

Wear of aircraft materials in case of emergency landing situations: an experimental investigation

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Abstract

During aircraft wheels-up emergency landings, wear and heat phenomena occurring due to the friction between aircraft parts and the runway might endanger the passengers' safety when fuel tanks are concerned, which must then be protected. This document is intended as a first explanation of the test procedure carried out as part of ongoing doctoral works whose objective is to clarify the thermal and wear phenomena occurring in such situations. It is a quick presentation of the available experimental devices, as well as a skim over the results obtained for the rubbing of an Al2024-T3 pad onto a gabbro disc.

1. Introduction

In case of an emergency landing, an aircraft lands “on its belly” (landing gear retracted) and slides on the ground until it comes to a stop (see Figure 1). Some structural elements such as the fuselage, the engines or other dedicated elements, may undergo extreme mechanical and thermal stresses, induced by friction on the runway. This situation translates into risks of structure destruction or fire, and might expose passengers to harm, making these issues significant for the aviation industry. Such risks are assessed today thanks to experience feedback for metallic structures, but they remain poorly known for composite elements, which are increasingly used in primary aircraft structures.



Figure 1: Phases of an aircraft emergency landing (gear retracted)

Therefore, the emergency landing situation presents a high-energy friction scenario, which raises questions about possible ways to study the thermal and wear phenomena occurring therein. One possible solution is to be inspired by studies carried out for other means of transport, such as the study of railway braking conducted by Desplanques et al. [1], and to use a similar pin-on-disc setup. A first set of experiments was carried out by T. Devo [2], performed in the frame of a French DGAC funded research project (PHYSAFE).

In the present document, the words pin and pad will be used interchangeably. The matter of scale change arises then for the ideation and implementation of laboratory tests on a smaller scale than that of the aircraft in an actual emergency landing situation, because of the impossibility of scale one experiments (for safety, environmental and budgetary

concerns), at least at this stage of research, and because of the obvious unpredictability of such events. The scope of this paper is to make a first presentation of test procedures carried out as part of ongoing research works, which aim to clarify the thermal and wear phenomena occurring during sliding in emergency landing situations (high-energy friction conditions), as well as to briefly introduce the limits of the experimental setups in respect to representativity of scale one situations.

For context, the chosen theoretical frame used to study these situations is the third-body approach proposed by Godet [3,4]. It has been shown that when there is friction between pad and disc, a tribological circuit is set and a third-body layer between the materials in contact bears the load, fed by flowing particles of various origins (rubbing materials and environment) [5,6], as can be seen in Figure 2.

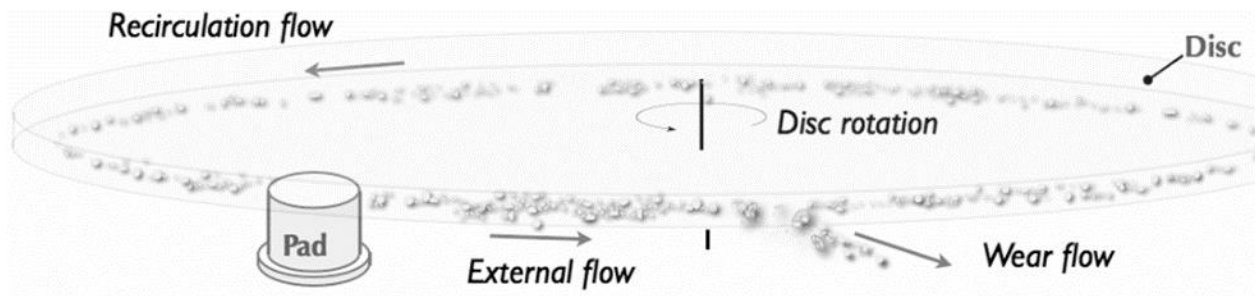


Figure 2: Flows of third-body particles activated by disc rotation [1]

As stated before, the use of a laboratory testing-device is the chosen option. Section 2 presents two test rigs used for carrying out tests, as well as the scale-conversion rule and the limits of the setups regarding scale one phenomena. Experimental conditions are given in section 3, and a results preview is presented in section 4.

