



**HAL**  
open science

# Effect of temperature on wear mechanisms of an aluminium - based abrasable coating for aircraft engines after a dynamic interaction with a Ti6Al4V blade

Baptiste Martinet, Andrea Cappella, Sylvain Philippon, Claudio Montebello

## ► To cite this version:

Baptiste Martinet, Andrea Cappella, Sylvain Philippon, Claudio Montebello. Effect of temperature on wear mechanisms of an aluminium - based abrasable coating for aircraft engines after a dynamic interaction with a Ti6Al4V blade. *Wear*, 2020, 446-447, pp.203202. 10.1016/j.wear.2020.203202 . hal-03331824

**HAL Id: hal-03331824**

<https://hal.univ-lorraine.fr/hal-03331824v1>

Submitted on 7 Mar 2022

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

# EFFECT OF TEMPERATURE ON WEAR MECHANISMS OF AN ALUMINIUM - BASED ABRADABLE COATING FOR AIRCRAFT ENGINES AFTER A DYNAMIC INTERACTION WITH A Ti6Al4V BLADE

*Baptiste Martinet<sup>1,2</sup>, Andrea Cappella<sup>1</sup>, Sylvain Philippon<sup>1</sup> and Claudio Montebello<sup>2</sup>*

1. Université de Lorraine, CNRS, Arts et Métiers ParisTech, LEM3, F-57000 Metz, France
2. Safran Aircraft Engines, Safran Group, Réau, Rond-Point René Ravaud, 77551 Moissy-Cramayel, France

## **Abstract**

Small blade-casing clearances in aircraft engines reduce fuel consumption but increase the risks of contact interactions due to working conditions. These interactions cannot be avoided but their effects can be reduced by using abrasible linings thermally sprayed inside the casings. To investigate these interactions and the mechanisms of wear deriving from them, a specific ballistic bench has been developed in order to perform representative tests of the low-pressure compressor environment (up to 270 °C) and enabling only one interaction between an aluminum-based abrasible sample and a Ti6Al4V tool. Contact forces and incursion depth were measured for a nominal depth of cut of 100 μm and at a mean velocity of 125 m/s. It has been shown that the temperature affects mainly the abrasible behavior under these high-speed interactions. In addition, the wear resulting at high temperature is driven by a process that can be very different from the low temperature case.

## **Introduction**

The efficiency increase of aircraft engines can be reached by reduction of the leakage flows between the different stages of a turbojet engine [1]. A closed gap between the rotating and stationary parts

is one well-known technical solution but might lead to undesirable contacts during the operating conditions. So, an abradable material, playing a sacrificial role, coats the inner of the casing [2] and avoids or minimises the consequences of these eventual contacts on the integrity of the blades.

For the aero-engine low-pressure compressor seals, an AlSi-polyester material is generally used [3]. Originally in powder form the lining is obtained by *APS (Atmospheric plasma spraying)* process as an heterogeneous and porous material with a microstructure satisfying a good compromise between the erosion resistance [4] and abradability criteria [5]. Most of the studies published in the literature on this material concern the experimental characterizations of these properties by using some specific sub-scale test rigs. For example, the abradability tests are generally carried out by using a simplified blade rigidly fixed on a rotating disk acting against a moving abradable sample. This approach is necessary because a test performed inside a real turbojet engine would be too expensive and difficult to carry out due to the difficulty to access the blade/casing clearance in real operating conditions. In addition, as a consequence of the multiple contacts between a set of real blades and the casing, the vibrational behaviour of the bladed disc could complicate the interaction so much that the understanding and characterization of the process and the resulting wear could be very difficult. By using a rotating test rig, the conditions of interaction between the blade-tip and the abradable specimen are simplified and could be varied over a wide range of values, thus facilitating a parametric identification of the interaction. These parameters can be used later to simulate the contact interaction inside a turbojet engine.

For the rotating test rigs [6–10], the typical values for the tangential and incursion speeds were respectively a few tens of m/s to 500 m/s and 0.2  $\mu\text{m/s}$  to 2000  $\mu\text{m/s}$ . In a few cases the abradable was heated at high temperature to obtain a temperature field representative of the in-service conditions [10–12]. The aim of these investigations were mainly the study of the wear mechanisms by the analysis of the worn surface as related to the coating weight loss and the change in the blade length. The measurement of the worn profile of the abradable material and the measurement of the

force during the blade/abradable interaction has been proposed as mean to establish a relationship between consumed energy during the interaction process and the wear of the abradable. The force measurement was performed by using a piezoelectric based sensor technology [11] or strain gauges glued on the blade [13].

With a reverse experimental bench where a flexible blade impacts an AISi abradable coated cylinder, the normal force (in the blade displacement direction) and the blade incursion were accurately estimated from indirect measurements in [14]. Although the interaction was analysed in detail to identify the mechanisms of incursion accommodation, the study was limited only to 95 m/s and 280 °C [19].

A different experimental approach has been proposed to perform dynamic characterization of a similar abradable material [15-17]. These works were based on a specific interaction set-up adapted on a ballistic bench allowed to measure the high-speed interaction force components between a rigid tool where the geometry of its cutting edge is representative to the blade tip geometry and an abradable specimen mounted on a projectile. One of the main advantages of this experimental configuration is the possibility to obtain an unique interaction at a near-constant depth of cut (DoC). With this technique the force components and the wear along the rubbed surface can be correlated at any time. In the case of an orthogonal interaction where the tool edge is perpendicular to the motion direction a good agreement between the force and the wear profile of the coating is observed for a large range of interaction velocities (from 100 m/s to 250 m/s). However, these investigations were carried out only at room temperature.

