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Effect of sliding speed and counterface properties on the tribo-oxidation of brush seal material under dry sliding conditions

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ABSTRACT

The performance of dynamic seals and hence the overall efficiency of the gas turbine is strongly dependent on the wear of individual seal elements and their ability to provide continuous sealing. Dynamic seals such as brush seals contact the rotating 'rotor' during operation, either transiently or continuously depending on factors such as thermal expansions, axial/radial displacements and eccentricities of the rotating components. This intermittent or continuous contact results in sliding wear of the seal tips and dictates the seal degradation and hence its efficiency.

The present work examines the effect of sliding speeds between 6 m s^{-1} and 150 m s^{-1} on the wear-oxidation of Haynes 25 brush seal 'tufts' sliding against nitrided steel and thermal sprayed chrome oxide coating.

1. Introduction

Gas turbine engines work on the principle of momentum imbalance created as a result of the high exhaust velocity compared to the low intake velocity. The intake air entering the core of the gas turbine engine is divided as the primary air flow, which passes through the combustor and gas stream, and the secondary air flow, which is used for applications such as internal cooling, external bleed for cabin air conditioning and accessory devices. A reduction in secondary air flow leakage past seals can result in approximately 4–6% increase in power together with reducing specific fuel consumption by 3–5% [1,2]. Dynamic seals such as labyrinth seals and brush seals are used to reduce air flow leakages in secondary air systems. The main advantage of using brush seals in place of labyrinth seals is their ability to accommodate transient shaft excursions due to an increased compliance which can lead to a significant reduction in leakage rates [3]. A schematic of a brush seal cross-section and side view identifying all the key features is shown in Fig. 1.

Individual bristles are oriented to the shaft with a lay angle (typically around 45°) pointing in the direction of rotation. Despite the increased compliance, bristles may contact the rotor transiently or continuously during operation and this contact can result in wear of individual bristles resulting in an increase in leakage between the seal and the rotor. Brush seals are expected to perform under a wide range of operating conditions with speeds up to 450 m s^{-1} [1] and tip loads up to 70 kPa [2] in ambient temperatures up to 800 °C [1,2]. These extreme speeds and temperatures, which are often difficult to replicate in controlled laboratory conditions, make tribological evaluation of candidate brush seal materials very challenging. Most of the work reported on tribological evaluation of brush seals [2,4] has been done at high temperatures, albeit at much lower sliding speeds. The general assumption under such conditions being that ambient temperature has a greater effect on dry sliding wear between the bristles and the rotor than sliding speed. In the present work, tribological tests are conducted at ambient temperatures but at representative sliding speeds. At high sliding speeds, the frictional heat generated is likely to dominate the thermal field at the sliding interface.

2. Background

The nature of this localised heating and the generation of the resultant "flash" temperature has been extensively investigated by Bowden and Tabor [5], Archard [6], Blok [7] and Ashby et al. [8]. This local heating is likely to influence the oxidation and hence the wear-mechanisms experienced during dry-sliding wear. The effect of speed on dry sliding wear from a mechanistic perspective was

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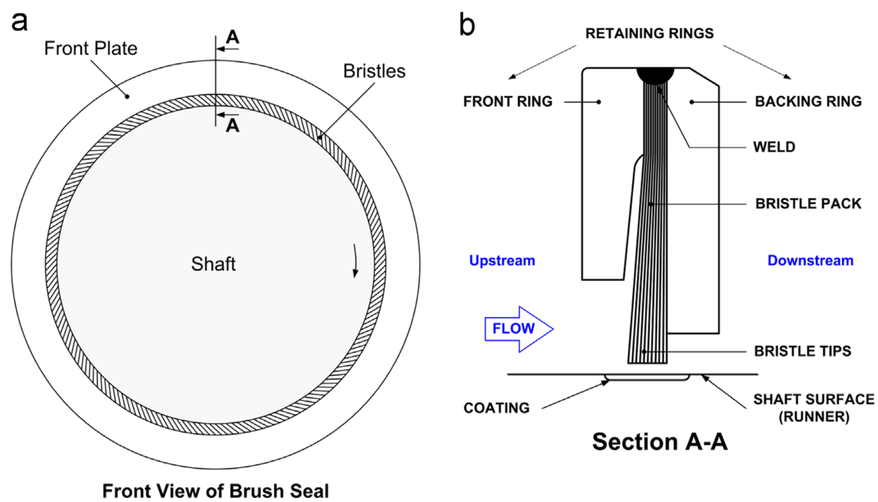

Fig. 1. (a) Schematic of the front view of brush seal showing the relative position of bristles and the shaft (b) cross sectional view across A–A section showing the position of bristles and shaft relative to the gas flow.

initiated by Archard and Hirst [9]. They identified mild and severe wear as two distinct mechanisms during unlubricated sliding of metallic surfaces. The distinction between the two wear modes was down to the size and mechanism of the formation of delaminated debris. Hirst and Lancaster [10–14] examined the effects of parameters such load, speed and surface roughness on the change in wear rates and concluded that the transition from severe wear to mild wear occurred when the rate of formation of surface films was greater than the rate of material removal by intermetallic contact and delamination of debris.