2. Description of Experimental Setups

2.1 LaMcube Braking tribometer and instrumentation

Since there was no specific testing bench dedicated to the retracted gear emergency landing situation (although the design of a prototype is under way), an available braking tribometer was first used, which was designed for reduced-scale pad-disc contact conditions to be as close as possible to those observed at full-scale in railway applications, as well as other scenarios in automotive braking (M. Briatte [7]). Figure 3a shows its architecture. A very important point here is that in accordance with braking situations, the pin representing the brake pad has a circular stroke and recirculates on the same track with each revolution. This tribometer is the same one used for the experiments of the thesis by T. Devo [2] for a first characterisation of wear and heating of aeronautical structural materials in retracted gear emergency landing situations, which consisted of constant speed brakings wherein a concrete pad was pressed into a rotating disc made of either Al2024 or T700M21.

For the proposed experiments, the idea was to dissipate the kinetic energy of a rotating disc (taking into account the inertia of the whole rotating system, I_p), which represents the runway portion of the tribosystem, by friction with a pin made of a material used to represent the aircraft element in the tribosystem. In order to do this, the disc rotation speed was set to an initial value ω_0 and, once stabilised, the pin was driven into contact with the disc by a loaded spring and slider mechanism, with an applied normal load F_n , until the final speed ω_f is reached at time t_f . This happens either because the pad has been worn out to the maximum permitted length (in this case, 3 mm), or because the set final speed has been reached.

An illustration of expected behavior is presented in Figure 3b. Indeed, a full stop experiment might cause the deposit layer to cool down and get stuck to the pad during the last seconds of braking, which could rip said layer off the disc. This would be problematic for post-mortem analysis, so the contact was decided to stop before reaching zero velocity.

In such a configuration, and unlike the chosen configuration of T. Devo [2], the pad is made of Al2024-T3, and the disc is made of gabbro, a very dark and dense granite with fine grains, which has been chosen to replace concrete as the runway element in the present work because of similar thermal properties but more convenient mechanical

properties and composition, especially regarding practical and safety issues. This material reduces rotating imbalances and is less likely to be torn apart by centrifugal effects.

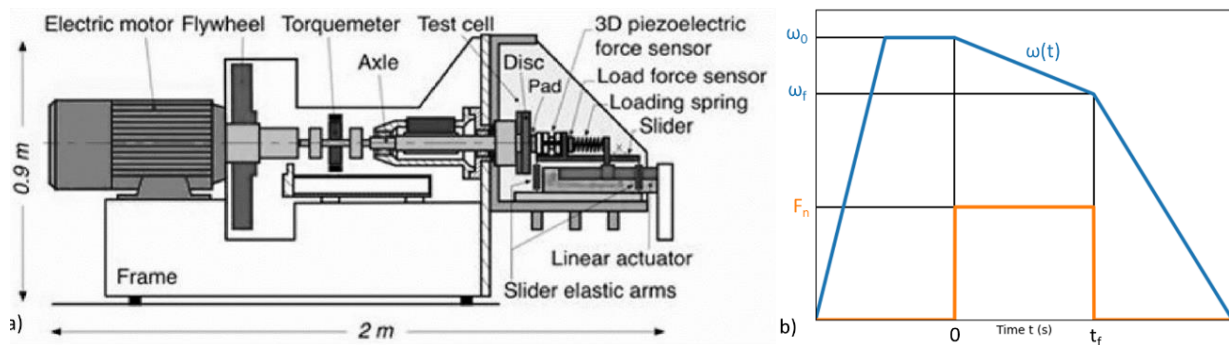


Figure 3: a) Braking tribometer diagram [7], b) Expected braking behavior

A set of distance measurements (laser line, capacitive sensors) taken on the disc's surface granted access to information about the friction track profile, axle bending and disc wobbling, which could be useful for further wear analysis. Figure 4a shows their positioning with relation to the disc and pin, as well as disc geometry. Al2024-T3 pads (20 * 10 * 30 mm³) were machined from a cylindrical bar (25 mm diameter), and mass pad temperature is measured by embedded type k thermocouples. Figure 4 (middle) shows a side perspective view of the positioning of the disc and pad.