In this paper, the experimental results from tests performed from room temperature up to 270 °C are reported. These temperatures are representative of the real operating conditions experienced by the abradable coating inside the low-pressure compressor-stage of the engine. The aim of the investigation is to determine the effects of temperature on the behaviour of the interaction between an AISi-PE abradable material during the interaction with and a titanium tool for a 100 µm average

incursion at 125 m/s. The measured forces and profile variation of the tested abradable samples revealed that different wear mechanisms can be defined and that the force components are reduced if the interaction is performed with a heated abradable sample.

### ***Materials and Methods***

The ballistic bench used in this work and the specific signal post-processing for the measured forces have been presented in detail in [17]. For this study, the heating of the abradable material layer was realised by conduction directly in the launch tube of the gas gun [18]. Before launching the projectile, the abradable coating has been heated at the set-point temperature. To do this, the AISi-PE abradable was coated on an aluminium substrate rigidly fixed on the projectile and a long hole allowing to integrate a FIREROD cartridge heating system (Watlow) was machined in this aluminium substrate. The cartridge (1/8" diameter – 120 mm length) was made up of a nickel-chromium 200 watts resistance with a built-in K-type thermocouple, located at the tip of this setup. By means of a regulator device (Omicron ROXM-T-1-SO2) the cartridge temperature was accurately controlled and reached more than 300 °C. Nevertheless, a monochromatic high speed pyrometer (Kleiber Infrared KGA 740-LO, 200 °C – 1000 °C temperature range and 6 μs response time) located 31 mm ahead the cutting tool was used to measure the final temperature profile of the top surface of the moving abradable sample just before the tool incursion. **Figure 1** shows the simplified experimental setup with the layout of the main parts and the local geometry of the grade 5 titanium tool edge. The values of the edge radius  $r$  and the sliding length  $e$  are confidential. Note however that the cutting depth of cut is much less than the edge radius.

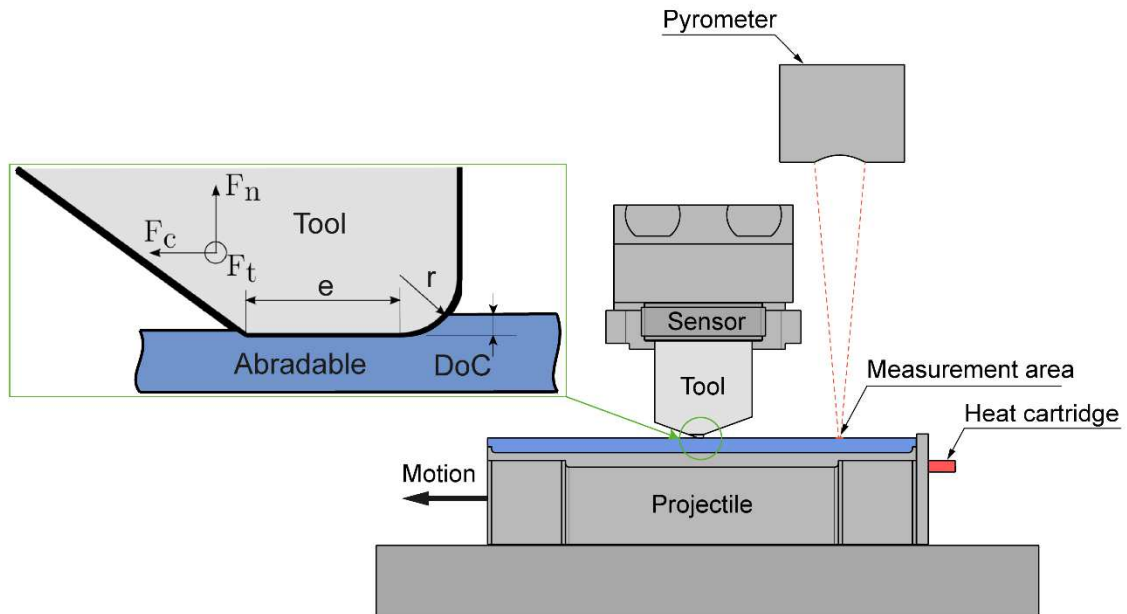


Figure 1 – Minimal cutaway of the experimental device for temperature and forces measurements at high speed. The picture box shows the local geometry of the cutting tool.

The experimental protocol provides for the bench to be under primary vacuum before launching the projectile in order to reduce perturbations at the force detector due to the gas pressure wave and to eliminate friction losses with the air. Nitrogen gas expansion was used to push the projectile up to its interaction speed toward the fixed tool and reducing at the same time the oxidation of the heated abradable sample. The titanium tool is assembled with a 3-axis piezoelectric force sensor (PCB 260A02) by screw and takes place on the interaction device support (see Figure 1). Signals recorded at 1 Msample/s by means of an acquisition system (Spectrum Ethernet Digitizernetbox) were then post-treated to obtain the forces generated during the interaction into the normal, cutting and transverse directions [15,17,20]. In this paper, the cutting force is assimilated to a global tangential force that include friction force, shear force and in general all forces induced along the interaction direction.

The measuring field diameter of the pyrometer has been fixed to about 2 mm for all tests to provide the smallest focal distance and allows an easy implantation of the optical head in the confined environment of the experimental device. **Figure 2** shows the temperature response for a test carried out for calibration without the cutting tool at a set-up temperature of 275 °C. **In order to analyse**

data only related to the established interaction (*i.e.* the plateau), the first and last 250  $\mu$ s of the thermogram duration were disregarded. It is worth noting that apart the expected effects at the sample ends the cartridge heated the sample in an inhomogeneous manner resulting in a two lobes thermal profile with a temperature varying between 270 °C and 285 °C. This behaviour was inherent to the cartridge design and all of the tests presented a similar profile.

