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Tribological characterization of a labyrinth-abradable interaction in a turbo engine application

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ABSTRACT

To enhance the efficiency of a turbo engine, one solution is reducing the clearance between the rotary parts in the secondary air system. This clearance reduction causes direct interactions in the secondary air system of a turbo engine when a rotary seal, called a labyrinth seal, rubs against the turbo engine casing as a result of successive starts and stops, thermal expansions and vibrations. To protect sealing systems from severe damage, abradable coatings are used on the inner periphery of the casing. The purpose of the present paper is to study the labyrinth-abradable interaction during high speed contacts through a detailed tribological characterization. The labyrinth-abradable interaction experiments were conducted on a dedicated test rig that was able to reproduce representative turbo engine operating conditions. A complete tribological analysis based on a third body approach and on accommodation flows was investigated using high speed imaging of the interaction. A schematic description of the interaction, with the addition of images extracted from recorded videos, is proposed to define two types of third body formation and their evolution during labyrinth-abradable interactions. Finally, the labyrinth-abradable interaction life cycle was used as a basis to discuss the coating subject to a labyrinth tip speed increase.

1. Introduction

Minimizing the interfering leakage between the rotating assembly and stationary parts of a turbo engine is crucial for improving the efficiency of engine modules ([1]). Secondary turbo engine air sealing systems are composed of a particular type of rotary seal called the labyrinth seal. The control of pressure differences and levels of cooling between the engine modules is provided by the clearance control between the rotating labyrinth teeth and surrounding casing. The rotary seals are primarily composed of several teeth, which are integral parts of the motor shaft. This constraint requires the turbo engine designers to deposit a sacrificial abradable coating on the casing that is specially designed to protect the integrity of the seal components ([2,3]). One of the most important properties of this coating is to accommodate incursions of the labyrinth teeth that might occur during turbo engine operation ([4]). Indeed, a turbo engine is subjected to successive start and stop cycles, thermal expansions, vibrations, and mechanical loading creating undesirable rotor-stator displacements leading to labyrinth seal interactions ([5,6]). The coating abradability and the turbo engine operating environment imposes requirements in coating design that are the result of a compromise among various coating properties ([7]). Knowledge and control of the wear behaviour of abradable coatings are required to maintain an optimum seal for the proper functioning of engines ([8]).

Research on the labyrinth seal behaviour has mainly focused on sealing performance. Many numerical studies aimed to characterize the sealing performance according to various tooth parameters ([9]), seal geometry ([10]), rate of leakage caused by the rub-groove left by the teeth on the coating ([11–13]) and so on. Very few studies have attempted to reproduce the labyrinth-abradable interaction using a dedicated test rig to study the behaviour of the coatings. A first full-scale facility, based on a grinding machine, has been developed by Dowson et al. ([14,15]) to study the behaviour of several abradable coatings (silicone rubber, tetrafluoroethylene (TFE), aluminium silicon-polyester, nickel graphite). The authors established an abradability condition based the ratio between the rub-groove penetration depth in the coating and the wear of the labyrinth seal to discuss their behaviour. Visual descriptions of the rub-grooves left by the labyrinth seal on the coating are used to describe the quality of the rub-groove (edges and sides), presence of cracking caused by thermal effects and increase in the coating hardness. Later, Whalen et al. ([16]) summarized all of the studies on the development of polymer coatings for centrifugal compressors and developed new

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labyrinth seal design geometries, such as labyrinth seals that incorporate teeth on the stator. In addition, the companies Sulzer Innotec and Sulzer Metco worked closely to develop coatings that were specially adapted for labyrinth-abradable applications ([17]). More recently, Delebarre et al. ([18]) developed a new high speed test rig based on a milling machine that was dedicated to stimulating interactions between labyrinth seals and abradable coatings under similar turbo engine operating conditions. A contact assessment under different turbo engine operating conditions has been carried out between an Al-Si 6% coating and a nickel alloy (Alloy718) labyrinth seal.

In a more precise understanding of the wear mechanisms involved, Delebarre et al. ([19]) studied interactions as a function of the incursion depth parameter to obtain a first chronological contact evolution under severe operating tribological conditions. Using a suitable instrument, macrographic and micrographic rub-groove observations are used to describe the wear process using a preliminary third body approach. Two different varieties of particle production have been identified providing two different types of third body and two different material flows. Finally, the authors demonstrated that the evolution of the third body and its life cycle during contact have a major impact on the final rub-groove morphology. This approach is reflected in several studies concerning interactions encountered between compressor blade casings in the primary turbo engine air system ([20,21]). The mechanisms of incursion accommodation were investigated using dynamic data and a post mortem analysis of the rubbed coating and wear debris. The authors proposed a schematic description of the accommodation mechanisms ([21]).