In order to have additional information about the third-body's thermomechanical behavior as well as visualising the wear process of the pad, multiple infrared and high-speed visible range cameras were placed around the tribometer which are not discussed in the present paper, as represented in Figure 4 (right)

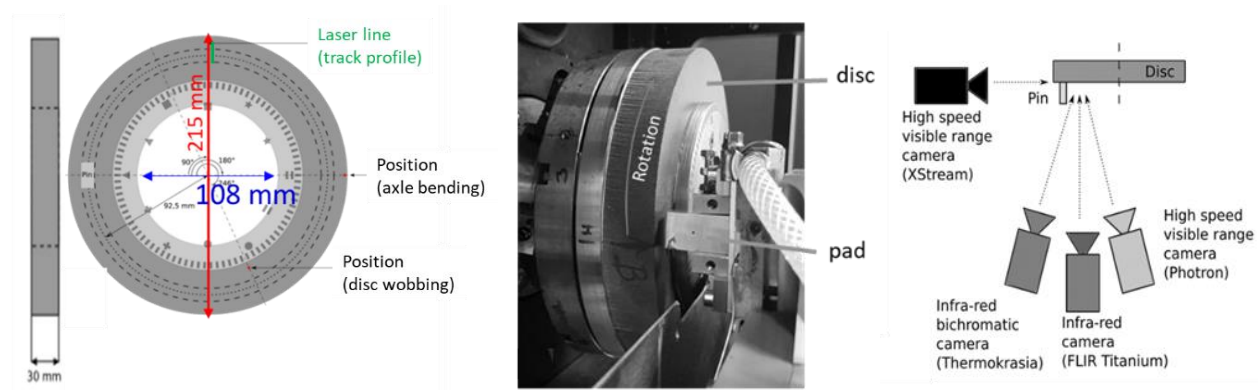


Figure 4: Distance measurement and disc geometry (left), Pad and disc side perspective view (middle), Diagram of camera placement around the pin/disc system, top view (right)

2.2 ONERA Abrasion Test Bench

In parallel to these research works, a new test rig was designed and set up at ONERA, in order to overcome some limitations of the LaMcube tribometer in terms of solicitation representativeness. The rotating disc is placed horizontally, and – very important – the possibility is given to perform spiral strokes, in order not to recirculate on the same track after each revolution, which is more representative of a real emergency landing situation. The new test bench is able to carry at least the same tests in terms of load and friction speed, compared to the LaMcube tribometer. The same aluminium pin geometry described in §2.1 was used for the tests presented in this paper. The Gabbro disks diameter is 40 cm instead of 21,5 cm. Figure 5a shows the general architecture of the ONERA abrasion test bench.

The load is applied onto the pin by a weight carrier, together mounted freely on a vertical slide and driven by a robot controlling the whole set-up (and pin) trajectory in the (X,Y) plane for the spiral move. The pin is placed as close to the triaxial piezoelectric cell force as possible, with an insulating Mika part in between in order to avoid temperature drift of the load measurement during the tests. In addition to force and optical z displacement of the guided mounting

(for wear) measurements, high speed visible and infrared cameras are used to observe the wear and heat phenomenologies during tests.