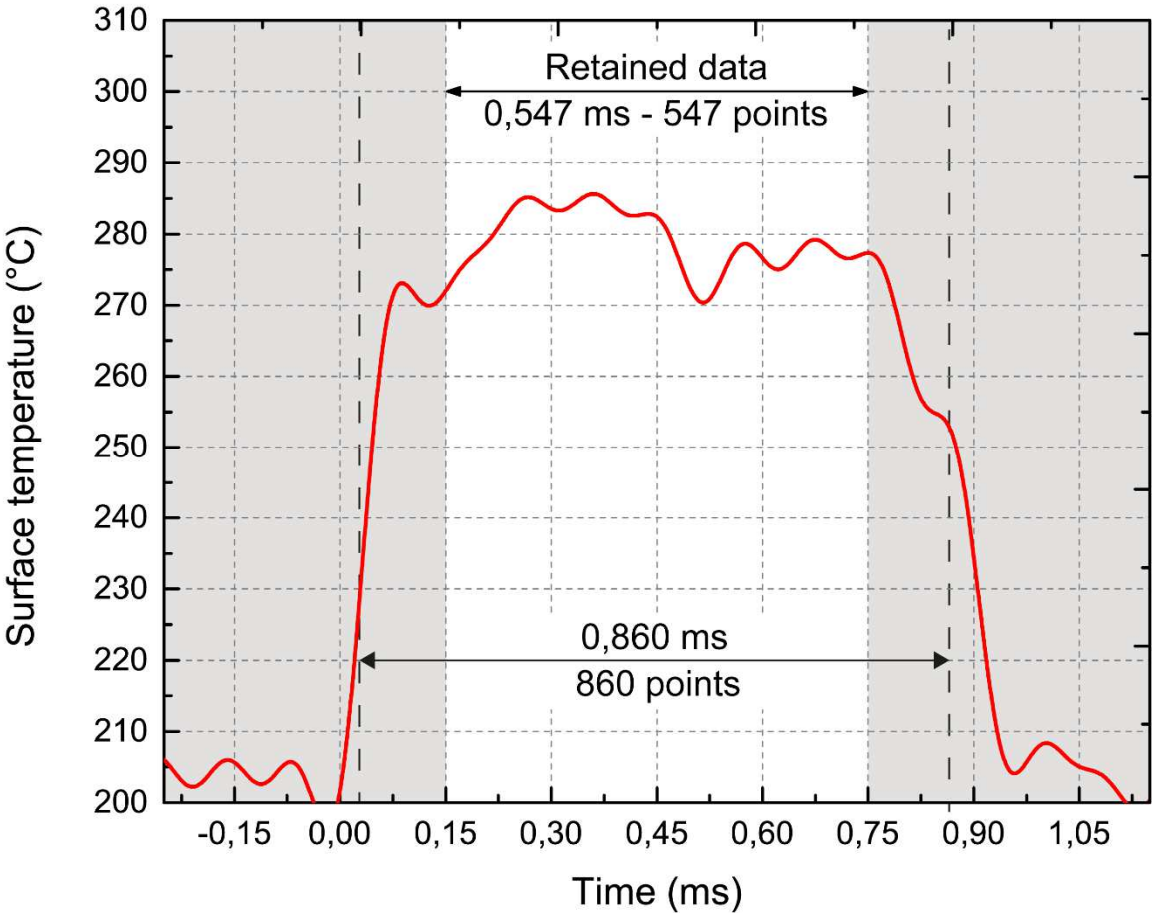


Figure 2 – Surface temperature measured by the pyrometer at 31 mm before the tool tip for a sample heated at the set-point temperature of 275 °C and propelled at 127 m/s.

The sample height profile was measured *ex-situ* before and after the interaction by using an inductive linear voltage differential transformer sensor (AX/1/S LVDT model from Solartron). The measured initial profile minus the measured final profile was defined as the wear profile and represents an equivalent value of the removed material and/or the densification due to the interaction. The wear profiles were obtained by measurement at room temperature for all tests and could be different from the real wear profile generated during the interactions. Projectile dilatations

have not been quantified and it is considered that the wear profile measured *ex-situ* corresponds to the wear generated during the interaction.

To study the temperature effect on the dynamic contact between the AlSi-PE abradable and the titanium tool four tests at room temperature (RT), 125 °C, 175 °C and 270 °C were carried out for one interaction velocity (125 m/s speed average). The targeted temperatures were chosen after the results of a dilatometer measurement performed on a NETZSCH DIL-402 with an abradable sample of 3,29 mm x 3,19 mm x 29,55 mm size. The sample was maintained at  $3 \times 10^{-5}$  bars during 24 hours for degassing. The heating cycle have been performed in ambient air from 20 °C to 300 °C at +1 °C/min and have been stabilized at 300 °C for 1 minute. The cooling have been controlled from 300 °C down to 20 °C with a rate of -1 °C/min. The retained temperature range was chosen taking into consideration the properties of the abradable constituent materials and the in-service temperature in the low pressure compressor. The temperatures for the four tests have been chosen on the base of the AlSi-PE thermal expansion behaviour as shown by the dilatometry results reported on the **Figure 3**. Between 125 °C and 180 °C a different slope was measured indicating the beginning and the ending of an irreversible material modification.

