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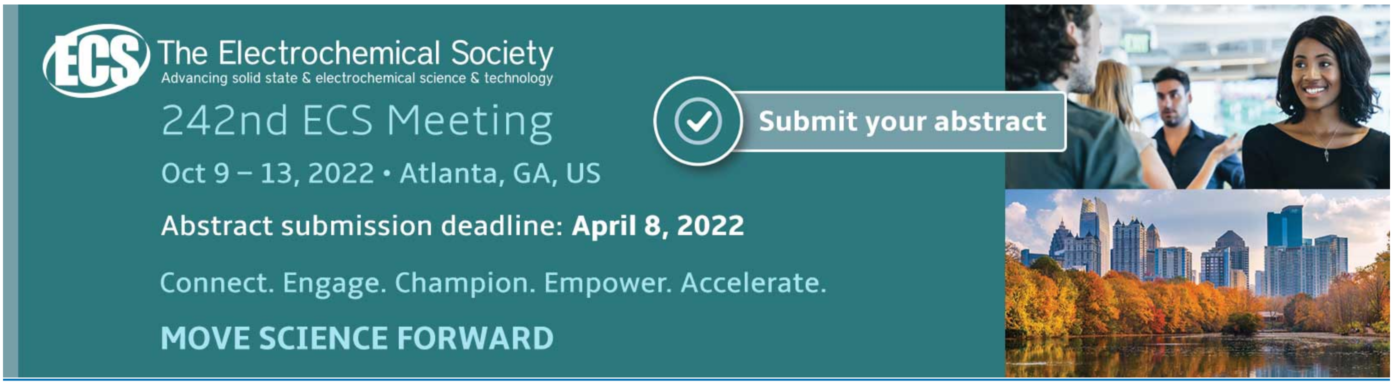

Experimental investigation of contact forces and temperatures in rubbing interactions of honeycomb interstate seals

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Abstract: The new architecture of high velocity aircraft engines includes labyrinth-honeycomb interstate seals to improve the engine's stability. To increase these engines capacity a commonly used strategy is to reduce the clearance between the blades and the sealing system. However, this reduction causes non-desired contacts (rubbing) between the rotating and static components of the engine. This rubbing interaction has an adverse effect on the engine life (wear and thermal cracking) and efficiency. In this work, experimental tests were carried out to recreate the rub between an F110 steel fin and a Hastelloy X honeycomb seal. A conventional CNC machine controlled the sliding and penetration velocities, and the interaction forces and fin tip temperatures were measured during the rub. Results demonstrate the dependence that both, interaction forces and tip temperatures, have with sliding and penetration velocities. However, it is clear that this influence is more pronounced in relation to the sliding velocity.

Keywords: Rubbing, Temperature measurement, Honeycomb, Thermography, Labyrinth seal.

1. Introduction

Nowadays, aircraft engine efficiency is improved by reducing the clearance between rotating and stationary components inside engines [1]. This reduction implies the increase of non-desired contact (rubbing) between these parts, which might cause subsequent wear and damage to the engine [2]. In the need to prevent the damaging effect of this rubbing, the use of labyrinth-honeycomb seals as abradable materials in the sealing system proved to be a solution [3]. The use of these labyrinth-honeycomb seals increases the engine stability, and if they are made of Nickel based materials it significantly increases the operating range of temperature and pressure [4,5]. On the other hand, this non-desired contact implies an increase in the working temperature of blades and the sealing system, which reduces the efficiency of the engine, and the operative life of these components. Therefore, it is imperative to understand the nature of the rubbing phenomena.

The study of the rubbing contact is very complex [6] because: (i) it involves multiple physical phenomena such as vibration, friction, heat transfer or wear, (ii) involved physical variables (forces, temperature and deformations) have nonlinear behaviour and (iii) it requires deep local studies, related to temperature and material characteristics, and global studies concerning contact velocities, vibration frequencies or resonance phenomenon. For these reasons, to the best of our knowledge, there is no a unique model able to describe the rubbing phenomenon in its whole complexity. Therefore, the current strategy is to develop simplified numeric [7–10] or analytic models, able to describe isolated aspects of this problem.