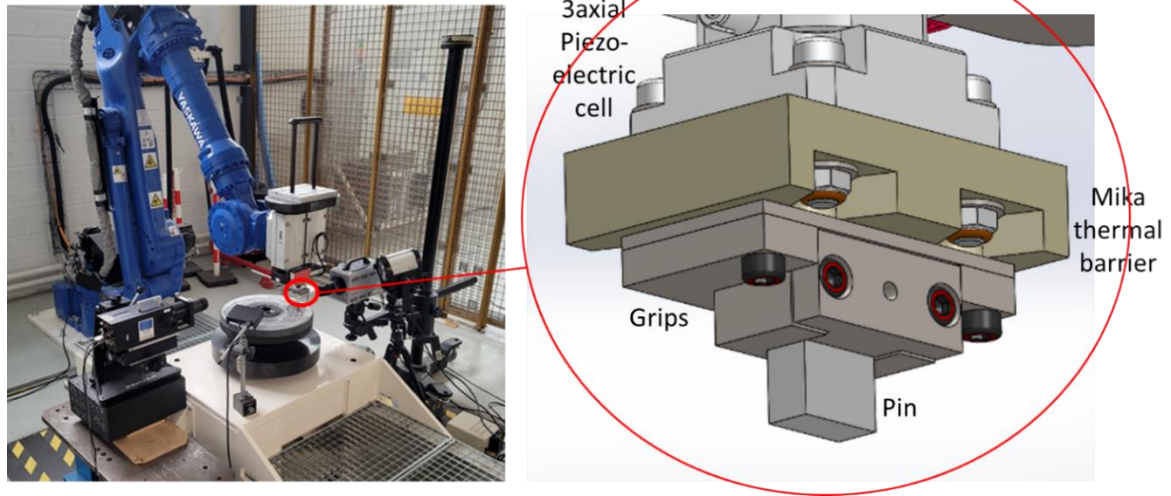


Figure 5: a) ONERA abrasion test bench and instrumentation b) detail of pin mounting on the sliding part

3. Downscaling rules

The principle of downscaling for railway braking is based on a similitude factor k , corresponding to the ratio of the energy dissipated at reduced scale q over the energy dissipated at full-scale Q . In that case, reproduction of the full-scale thermal loading in the pin-on-disc contact relies on maintaining the same similitude factor k for the disc rubbing surfaces, s_d and S_d , as well as for the pad rubbing surfaces, s_p and S_p , respectively at reduced and full scale [1] as shown in Fig. 6.

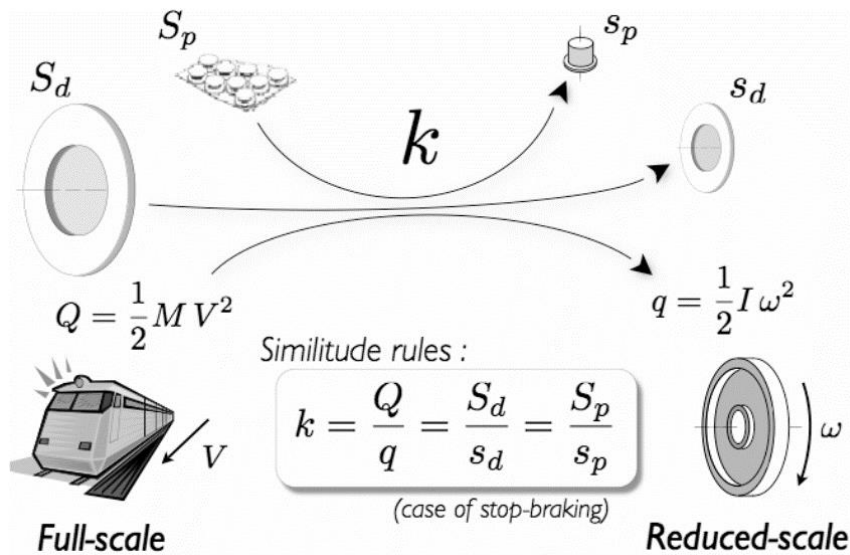


Figure 6: Similitude rules for downscaling railway braking experiments [1]