As a consequence of the complexity of the experimental setup, only one test per temperature has been performed. Nevertheless, the good repeatability of the results produced with this bench has been already proved by Vincent *et al.* in [17] by using the same couple of blade/abradable materials and a similar experimental configuration. Moreover, a fifth test performed at 150 m/s and at room temperature was realised in order to show the low sensitivity of the measured forces to regard small variations of the speed of the projectile.

## **Results**

**Table 1** resumes the measured initial speed and temperature for the five tests carried out on the ballistic bench. The temperature value was obtained as the arithmetic mean of the central part of the measured thermograms.



Test.	Speed (m/s)	Mean temperature (°C)
A	129	RT(1)
B	123	125
C	120	175
D	124	270
E	150	RT(2)

Table 1 – Summary of the performed tests, with speeds and temperatures values

These temperatures have been chosen on the base of the AlSi-PE thermal expansion behaviour as shown by the dilatometry results reported on the **Figure 3**. Between 125 °C and 180 °C a different slope was measured indicating the beginning and the ending of an irreversible material modification.

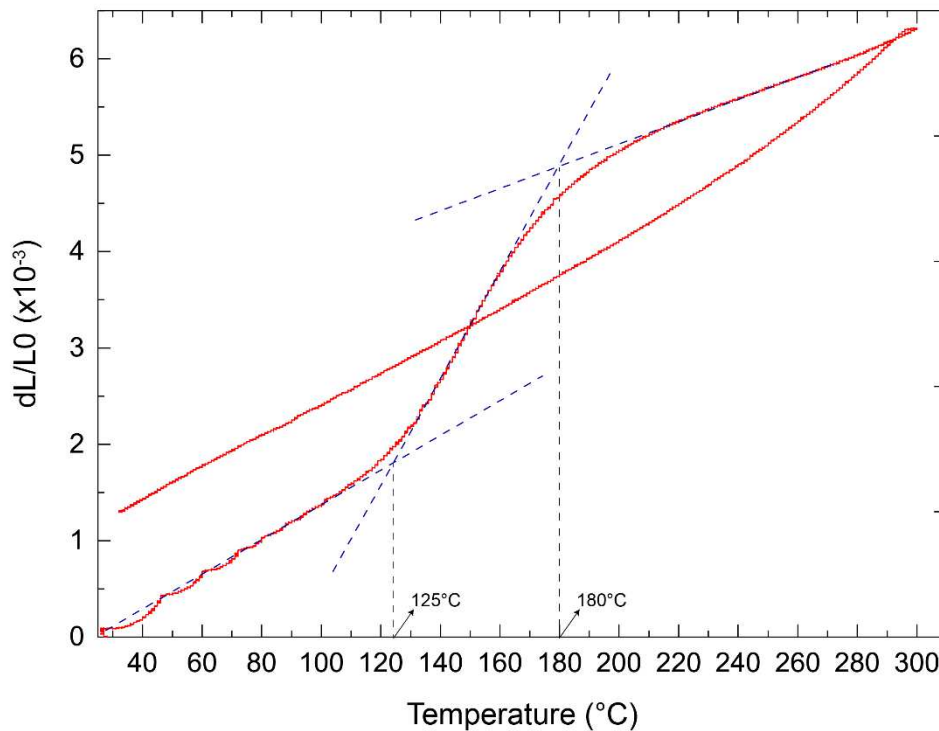
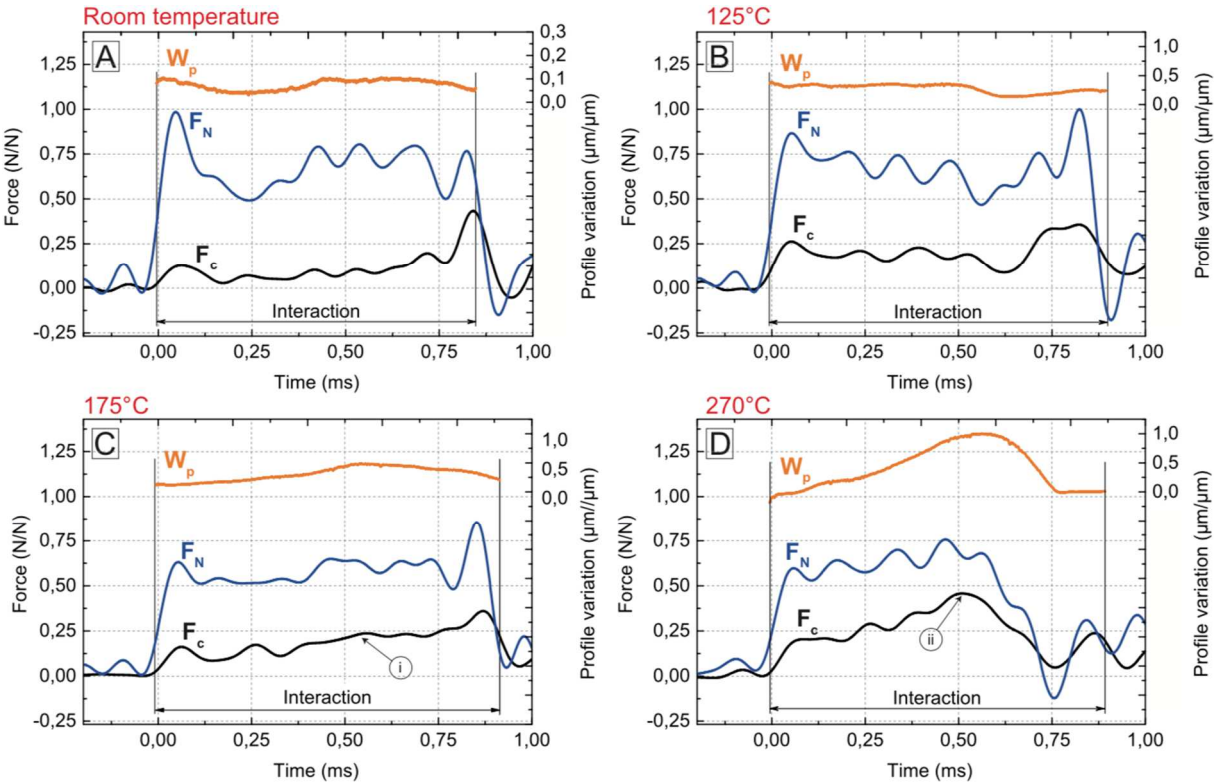