The experimental investigation of the rubbing interactions has also been a research line focused on the understanding of these above-mentioned phenomena. Although there is a large number of interesting publications covering this problem, see for instance [11–14], only a few of them take thermal effects into consideration (none measure the tip temperature), while most of them focuses on rotor-dynamics analysis.

The particular behaviour of involved variables (i.e. forces and temperature) strongly depends on selected materials and, therefore, no general behaviour can be extracted from literature. As an example, considering the relation between forces and sliding velocity (v_s), when penetration velocity (v_p) is kept constant, Delebarre et al. [11] stated that there seemed to be a linear relationship between them, having a linear increase in forces at high velocities, and a reduction at low velocities. In [13], the same behaviour was reported, while in [14] no linear relationship was observed.

These diverse results proved the need for a further research into this topic. In this context, a set-up has been developed to experimentally simulate the interaction between a fin of an aircraft engine blade and a labyrinth-honeycomb seal. In particular, Hastelloy-X and F110 steel were the materials selected for the honeycomb structure and the fin respectively.

In the next section of this paper, the experimental set-up is described and the experimental plan is explained. Then, in section 3, experimental results are given and discussed. Finally, some conclusions are drawn, which are summarized in the last section.

2. Experimental Set-up

The main objective of the set-up is to experimentally analyse the high-speed rubbing between a Hastelloy-X honeycomb seal and an F110 steel fin, simulating the interaction occurring inside an aircraft turbine engine. The set-up was mounted in a Lagun HS 1000 vertical CNC machining center. Figure 1 shows a schematic view of designed set-up.

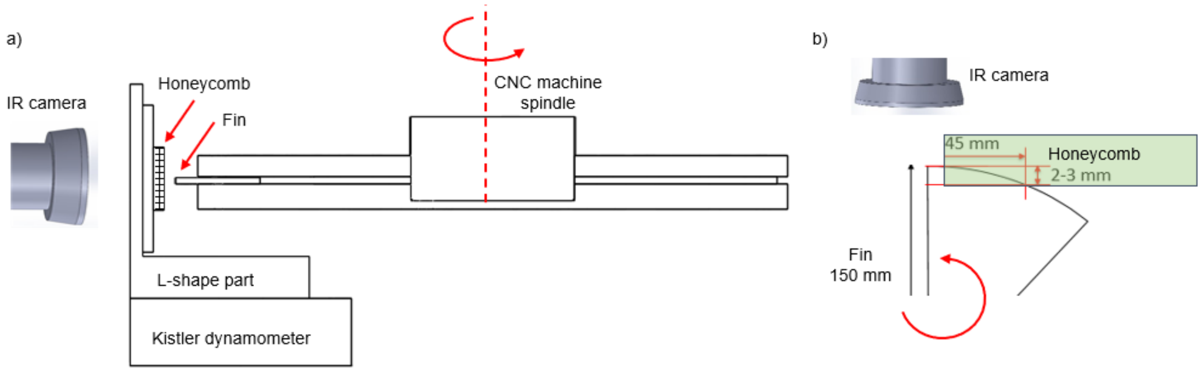


Figure 1. **(a)** Schematic view of designed set-up. **(b)** Schematic view of camera position relative to honeycomb sample

Hastelloy-X honeycomb samples were mounted in an L-shape part, which was clamped to a 3-component dynamometer (Kistler 9129) to record the dynamic changes in the rubbing forces throughout the tests. The dynamometer was placed on the moving table of the CNC, allowing a precise control of the relative position between the rubbing surfaces.

The fins were clamped in a rotating disk (see figure 1(a)) of 150 mm of radius, which was held to the spindle of CNC machine. The rotating speed of the spindle gives the desired sliding or tangential speed for each of the trials. It is important to highlight that, the geometry of the fins was machined in the same CNC machining centre before each of the tests, which provides a high degree of precision in shape of the tip of the fin.

To prevent undesired vibrations, before each test, the rotating disk together with the fin sample were balanced in a HAIMER Tool Dynamic balancing machine.