It is important to note that the similitude is established with regard to comparable quantities. In the emergency landing case, these are the contact surfaces and the dissipated energies of both aircraft-runway and pin-disc systems. Quantities relating to the runway and disc surfaces are not comparable due to their different nature. The rubbed surface on a disc is a closed loop within which the pin circulates over and over again, whereas the runway surface consists of a sum of distance increments multiplied by the width of the apparent contact area. There lies the major limitation of the LaMcube experimental setup, which might have a direct impact on the wear and heat phenomena to be observed (contact with a

cold surface at each distance increment for scale one, and contact with a heated and debris coated surface at each revolution for the LaMcube pin-on-disc system).

There is, then, the possibility for an energetic and a partial geometric similitude. So, let us define a coefficient k , corresponding to the ratio of dissipated energies Q_a and Q_p , for aircraft-runway and pin-on-disc situations respectively, which are assimilated to the value of the maximum kinetic energy, with the hypothesis of total dissipation by friction. This factor k will then be of the same value as ratio of the apparent contact surfaces of the aircraft and the pin, namely S_a and S_p . Since the masses are assumed to be known and unchangeable for the aircraft and the disc (for the calculation of kinetic energies), the energetic similitude will give the necessary rotating speed value for a given value of k .

$$k = \frac{Q_a}{Q_p} = \frac{S_a}{S_p} \quad (1)$$

$$\begin{cases} Q_a = \frac{1}{2} M_a V_a^2 \\ Q_p = \frac{1}{2} I_p \omega_0^2 \\ S_a = \frac{F_{a,n}}{P_a} \\ S_p = h_p w_p = \frac{F_{p,n}}{P_p} \end{cases} \quad (2)$$

In the equations above, M_a , V_a , $F_{a,n}$, P_a , $F_{p,n}$, P_p , h_p and w_p correspond to aircraft mass, aircraft sliding speed, aircraft on runway normal load during sliding, aircraft on runway contact pressure, pad on disc normal load, pad on disc contact pressure, pad height and pad width respectively.

Since the experiment is already known not to be fully similar to scale one, as stated above, the degree of thermal similarity would be determined by analysis of the results, which is not addressed in this document.

4. Experimental Conditions

Let's consider M_a # 28 tons and V_a # 200 km/h = 55 m/s, which are mean values calculated from various business jet aircraft weight and approach speed values publicly available. Q_a # 42 MJ. Contact area is not known for the real scale, so contact pressure is not known either. In other words, S_a and P_a are unknown. A value of P_a has been chosen arbitrarily. The chosen value for aircraft on runway contact pressure is $P_a = P_p = 2,5$ MPa. This value can be modified in order to obtain more or less severe test conditions.

It was possible then to calculate an Assumed Contact Surface ($ACS = S_a$) value for such a pressure, since the mass M_a and so the normal load $F_{a,n}$ are known. Indeed, $P_a = M_a \cdot g / ACS = F_{a,n} / S_a$ (from equation 2), with $g = 9,81$ m/s², the gravitational acceleration. So, $S_a = 0.11$ m². Knowing S_p , pin contact surface, this allows access to a value of k (equation 1): $k = 550$. Knowing Q_a , ($0.5 \cdot M_a \cdot V_a^2$) the k value finally gives access to experimental conditions (rotating speed ω_0 and normal load $F_{p,n}$): considering $I_p = 3.37$ kg·m², from equation 2 the rotational speed would be $\omega_0 = 2053$ rpm. Normal load $F_{p,n}$ is determined directly by consideration of contact pressure P_p (2,5 MPa) and pin surface S_p (2.10⁻⁴ m²): considering equation (2), this would result in $F_{p,n} = 500$ N.