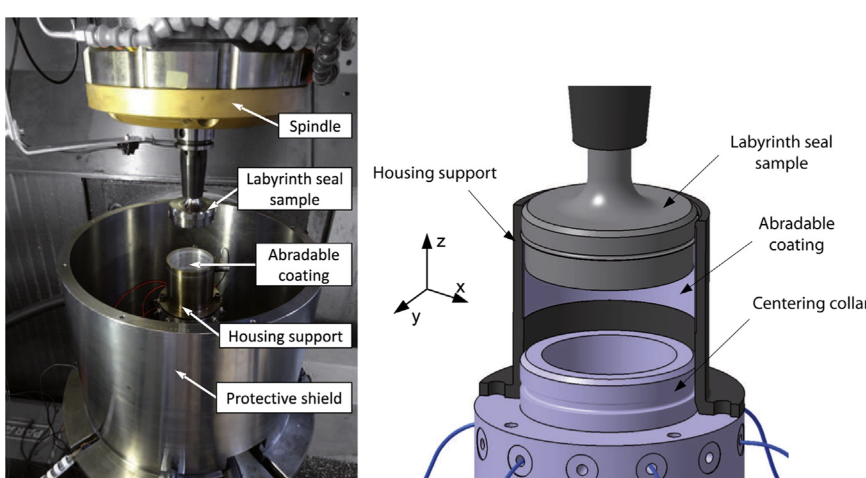
The present paper proposes a complete tribological analysis of the labyrinth-abradable interaction based on the description of the contact life cycle interaction. The test rig presented in previous papers ([18,19]), is used to simulate in-service interactions with respect to the full scale, integrating dedicated high speed imaging of the interaction. Our efforts are focused on conducting a tribological analysis of a specific interaction condition ("the severe wear condition" ([19])) between an Al-Si 6% coating and a stainless steel labyrinth seal. This experiment is representative of the most substantiated contact condition that occurs in turbo engine life in terms of the materials used, relative rotor/stator speeds (labyrinth tip speed of 17 $\mathrm{m{\cdot}s^{-1}}$) and kinematic interactions of the labyrinth seal (incursion speed V_{inc} = 9.41 $\mathrm{m{\cdot}s^{-1}}$). The high speed imaging of this specific condition and results of a previous study ([19]) are used to define an accurate interaction life cycle based on a third body approach and on the definition of a tribological circuit. The labyrinth-abradable interaction life cycle will be used as a basis to discuss the behaviour of a coating subjected to a labyrinth tip speed increase to reach a conclusion regarding the coating behaviour.

2. Labyrinth-abradable interaction

2.1. Test rig

To simulate the interaction dynamics between labyrinth seals and abradable coatings, a dedicated test rig, discussed in detail in previous papers ([18,19]), was used in this study. The test rig configuration remains unchanged and allows the test rig to reproduce labyrinth seal interactions under operating conditions similar to those of a turbo engine. As shown in Fig. 1a, a 5-axis milling machine from Mikron and a special device fitted on the machine tool table are used to reproduce the working in-service kinematics of the labyrinth seal. A labyrinth seal sample, representative of an actual motorshaft section part, shrinks on the HSK-50 tool holder instead of the cutting tool. A simplified geometry was chosen for the labyrinth seal sample using a single tooth configuration with respect to full-scale turbo engine components. The labyrinth tip speed V_t is generated by spinning the labyrinth seal sample through a magnetic bearings spindle ([22]). A tube sample, representative of a turbo engine housing, is coated in the inner periphery with an abradable material. Once the labyrinth seal sample is precisely positioned inside the housing support (Fig. 1b), the CNC capabilities of the 5-axis milling machine (machining program executed by the CNC) are used to make labyrinth-abradable contacts under realistic and controlled operating conditions. The contact is generated by a translation of the housing support and is defined by an incursion speed V_{inc} and a penetration depth D_p in the coating, generating a particular interaction area that is induced by the radial incursion of a circular tooth (with a trapezoidal section) in a tube.

The first investigations of the labyrinth-abradable interactions were achieved using the in-situ instrumentation that was specially developed on the test rig ([18,19]). The labyrinth seal tooth tip penetration depth D_p in the coating and the interaction time t are estimated through a contact tracking sensor (voltage circuit generated by the opening and closing of the circuit between the labyrinth seal tooth and coating). A continuous acquisition of this



(a) (b)

Fig. 1. (a) Overview of the dedicated test rig that was specially developed to simulate labyrinth-abradable interactions; (b) closer view of the labyrinth seal sample precisely positioned inside the housing support.