The set-up was also equipped with a high-speed infrared (IR) camera FLIR Titanium 550M, placed in a 3D micrometric stage to ensure the focus of the infrared image. The camera was placed in a position relative to the tip of the fins, thus allowing the detection of the infrared radiation just after the rubbing (see Figure 1(b)) when the penetration depth is at its maximum. In this case, the IR camera was equipped with a macroscopic lens, giving a spatial resolution of 1 pixel=10 μm^2, with an image resolution of 80×128 pixels, and an acquisition frame rate of 1870Hz. The integration time was adjusted to be between 10 and 200 μs depending on the rubbing condition. Due to the good surface finishing of the tip of the fin, the emissivity of this was stated to be 0.4 (polished metal).

2.1. Rubbing conditions

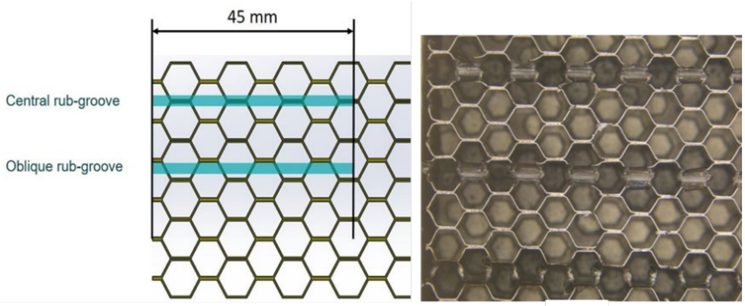
Test conditions, sliding velocity (v_s) and penetration velocity (v_p) were controlled with the CNC machining center. The selected velocity range was set between 1-100 m/s for v_s and 0.05-10 μm/rev for v_p. These rubbing conditions were selected to cover a v_s up to that found in the interstate seals of the turbines, and realistic v_p occurred when the fins interact with the honeycombs. Table 1 shows the tested rubbing conditions. In all cases, the depth of the rub was programmed to be 2 mm. Six repetitions were carried out for each rubbing condition, and a new fin was used for each condition to prevent undesirable effects of wear in fin's tip.

Table 1. Rubbing conditions.

Rubbing Condition	v_s (m/s)	V_p (μm/rev)
1	1	10
2	10	10
3	100	10
4	100	1
5	100	0.5
6	100	0.1
7	100	0.05

3. Results and discussion

Before discussing the results of forces and temperatures, it should be explained the two types of rubs that could be distinguished in the different trials. The fins-seal interaction could be central or oblique, as can be seen in figure 2(a), depending if the fins touched only with the oblique walls of a honeycomb cell (oblique) or with the walls between two honeycomb cells (central). This analysis was done post-process with a Leica DM-IM macroscope. In figure 2(b), three repetitions of test number 6 can be observed, in which the two rubs on top were considered as central, and that of the bottom oblique.



(a) (b)

Figure 2. Rub-grooves left in a honeycomb sample. Picture corresponding to three repetitions of test number 6. First two, centrals, and the bottom one, oblique.

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3.1. Temperatures

As described previously, temperatures were measured using a thermal camera, which enables the recording of thermal fields. As an example, figure 3 shows a thermography sequence of one rub of the third repetition of test 7, were three consecutive frames are depicted in a time lapse of 5.61ms. taking into account that the sliding velocity was high (100 m/s), the acquisition frame rate (1.87 KHz) allowed to have a unique valuable thermography to observe the tip of the fins after having rubbed with the honeycomb, the one in the centre of the figure, from which is extracted the temperature value.