Because of limitations of the ONERA test bench in the qualification phase (for safety of use), it is not possible to run a spiral test at higher speeds than 1200 rpm. It was then decided hereafter to limit the amount of energy to be dissipated down to values that can be tested and compared with the 2 test rigs. But we kept the same load level, friction speed evolution, and considered the same test duration (10s) for the tests to be compared (see Table 1). Let us also remind that we do not want to perform full-stop test cases.

These considerations finally led us to the following test conditions (for information the correspondence to a full scale case). It is interesting to note that, to keep the same speed evolution compared to the LaMcube test case, with a spiral stroke, the rotating speed had to be increased for the ONERA test case. One should also note that to reach the same friction length for both tests, a track overlap is necessary for the ONERA spiral test.

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Table 1. – Test conditions for comparison between the LaMcube tribometer and ONERA abrasion test bench

	Scale one	LaMcube Test	ONERA Test
Mass / Inertia / Friction Coef.	Ma = 28 000 kg	Ip = 3.4 kg·m ²	$\mu = 0.245 (-)$
Stroke Radius	-	90 mm	180-80 mm
Prescribed test Speed	Va = 19-10 m/s	ω_0 # 2000-1100 rpm V # 19 – 10 m/s	$\omega_0 = 1040-1200$ rpm V = 19 – 10 m/s
Contact area	Sa = 0.11 m ²	Sp = 0.2 x 10 ⁻³ m ²	Sp = 0.2 x 10 ⁻³ m ²
Normal load	Fa,n = 274 kN	Fp,n = 500 N	Fp,n = 500 N
Energy theoretically to be dissipated / Friction force external force	3,65 MJ (Ec)	6,65 kJ (3,65 MJ/k=550)	6,65 kJ ($\mu \cdot F_N \cdot d$)
Prescribed/analysed test Duration	-	10 s	10 s

5. Results

The following figures present the comparison of test results of Al2024-T3 pins rubbing onto gabbro discs, on the one hand for a circular stroke with the LaMcube tribometer, and on the other hand for a spiral stroke with the ONERA abrasion test bench. Comparisons were made over normal and tangential forces, friction speed, rubbing length, wear, and friction coefficient.

The difference of friction coefficient in Figure 7 (right) is partly due to the rugosity of the Gabbro discs which was not exactly the same for the two tests. The friction force external work is about 7 kJ and 6.5 kJ for the LaMcube test (at 2s) and the ONERA Test (at 3s) respectively, because of different friction coefficients. Note that circular tests were also done using the ONERA test bench, with the same rugosity compared to the spiral one, which are not presented in the present paper.