Figure 3 – Dilatometry results obtained with a 3,29 mm x 3,19 mm x 29,55 mm dimensions sample up to 300°C at +1°C/min then stabilization for 1 minute at 300°C then cooling at -1°C/min down to the room temperature

The measured normal and cutting forces ( $F_N$  and  $F_C$ ) and the wear profile ( $w_p$ ) for tests A, B, C and D are reported in **Figure 4**. The results are normalised for confidentiality reasons. Analysing the slope of the signals, the room temperature test, RT1 (**Figure 4-A**) shows a decreasing cutting and normal

forces at the very beginning of the interaction then a smooth increasing force during all the rest of the incursion. Forces are in good agreement with the wear profile. **Figure 4-B** shows for the test performed at 125 °C a constant wear profile as well as a constant cutting force and a slightly decreasing normal force component. For the 175 °C test shown in **Figure 4-C**, the signal evolution can be described as composed by two parts. **At the beginning of the interaction, the wear profile increases more quickly than in the former two cases (RT1 and 125 °C) and this until the point labelled (i) on the figure.** Both the cutting and normal components of the force increase too.



*Figure 4 – Cutting force ( $F_c$ ), normal force ( $F_N$ ) and post-mortem wear profile ( $w_p$ ) measured for tests at room temperature (RT), 125°C, 175°C and 270°C at 125 m/s mean speed*

After this point, the wear profile decreases but the normal force signal remains constant. **On the contrary, the cutting component of the force increases continue to increase. but on the second part of the test the signal oscillations are damped regarding to the first part (label (i) on the figure).** For the test performed at 270 °C and reported in **Figure 4-D**, both the force and the wear profile are found to increase rapidly to the same maximum force value measured among all the tests (labelled

(ii) on the figure), but after this point the wear profile decreases rapidly to zero incursion. The force shows the same fast decrease ending with the typical oscillations of a free cantilever (*i.e.* the tool is no more in contact with the abradable). The last part of the abradable surface did not show wear confirming that the tool was not in contact at all with the surface.

### ***Discussion***

The AISi metallic matrix provides to the coating its mechanical strength and its corrosion and oxidation resistance. The polyester phase controls porosities rate and erosion behaviour of the material up to 350°C. Over the spanned temperature range, the forces as well as the wear profile were found to be of same magnitude between all the tests. Only for the 270 °C test (case D) the maximum wear profile were found to be two times higher than the same quantities at lower temperatures. At this high temperature, the polyester contained into the abradable facilitating the diving of the tool deeper inside the abradable coating. This hypothesis is supported by the fact that looking at the magnitude of the normal component of the force the abradable do not show much more strengths to the tool incursion than the tests at lower temperatures. As shown by Mandard et al. [14], the accommodation of the incursion seems to be related to different mechanisms among which the coating compaction by porosities closure. Nevertheless, for an increasing temperature the tool has been found to penetrate deeper inside the abradable in opposition to the value of the normal force that remain the same for all the tests. Considering that the mean concentration of porosities is not influenced by the temperature of the abradable, in order to have the same maximum force value for all the measured normal components the abradable must necessarily be less rigid as the temperature rises. This behaviour could be considered as the consequence of the thermal polyester softening. A more softened abradable (as the combination of softened AISi matrix with softened/melted polyester) could explain the evolution of the cutting force considering the effect that this thermal softening could have on the shear process of the abradable during the incursion of the tool. At 175 °C the cutting component of the force continues to increase in

opposition to both the normal component that remains constant and to the wear profile that decreases during this phase of the interaction. ~~The dampening of the oscillations could be also explained taking into account the effect of thermal softening.~~ For the test at 270 °C this behaviour of the cutting force is even most explicit by increasing faster in magnitude than the normal component.

The authors assume that, the *post-mortem* wear profile variation has been determined by porosities closure, plastic deformation, material pull-out and particle rupture. The nominal DoC was set at 100 µm for all the tests, but due to the thermal dilatations and to the projectile/tube clearance, the real DoC reached for the high temperature tests was higher than this value. These differences between the nominal and the real DoC make the analysis of the resulting forces as a function of temperature not so straightforward. However, the linear correlation between the tool incursion and the force suggest that using the ratio between the force and the DoC it is possible to highlight the differences between the results obtained at different temperature. This ratio has been defined as the specific force. ~~because at RT, 125 °C and 175 °C, 270 °C it is related to the sensitivity of the force per micrometer of incursion.~~ Conversely, at higher temperatures, the intrinsic state of the AlSi-polyester material makes its interpretation more complex. Figure 5 and 6 show the evolution of the specific cutting force and the specific normal force respectively as a function of time. ~~These cutting and normal specific forces have shown a similar trend with values at room temperature that are higher than those related to the 125 °C, 175 °C and 270 °C. In the same manner, the cutting and normal specific forces related to the high temperature tests have shown a smoother linear evolution regarding to the room temperature tests. The increasing of the specific forces at the end of the 125 °C curves could be related to a modification of the polyester induced at this speed and temperature. At 270 °C the decreasing may be explained by a thermal softening of the abradable materials and by the heat accumulation at the tip of the tool. The diving of the tool throughout the interaction and especially at the end of the interaction was more important than that of the lower temperature levels. Thus, for a comparable force level, the specific force at high temperature decreases more quickly.~~

The specific normal force showed a low sensibility to the temperature compared to the specific cutting force and at 125 °C, 175 °C and 270 °C, all specific normal forces are superimposed. Anyway, at room temperature the normal force component showed its higher value and this for a low incursion resulting in a higher value for the specific normal force.