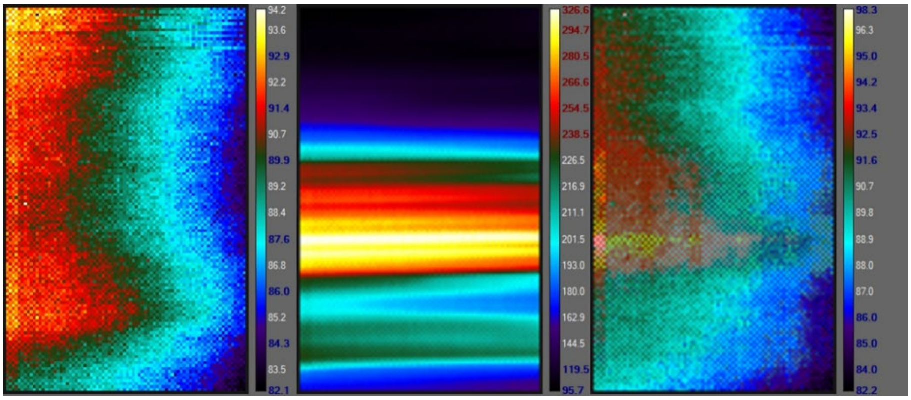

Figure 3. Thermography sequence of one rub of test 7. Three consecutive frames are shown, a time lapse of 5.61 ms.

For most of the tests, the whole experiment length was recorded continuously. However, those conditions in which the trials were longer, in order to minimize file size, this was saved for periods of 20 s every 60 s. See for instance figure 4, where measured temperature versus time during the first repetition of test number 1 is shown.

In figure 4 (right) the typical behaviour of the recorded temperature during a short test is shown, in this case, the sixth repetition of test 3. There, it could be observed how the temperature rose during the test, and how by the end of the trial this maximum temperature becomes almost stable.

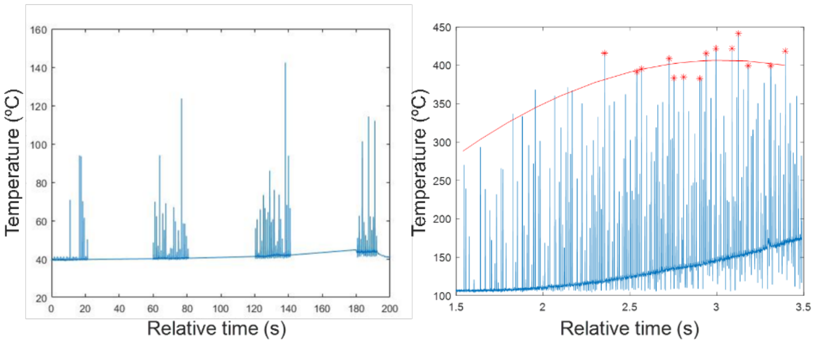

Figure 4. Temperatures during tests 1(left) and 3 (right). Quadratic was done with maxima to illustrate maxima stabilization.

Table 2 summarizes the measured values. Concerning temperatures, values appearing in table 2 correspond to the average of the maximum values recorded during the last 50 rubs of the six repetitions of each test. Unclear correlation between temperature values and the nature of rub (O) or (C) was observed.

As mentioned in section 2, the emissivity was assumed to be 0.4, property which turns out to be an uncertainty source when infrared techniques are employed. Emissivity not only depends on the material, but also on the surface roughness and temperature of the recording surface itself. Taking into account that, during the rubs, honeycomb material could be deposited on the fins, roughness might change as a consequence of wear and the temperature is obviously variable during the trials, reported temperatures should be taken as approximated values, with an uncertainty of roughly 20%.

Table 2. Rubbing conditions

Test	F_r (N)	F_t (N)	Temp (˚C)
1	45 ± 24	40 ± 11	86 ± 12
2	56 ± 55	30 ± 17	296 ± 8
3	87 ± 55	9 ± 5	414 ± 12
4	43 ± 33	5.6 ± 1.5	404 ± 7
5	31 ± 8	4.7 ± 1	330 ± 3
6	24 ± 21	1.2 ± 1	345 ± 10
7	27 ± 17	0.9 ± 1.4	314 ± 39

In spite of these uncertainties, it is possible to extract some general trends from obtained results. Considering the test at constant v_p= 10 μm/rev, the higher v_s, the higher temperatures. Considering tests at constant v_s = 100 m/s, the higher v_p, the slightly higher temperature.