The role of oxidation in high speed dry sliding was also investigated by Cocks [15,16], who observed that there is another mechanism that is likely to occur whereby an increase in load or speed resulted in disintegration within the oxide film and this potentially leads to a sharp rise in wear rates. This behaviour was influenced by factors such as geometry of the tribo-pair and the relative hardness ratio between the metal and its oxide. Rigney et al. [17,18] developed a model to predict the delamination of flaky debris in the wear interface based on the shear strength between the oxide layers and substrates. They also identified the possibility of material transfer between the tribo-pairs and the formation of a transfer film on one or both surfaces during dry sliding. They further proposed that these were formed as a result of a three-step process involving (a) formation of elongated and ultrafine grained microstructure near the surface due to high levels of plastic strains, (b) delamination and mixing with the counterface material and (c) stabilising by mechanical alloying with a second phase, all of which depended on factors such as load, sliding speed and relative hardness ratio between the tribo-pairs. Direct observations of the glazed layer were made by Inman et al. [19]. They studied a nickel based superalloy after sliding against Stellite at elevated temperatures using Transmission electron microscopy (TEM). The glazed layers were characterized by a grain size of around 10 nm and composed of mixed oxides and metal particles. A mechanical mixing mechanism similar to that above was proposed. The benefits of a nano-structured layer were recognised by Kato and co-workers. They introduced a range of metal oxide nano-particles to the wear track [20] and found that a mild wear regime was established for those oxides with the higher diffusion coefficients and observed coherent tribo-films being formed. They also looked at self-generating tribo-films in various wear couples [21] and produced films ~40 μm thick in steel on steel which had a higher hardness than the parent metal.

Stott and Wood [22] examined the influence of oxidation on the formation of surface films and defined a stable compacted film as a "glazed" layer. They proposed that formation, agglomeration and compaction of oxide debris glazed layers results in 'sintering' of the material to form hard and compacted layers on the wearing surfaces, often leading to a decrease in wear and friction with an increase in test temperature and time. Jiang et al. [23,24] further expanded on this by identifying the ability of oxide debris to be re-entrained in the contact as the key parameter responsible for the formation of a glazed layer. They further developed a mathematical model for capturing the transition from severe to mild wear based on the probability of wear debris particles entraining in the interface. As the probability of debris entrainment and compacting was higher for low speed and high temperature conditions, the formation of a glazed layer was mostly observed under such conditions.

There is a limited literature devoted to high sliding speeds although all involve much higher contact pressures than those used in this work. Montgomery [25] made an extensive study of various wear couples for gun barrel and projectile applications using a pin on disc arrangement at sliding speeds up to 457 m/s and contact pressures in the range 6.2–162 MPa. The energy input was seen as the key parameter and for low Normal pressure x velocity values friction tended to be erratic and wear rates high whereas at higher PV values friction and wear was more stable and wear rates lower. Philippon et al. [26] studied friction in the range 1–60 m/s and found that low friction correlated with the higher pressure and sliding speed combinations. Qiu et al. investigated the effect of atmosphere on wear and friction [27] and found both were improved by the presence of O_2. In a later study they made an estimate of the contact temperature For Titanium against steel and speeds in the range 30–70 m/s [28]. Temperature estimates were ~1000 °C for the higher speeds and pressures. Wear rates were also high this was attributed to unstable oxide films. Song et al. [29] tested a tungsten carbide/steel composite against steel at speeds up to 80 m/s. Wear rates increased rapidly above 60 m/s this was attributed to increased oxidation rates.

In their review of dry sliding wear mechanisms under a wide range of load-speed conditions for steel on steel, Lim and Ashby [30] identified two distinct regimes for oxidation-dominated wear as mild and severe, where these refer to levels of oxidation. In the load-speed space, mild oxidative wear was likely to occur when there is sufficient frictional heat to generate an oxide film to reduce asperity contact. A transition to severe oxidative wear was