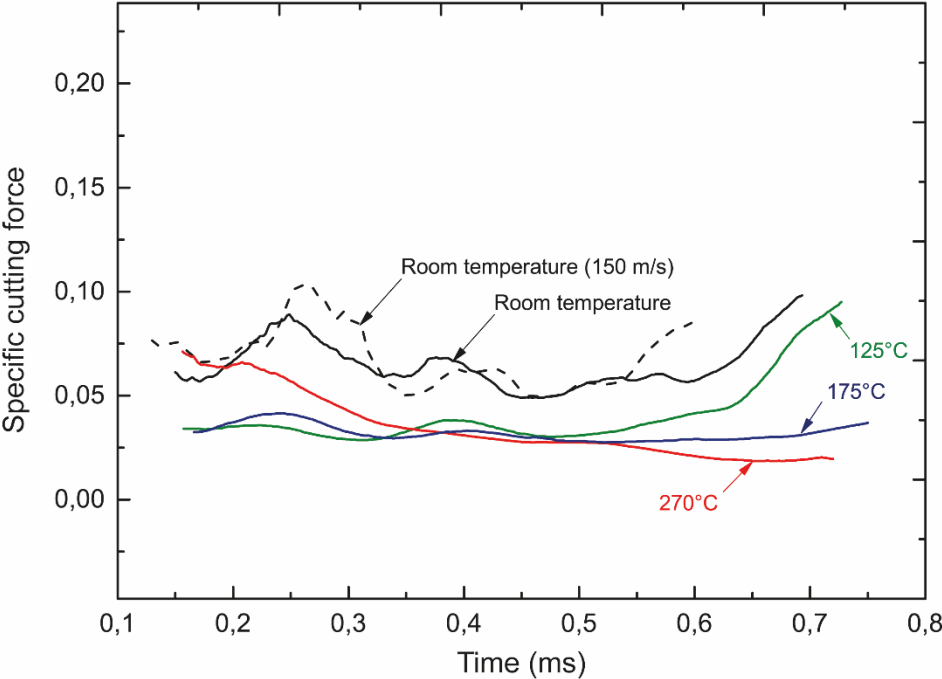


Figure 5 - Evolution of the specific cutting force for tests performed at room temperature (RT1 and RT2), 125°C, 175°C and 270°C

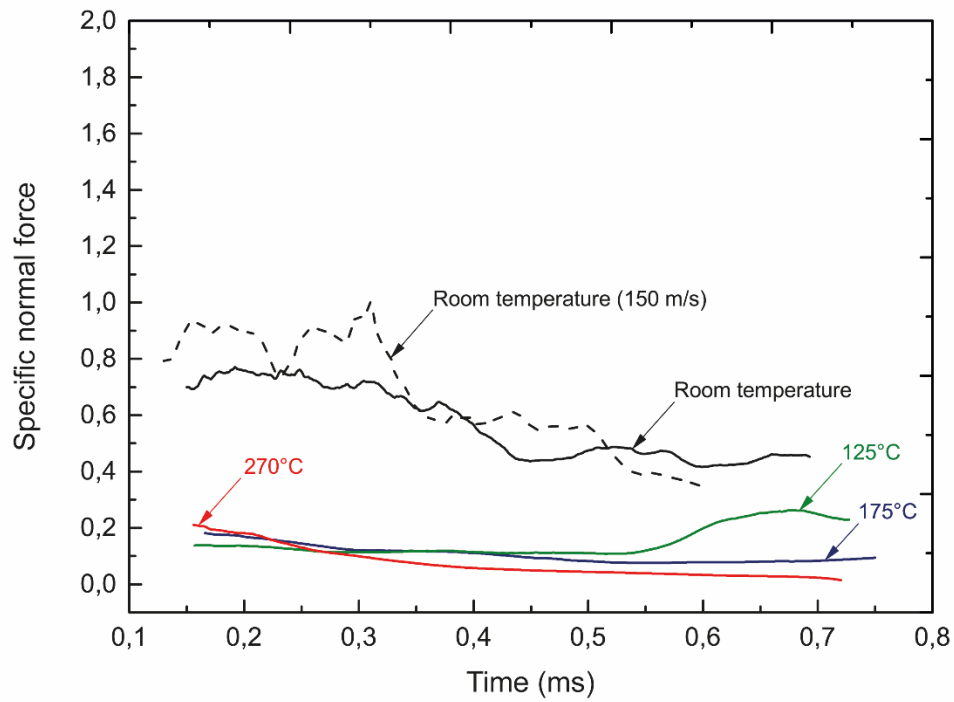


Figure 6 - Evolution of the specific normal force for tests performed at room temperature (RT1 and RT2), 125°C, 175°C and 270°C

In order to analyse the relation between wear profile and temperature, macroscopic pictures of the surface samples have been acquired for two regions of interest and for the test related to the lower and the higher temperature (**Figure 7**).