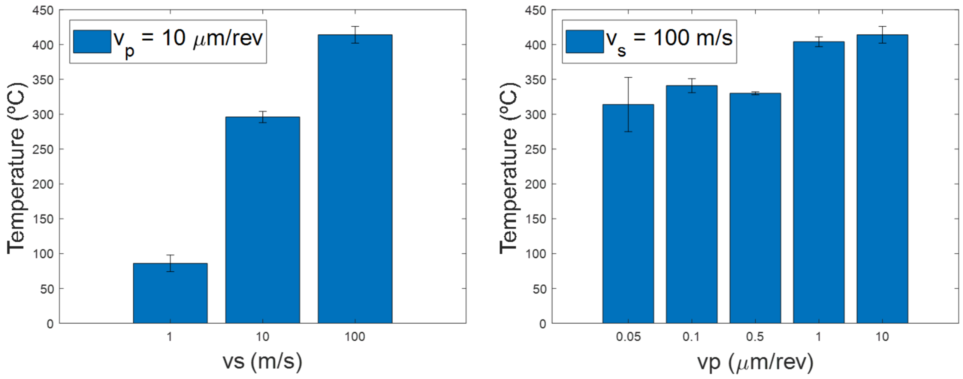

Figure 5. Temperatures during tests 1 (left) and 4 (right).

Two main factors contribute to the tip temperature rise, in one hand, the amount of rubbed material, linked with penetration velocity, v_p. The higher the v_p, the bigger volume of material deformed, the plastic work done by the fin becomes heat. On the other hand, the friction work is also transformed in heat, this energy is related with sliding velocity, $v_{s,}$. Figure 5 proves that the second mechanism is the dominant, as tip temperature is more sensitive to the variation of $v_{s,}$ than that of v_p.

3.2. Forces

Forces were measured in two directions: radial and tangential. The radial force is linked to the penetration movement, and the tangential force to the sliding velocity. It is important to remark that, when the sliding velocity was 100 m/s, a high degree of vibration was observed in the radial forces, while at low velocities this did not happen. In figure 6, measured forces during one repetition of tests 1 and 3 are shown to illustrate this phenomenon. In the same figure, it is possible to observe another general trend, which is that forces increased with time as the fin penetrated into the honeycomb seal.

Concerning the forces, the given results correspond to the average of the maximum values recorded during the last 50 rubs of the six repetitions of each test. In all cases, the uncertainty given is the standard deviation of the measured magnitude, and as it could be observed, these are relatively large (almost 100% in some cases), which means that the rubbing interaction had low repeatability. At first, it was thought that this lack of repeatability was related with the nature of the rub, to be central (C) or oblique (O), however, as in the case of the temperatures, no significant correlation between forces and this factor was observed.

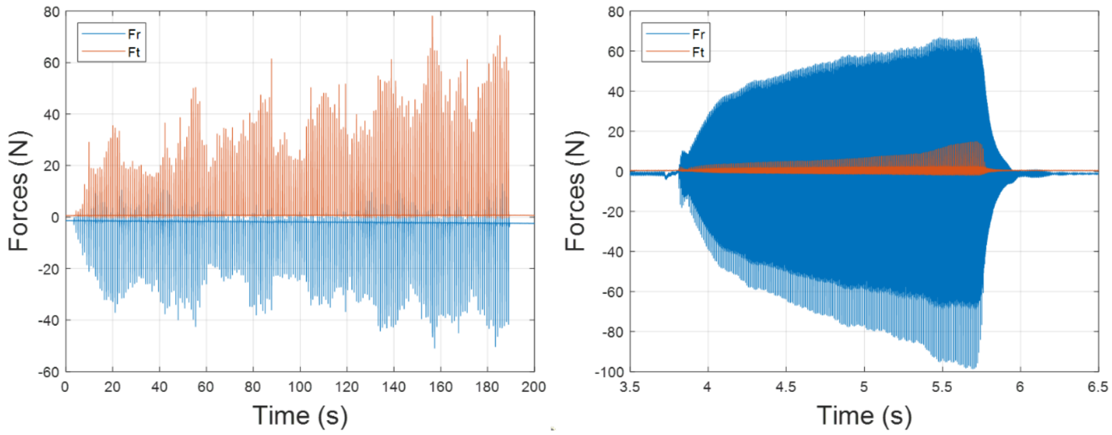

Figure 6. Forces during test 1 (1 m/s) and 3 (100 m/s). Vibration can be observed at high velocities.

