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Influence of carbon-based solid lubricant on fretting wear response for alumina-based ceramics versus cobalt superalloy contact

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ABSTRACT

In aircraft motors, blade–disk contacts are subject to fretting wear that implies surface degradation due to relative small-amplitude oscillatory movements. The present work investigates one selected alumina-based ceramics as a protective coating for the composite subjected to fretting wear against the HS25® disk. This contact is compared to its equivalent with a thin layer of carbon-based solid lubricant applied on the same ceramic coating between 100 and 700 °C. Under unlubricated conditions, wear is abrasive, whereas lubricated interfaces show the formation of 40 μm thick adhesive glaze layer. With this glaze layer, wear volume is reduced by at least a factor of 10 compared to a naked interface. This third body becomes unstable under 500 °C, even if an intermediate tribofilm is created to relatively limit wear. Chemical analyses show that the third body is composed of debris from both counterparts that are probably aggregated together by the lubricant's binding agent. Besides, wear volume is strongly related to a sintering process whose progress depends on the debris' ability to be grinded, mixed together and compacted.

1. Introduction

In stages of civil turbojet motors where temperature exceeds 600 °C, thermostructural materials are needed. CMCs (ceramic matrix composites) are notably considered for the substitution of metallic alloy blades [1,2]. This would contribute to improving motor performance by dividing blade mass by 3 and enabling the stage to even higher temperatures. The blade root is dovetail inserted in the disk. In the engine, successive flight missions (taxi, take-off, landing) coupled with motor vibrations, may lead to fretting wear damages in the contact between the blade root and the disk. This phenomenon has already been described for Ti-involving contacts [3]. Here, the disk is made from commercial cobalt superalloy HS25® and in order to avoid chemical interactions, the CMC at blade root is covered by a thick ceramic layer containing alumina. With such a setup, fretting phenomena take place between the superalloy and the ceramic coating. Moreover, a solid lubricant layer containing graphite can be applied on the ceramic coating to limit friction and dissipated energy in the interface. The present paper aims at studying the tribological behavior and the physicochemical phenomena generated for both alumina-base ceramics versus cobalt-base alloy contact, lubricated or not, under fretting wear conditions at high temperatures.

The issue of friction and wear at high temperatures has been widely studied in the past decades, especially for metal–metal interfaces [4–6]. It is commonly accepted that near the contact surface, complex phenomena such as plastic deformation and mixing of particles in the interface occur to create a physically and chemically modified layer, sometimes called mechanically mixed layer (MML) [7] or tribologically transformed layer [8] when emphasis is put on material recrystallization. Diffusion processes are also involved [5] to promote the formation of preventive glaze layer when high diffusivity materials are present [6]. Such glaze layer structure is usually generated through an adhesive wear process [9]. Stott [10] showed that for nickel-base contacts, this glaze layer is formed by compaction and sintering of oxidized wear debris and protects interface from wear for temperatures above 200 °C. Wear behavior under 200 °C is abrasive for steel versus nickel–zirconia composite, which is the main observed process for metal–ceramic contacts [11]. Fretting contacts between metals and ceramics, especially against alumina, have been studied throughout many approaches [12–14]. Despite other observations [11], in work of Endo and Marui [15], adhesion of particles is depicted on sliding areas for a steel-alumina contact and worn volumes are bigger for the metal than for the alumina part. However, if metal is transferred onto the ceramic surface, no ceramic particles seem to stick on the metallic counterpart. Besides, oxidation is said to be crucial: the oxides may enhance damage in the interface when created (Fe_xO_y oxides [16]) or may be added to support the creation of a protective tribofilm [17]. By contrast, according to [4] and [8], oxygen does not influence the formation of MML. Aside from oxidation, the role of debris stands out as a key parameter for

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processes in the interface, and highly depends on the environment (relative humidity [18], temperature [19]). Varenberg [20] sums up that debris can be either positive or harmful towards wear protection, whether wear is respectively adhesive or abrasive. Kato [21] found that for a steel–steel contact, only under a critical size of Fe_2O_3 particles of about 1 μm, the glaze layer can be formed.

Tribological studies on lubricated interfaces have been lead, most of time through lubricated particles in composite structures [22,23] but more rarely with a solid lubricant layer. The aim of the present study is to observe how the presence of a carbon-base solid lubricant can improve the protective glaze layer formation that reduces fretting wear rate in the interface. To achieve such analysis, a comparison with a non-lubricated contact is presented, investigating wear kinetics through a large temperature range from 100 to 700 °C. A specific methodology based on chemical analysis on cross sections has been developed to better understand the interface evolution and scenarios of glaze layer formation.

2. Experiments

2.1. Materials

A representative plane to plane contact for disk against the ceramic coating of the blade has been chosen. The studied geometry consists in a punch on plane contact that model the dovetail connection. Like the turbine blade, the plane is coated by a 0.5 mm thick ceramic layer and potentially lubricated. The punch is a chamfered cylinder with a flat 4 mm diameter circular top. This top surface is ground to a low surface roughness ($Ra = 0.4$ μm). The resulting contact path is a 4 mm diameter disk.