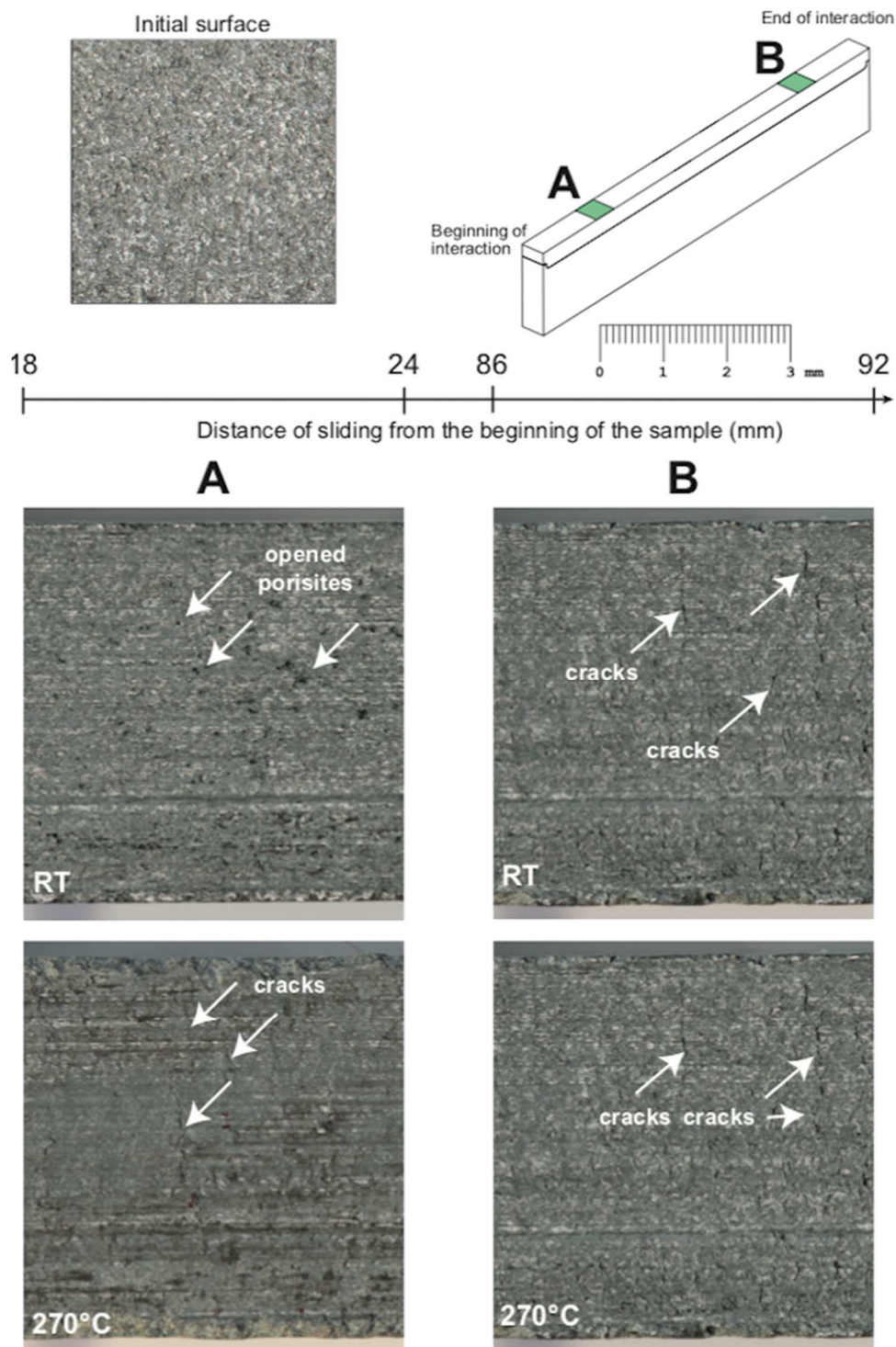


Figure 7 – Macroscopic views of sample surfaces in 2 regions of interest (RT and 270 °C).. Arrows point opened porosities and transverse cracks. The initial surface is also shown as reference.

Each region of interest is a 6 mm by 6 mm square. ~~Areas A and D represent respectively the beginning and the end of the interaction part retained for the specific forces calculation and are~~

~~located at 18 mm and 86 mm from the beginning of the sample. Area B is located at 44 mm from the beginning and represents a transient region where DoC is constant or increasing. Area C is located at 60 mm from the beginning of the sample and represents the region where DoC reaches its maximal value. Areas A and B represent respectively the beginning and the end of the interaction part retained for the specific forces calculation and are located at 18 mm and 86 mm from the beginning of the sample.~~

At room temperature, the sample surface in the regions A, ~~B and C~~ shows mainly grooving (~~yellow lines~~) and apparent opened porosities (~~white arrows~~) as generated by a clean release of abradable particles. At the end of the interaction (~~area B~~), some cracks oriented in the transverse direction with respect to the interaction motion are visible. (~~red lines~~). From the mechanical point of view, Guler et al. [21] give a possible explanation of cracks generation as a high tensile stress level occurring at the back of contact and which may drive the wear behavior of material. From the thermal point of view, friction between the tool and the abradable sample could have generated enough heat to initiate a steep thermal gradient at the surface and the followed rapid cooling that explains the observed cracks.