Figure 7 shows the dependence of radial and tangential forces versus v_p and v_s. It is worth noting that large uncertainties were found during the trials, mainly caused by the large variations that are found between the different repetitions of each tested condition. However, some conclusions can be extracted from the obtained results.

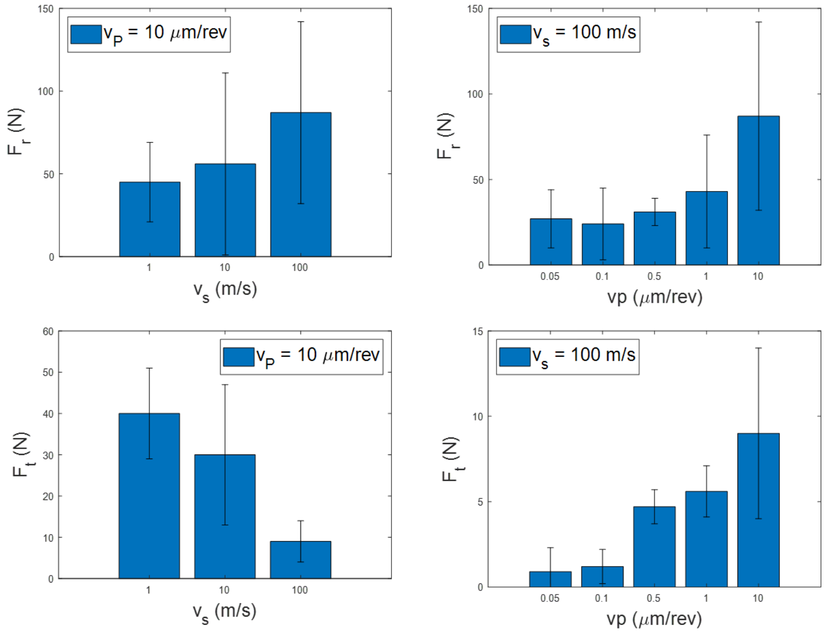

Figure 7. Obtained mean values of maxima radial and tangential forces.

At a fixed v_p, the higher the v_s, the greater the radial force, whereas, the lower the tangential force. Indeed, the increase/decrease of forces was not linear, in contrast to that stated by [11].

An increase in v_s directly affects to the rate at which the material will plastically deform. This usually activates two different mechanisms: work-hardening of the material due to an increase in plastic strain rate, and thermal softening due to the temperature rise caused by the plastic work. From the experience of the authors, forces tend to decrease when increasing the rubbing speed, as the effect of thermal softening is greater than that of strain rate hardening. This statement would be in-line with the results of F_t, and would also be linked to the temperature increase with v_s analysed previously. However, F_r results present the opposite trend which is difficult to interpret with these experimental results and without further information.

On the other hand, at fixed v_s, it could be said that both forces increased when increasing v_p. this is not surprising as increasing v_p means a greater amount of material to rub in each turn, which directly drives to an increase in both forces, F_t and F_r. However, is remarkable that at very low v_p (0.1 and 0.05 um/rev) both forces remained almost constant, further tests at lower v_p might be done to confirm this trend.

4. Conclusions and future works

Rubbing test were carried out in a specially developed set-up mounted in a CNC machine, with sliding velocities in the range of 1-100 m/s and penetration velocities in the range of 0.05-10 µm/rev. During the rub, radial and tangential forces, and blade tip temperatures were measured. The analysis of experimental outcomes provide some general conclusions:

- Very low repeatability was observed, implying that in spite of having done six repetitions of each test condition, large uncertainties were reported in force measurements. Indeed, the variation of results was not linked with the nature of the rubbing, oblique or central.
- Tip temperature of the fin rose while increasing the sliding and penetration velocities. However, this was much more sensitive to the sliding velocities. In contrast to other authors, no linear trends were found between temperature and sliding conditions.
- The influence that sliding velocity had on forces showed different trends: the tangential force decreased and the radial force increased with the increasing v_s. While the results of F_t were as expected, those of F_r had the opposite trend.
- Both, tangential and radial forces, increased while increasing the penetration velocity, as this involves a greater amount of material to rub in each turn.

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