from using this equation are in tables 1 and 2 and are .04 for Tribaloy T-800 and .25 for Inconel 783. There is a substantial benefit by reducing the coefficient of friction from coating the aircraft engine parts with the cobalt coating Tribaloy T-800. It also can be seen from figure 3 that the frictional coefficient for cobalt base materials decreases at temperatures above 800° Fahrenheit.

Another important tribological contact process to examine is the wear of the surface material. Equations 3 and 4 were used to analyze the wear of cobalt coating Tribaloy T-800. The worn volume and wear rate are widely used to place a quantitative value on wear capability of a material in its environment [1, 52-53]. It can be seen that with the low wear rate of the cobalt coating the material removed does not exceed the thickness of the coating over the life of the part.

6. Conclusion

When temperatures are high, wear is a concern, and the contacting part materials were not chosen with tribological issues as a concern, then it is important to apply a coating to the components. With the right coating and application process the friction and wear between parts can be minimized and extend the life of the components. In the case where the aircraft engine compressor and combustor parts are in an atmosphere of 538° Celsius then Tribaloy T-800 was the right cobalt coating to meet the parts low cycle fatigue life. The HVOF application process was also chosen correctly to produce a well-bonded coating that reduced the mixing of Tribaloy T-800 and Inconel 783.

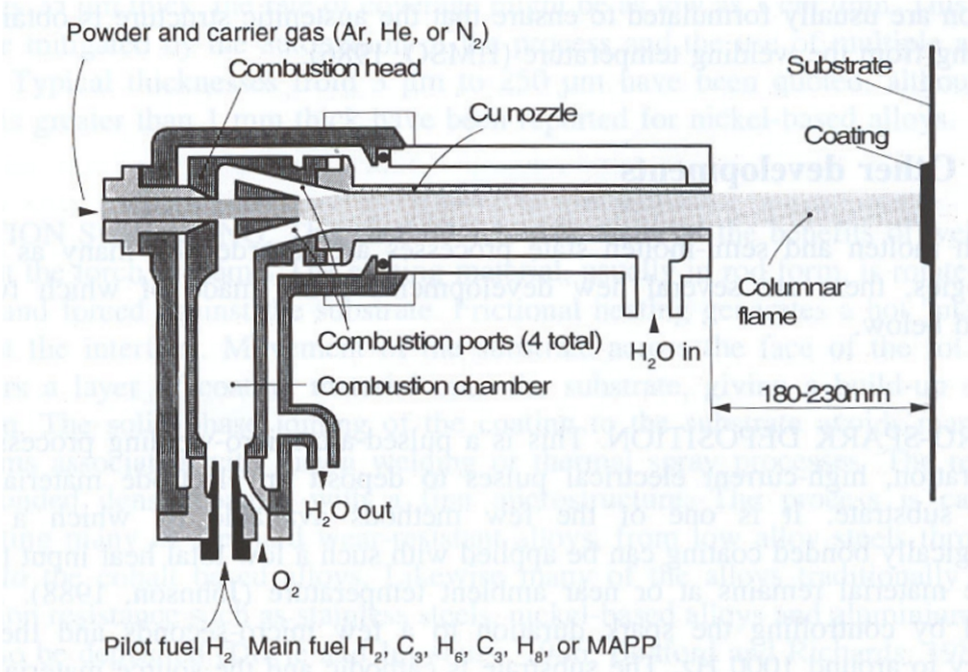

Figure 1. Typical high HVOF process layout [1]