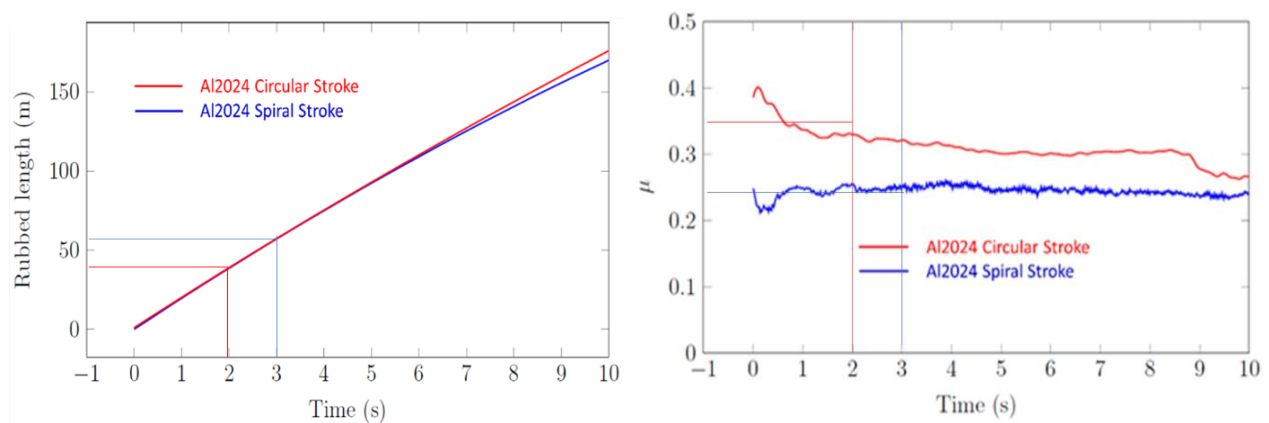


Figure 7: Comparison of LaMcube circular vs ONERA spiral stroke for Al2024 pin on Gabbro disc tests. Rubbed length (left) – Friction coefficient (right)

Figure 8 compares the friction speed (left) and wear value (right) for the LaMcube circular and ONERA spiral tests. After 10s, the LaMcube test reaches 3 mm wear (position of thermocouples) much before the 10 m/s friction speed was reached (target test duration was 30 s), when the ONERA test reaches both a lower speed and wear value.

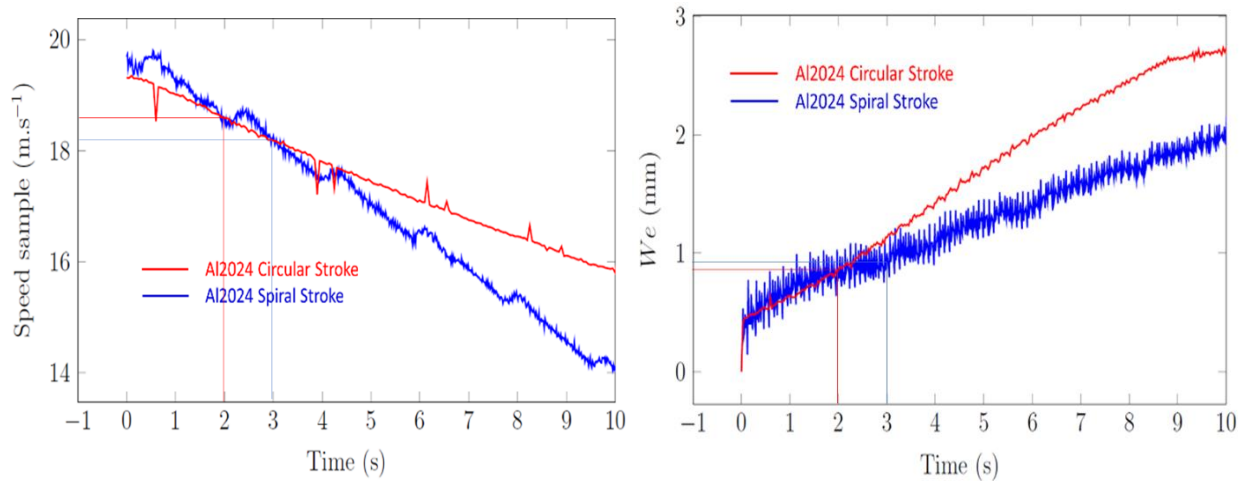


Figure 8: Comparison of LaMcube circular vs ONERA spiral stroke for Al2024 pin on Gabbro disc tests. Friction speed (left) – Wear (right)

The following pictures present the pin and disc post-mortem pictures for the LaMcube and ONERA tests. The surfaces clearly show that the aluminum has melted and deposited on the stone. Chipped deposit on the laMcube tribometer due to melting have been “ripped off” by a cooled contact at the end of the test. For the “non ripped off” aluminium deposit for the spiral test with ONERA test bench, the disc surface is non-uniformly covered, probably due to beating that should be improved in the future.