The material for the punch is a commercial HS25® alloy (Haynes International, USA), chosen for its good high-temperature strength. The main properties and composition of HS25® are summarized in Table 1. Before wear tests, the HS25® punch is thermally treated for 1 h at 1065 °C. A thin layer of Cr_2O_3 is formed on the punch surface and acts as an early lubricant.

The plane is a flat sample of CMC, coated with a 0.5 mm plasma sprayed ceramic layer and potentially lubricated. The ceramic is a porous material mainly composed of alumina Al_2O_3. The properties of the ceramic layer are in Table 1. After spraying, the ceramic is heated at 1100 °C for 2 h to crystallize it. DRX analysis (Cu anticathode) was performed on the crystallized ceramics and showed random orientation of grains but rather poor quality of crystallization, with 22 nm long crystallites within grains. To highlight the effect of the selected solid-like lubricant, some of the planes were lubricated applying an inorganic solid-like lubricant containing graphite and other high temperature lubricating additives (Table 1). The lubricant film is applied by dip coating and is finally cured. The lubricated surface of the ceramic is covered with discontinuous aggregates of particles, also obtained by Fazel [23]. The lubricant layer is porous and unevenly applied on 5–15 μm in thickness.

Table 1
Material data.

	HS25® alloy	Alumina-base ceramic coating	Graphite-base lubricant
Composition	(at.%) 54% Co[a], 24% Cr, 11% Ni, 5% W, 3.3% Fe, 1.6% Mn, 0.7% Si[b], 0.4% C	(at%) 29% Al, other	(wt.%) 20–30% C, 4–10% Na, silicate resin
Moduli (GPa)	Dynamic modulus of elasticity: 225 (20 °C), 174 (700 °C)	Young's modulus: 145 GPa	–
Density	8.94	3 (estimation)	–

[a] As balance.
[b] Maximum (commercial data).

2.2. Methods

The moving part of the fretting device is a top mechanical arm connected on an electrical shaker that provides horizontal reciprocating movements. The tribometer is set to align a plane to plane contact between punch and plane and to tune the frequency f, the displacement δ, the normal force P and the number of cycles Nc. The sliding amplitude δ_g^* is defined as δ when $Q = 0$ and is kept constant during the test. Imposed fretting test parameters are $\delta_g^* = 50$ μm, $f = 50$ Hz, $P = 800$ N during $Nc = 1$ million. Under these conditions, the contact is subject to total sliding regime. The friction coefficient μ is computed in real time.

After test, samples are ultrasonically cleaned in ethanol. Wear volumes of both plane and punch are measured using a profilometric method, based on a laser interferometer (Veeco Instruments, USA). Wear is measured by computing the missing volume in the fretting scar using the lateral unworn surfaces as a reference.

Morphological observations are performed with a SEM (Tescan, Czech Republic) using a tungsten filament, equipped with an EDX detector (Bruker, USA). Samples are cut, mounted and polished before being metallized.

3. Results

3.1. High temperature (700 °C) results

First of all, the investigation focuses on the response of the interface under high temperature conditions defined at 700 °C. This part is aimed at comparing fretting wear responses of lubricated and unlubricated interfaces at reference temperature for blade–disk contact. Fig. 1 is the evolution of friction coefficients μ during tests for both configurations. Apart from the early running-in, μ is increasing during the whole test for the unlubricated contact, which is good evidence of unstable interfaces. By contrast, after an accommodation period between 1.9E4 and 1.8E5 cycles, the lubricated interface become stable and μ is constant at 0.37. This is a close value to those obtained for glaze layered interfaces, where the friction coefficients are typically between 0.4 and 0.5 [9,10]. A stabilization of μ has often been observed, for example for alumina-TiN [12], steel–steel [21] and Nimonic® [10] contacts. It has also been found [23] that the addition of graphite particles in a contact of a Ni–SiC composite against alumina enabled to stabilize and reduce

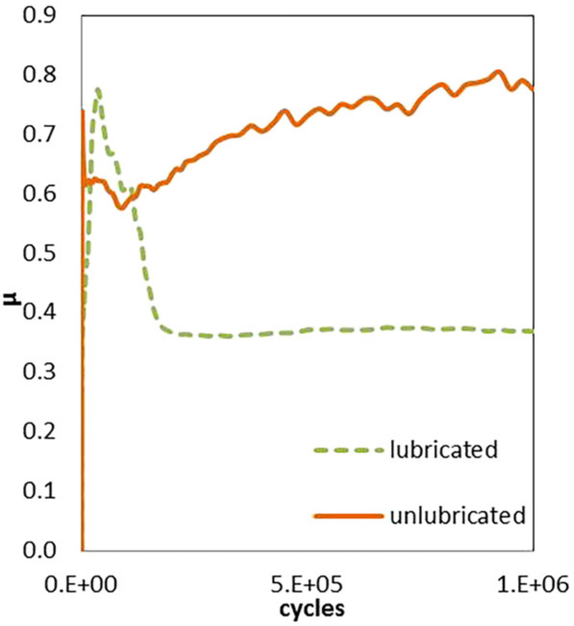

Fig. 1. Coefficients of friction for unlubricated and lubricated interface. $T = 700$ °C, $\delta g^* = 50$ μm, $f = 50$ Hz, $P = 800$ N, $Nc = 1$ million.