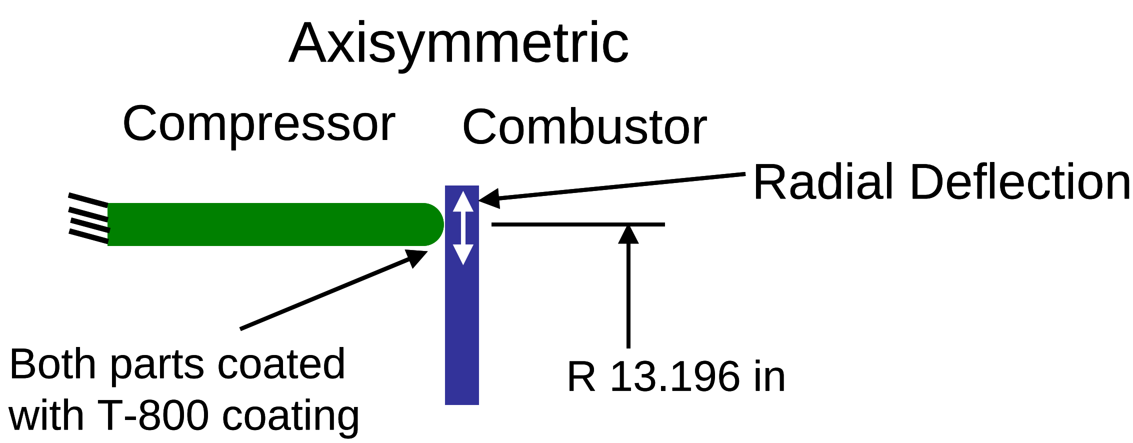

Figure 2. Layout of the Aircraft Engine Contact Example

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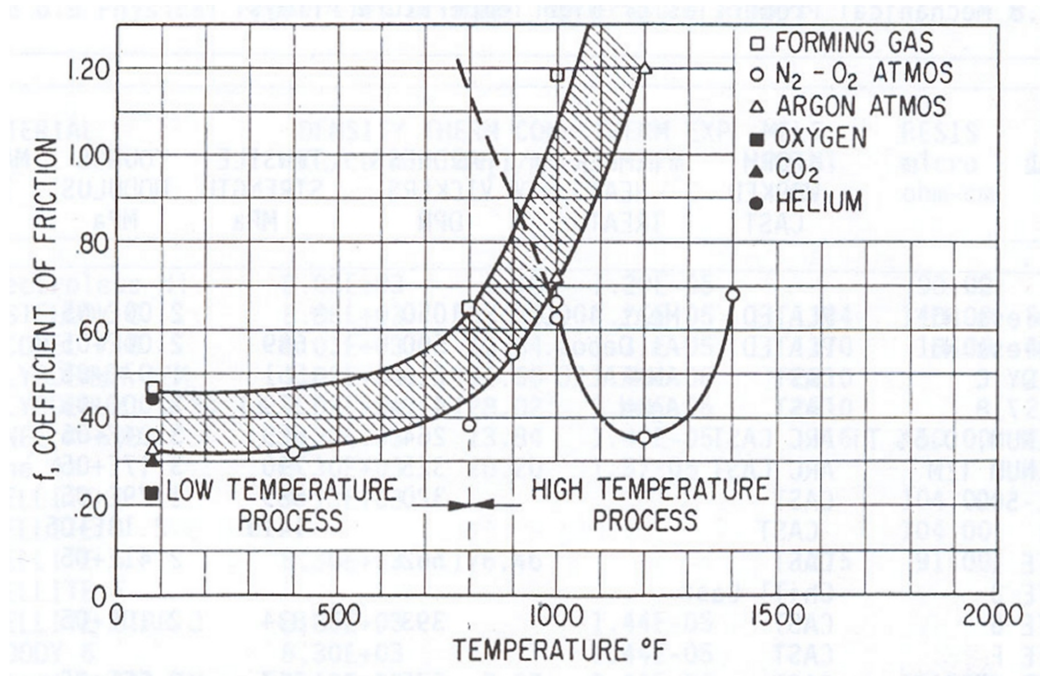

Figure 3. Effect of Temperature on Cobalt Friction [2]

H	7.26	GPa	Hardness	Tribaloy T-800
E	2.410E+05	MPa	Young's Modulus	
	124.090	MPa	Bearing Strength	
S	71.643	MPa	Shear Strength	
υ	0.290		Poisson's Ratio	
E'	1.316E+11	Pa	Reduced Young's Modulus	
	0.335	m	Radius at interface	Geometry
	2.106	m	Circumference at interface	
R	0.006	m	Radius of cylinder	
b	9.486E-05	m	Half Contact Width	
	1.3E-04	m	Min Coating Thickness	
	4.826E+06	Pa	Combustor Pressure	Loads
	4.137E+06	Pa	Compressor Pressure	
	689,476	Pa	delta pressure	
s	0.001	m	Distance Moved (Vertical)	
w	275	N	applied normal load	
Po	141.585	MPa	Maximum Pressure	
t	42.476	MPa	Maximum shear stress	
	68.67%		Margin of Safety	
y	7.4E-05	m	Max Depth of shear stress	
μ	0.04		Friction Coefficient	Friction
F	9.68	N	Frictional Force	
K'	0.0008		Wear Coefficient	Wear
V	3.9E-05	mm3	Worn Volume	
K	1.1E-04	mm3/Nm	Wear Rate	
	1.4E-11	m	Worn Depth	
	8.811E+06	Cycles	Takeoff to Landing for a Jet	
	3.000E+04	Cycles	Required Cycles	
	29271%		Margin Of Safety	

Table 1. Calculations Results for Tribaloy T-800

Material Properties are taken from [2]

H	2.75	GPa	Hardness	Inconel 783
E	1.77E+05	MPa	Young's Modulus	
	724	MPa	Yield Strength	
S	418.002	MPa	Shear Strength	
υ	0.31		Poisson's Ratio	
E'	9.802E+10	Pa	Reduced Young's Modulus	
	0.335	m	Radius at interface	Geometry
	2.106	m	Circumference at interface	
R	0.006	m	Radius of cylinder	
b	1.099E-04	m	Half Contact Width	
	1.3E-04	m	Min Coating Thickness	
	4.826E+06	Pa	Combustor Pressure	Loads
	4.137E+06	Pa	Compressor Pressure	
	689,476	Pa	delta pressure	
s	0.001	m	Distance Moved (Vertical)	
w	319	N	applied normal load	
Po	131.540	MPa	Maximum Pressure	
t	39.462	MPa	Maximum shear stress	
	959.25%		Margin of Safety	
y	8.6E-05	m	Max Depth of shear stress	
μ	0.25		Friction Coefficient	Friction
F	79.61	N	Frictional Force	

Table 2. Calculation Results for Inconel 783

Material Properties are taken from [11]

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