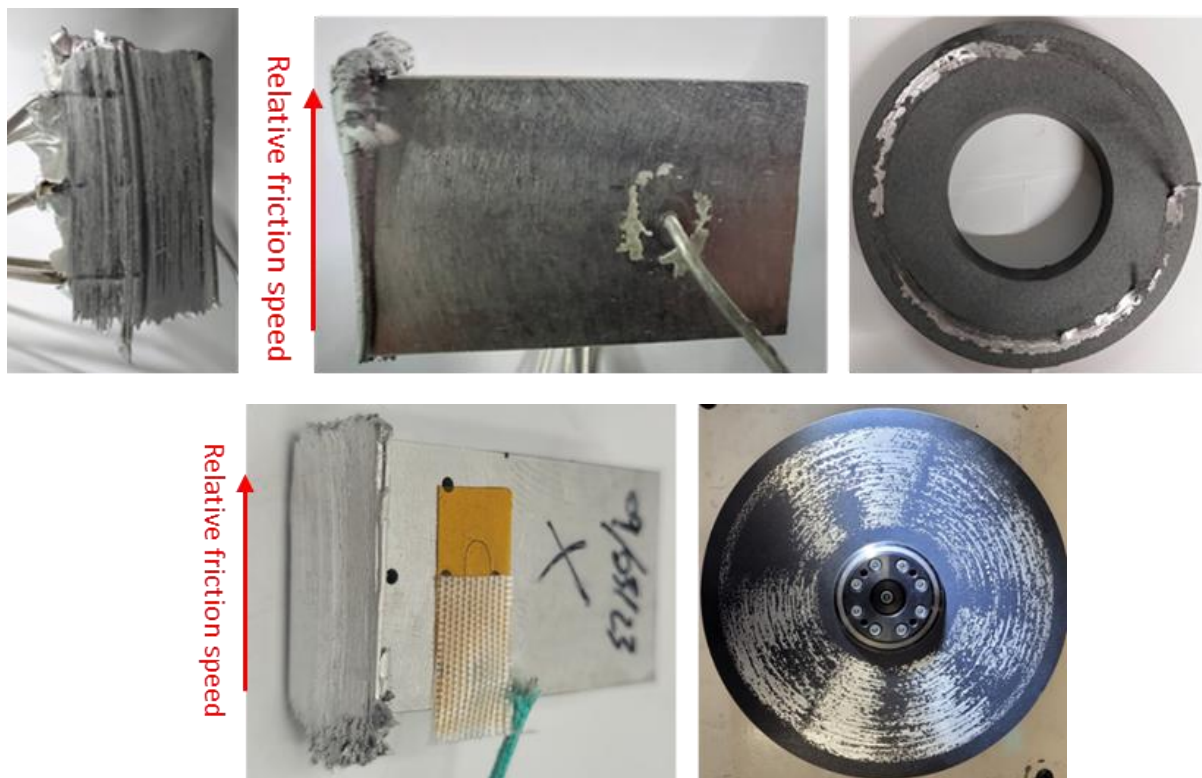


Figure 9: Worn pad and third-body remains on disc surface after test. LaMcube test (top) and ONERA test (bottom)

6. Conclusions

This article looks at the study and characterization of the abrasion response of aeronautical structural materials in emergency landing situations. To this end, two laboratory test methods are used, and their results compared. The first is a tribometer historically developed at LaMcube to study high-energy braking in ground transportation, while the second was recently developed at ONERA to study the problem of emergency landing. To make the comparison

meaningful, quasi-similar tests, although different by construction, are defined and studied, using school materials (aluminum, gabbro) to reduce possible experimental discrepancies. Initial results suggest that the dedicated ONERA test bench is producing results of acceptable quality and usability, compared with the initial results obtained with the LaMcube's academic test bench. Even if the wear rates seem to be fairly close, investigations should be carried out into their correlation with friction mechanisms, in particular the onset of melting. The difference in friction coefficient, even in the melting phase, could be associated with a difference in surface condition or contact dynamics, etc. Last, areas for improvement of the ONERA test bench have been identified, thanks to the comparison with the LaMcube one.

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