~~At 125 °C, cracks are present all along the sample surface in addition with grooving. However, in the area C where maximal value of the DoC is reached cracks seems to be covered by a third body that is generated during the contact interaction. At 175 °C, only a small amount of cracks is present in comparison to the sample surface at 125 °C and could be explained by the same process. For the higher temperature test (i.e. 270 °C) the beginning of the contact shows cracks initiation that grow up to a maximum in the area C (area where the DoC almost reaches its maximum value). Conversely, for the 270 °C the beginning of the contact already shows cracks initiation that grow up to a maximum in the region just before the area B (area where the DoC almost reaches its maximum value). However, cracks in the area B are less visible in comparison to the other test. When temperature becomes enough high, polyester phase becomes soft and slimy. This state of the~~



polyester phase avoids a clean cutting of the metallic particles. In this case, friction temperatures have to be significantly higher due to friction process and polyester phase have to be spread at the top and at the back of the tool. This assumption is supported by the ~~dynamic cutting coefficient~~ ~~dynamic interaction coefficient~~ that is the ratio between the cutting and the normal forces  $F_c/F_n$ . Figure 8 shows that the higher the temperature, the higher the ~~coefficient of dynamic cutting~~ ~~dynamic interaction coefficient~~. This behavior is mainly due to that of the softened AISi and polyester that avoid a plastic deformation of the metallic matrix. Consequently, brittle cutting is not the main mechanism that is activated at 125 °C, 175 °C and 270 °C. Due to thermal softening and glued nature of the PE beyond 125 °C, polyester entrapped in the metallic matrix increases the plastic deformation energy necessary to create adiabatic shearing in the material.

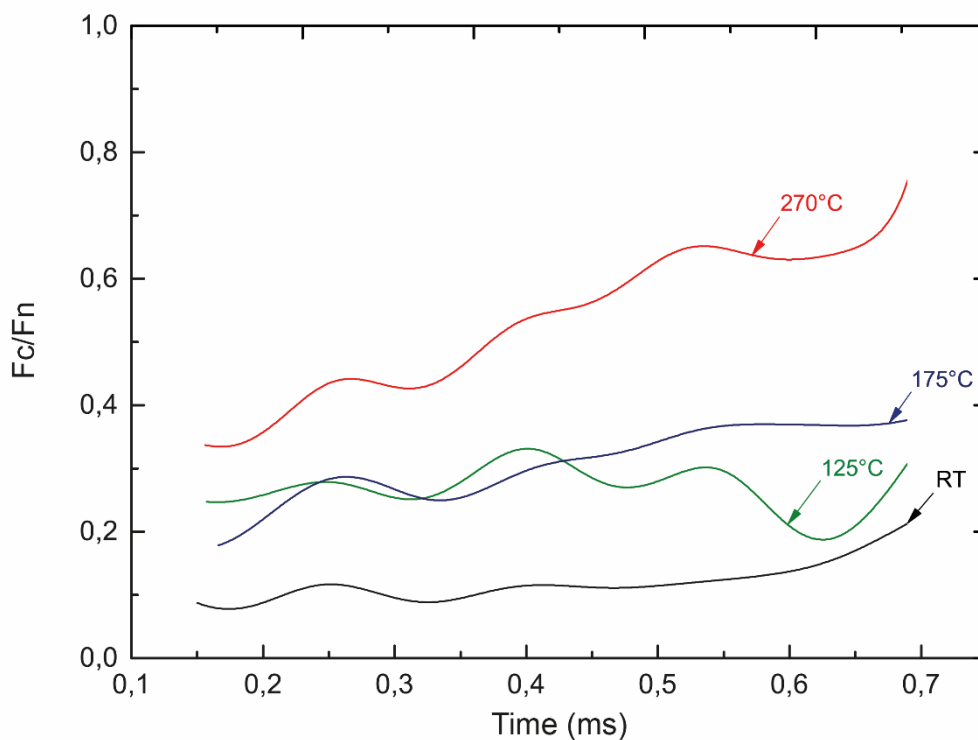


Figure 8 – ~~Dynamic friction coefficient~~ ~~Dynamic interaction coefficient~~ ( $F_c/F_n$ ) for RT, 125°C, 175°C and 270°C tests

## Conclusion

Four thermally sprayed AISi-PE abrasible material samples have been tested with a specific ballistic bench that allows high-speed interaction (up to 125 m/s speed average) between an heated

abradable sample and a Ti6Al4V tool (that simulates a blade tip). The cutting and normal forces evolution during the interaction have been accurately measured. A *post-mortem* wear measurement gave the profile variation of the sample that traduces the material removal during the test. The forces have been found to be in good agreement with the profile variation evolution. As a consequence of a not constant incursion depth between the different tests, a specific force criterion has been proposed to discuss the influence of the temperature on the results. The higher temperature test has shown a significant influence of the temperature on the thermomechanical material behavior. As shown by the surface analysis, different wear mechanisms have been activated for different abradable temperatures and different friction lengths. Only the grooving mechanism has been activated at any temperature.

In conclusion, at room temperature, clean cut gives to the abradable a smooth surface with opened porosities. At high temperature, a phase transition of the material led to other wear mechanisms (friction, cracks, grooving) resulting in a poor surface finish and a high ~~dynamic coefficient of friction~~ dynamic interaction coefficient. Polyester plays then a major role in the thermomechanical behavior of AISi-PE, justifying the need to characterize this material in conditions close to those of its real operating conditions.

### ***Acknowledgement***

The authors gratefully acknowledge Safran Aircraft Engines for their financial and technical support.

## References

- [1] R.C. Bill, L.P. Ludwig, Wear of seal materials used in aircraft propulsion systems, *Wear*. 59 (1980) 165–189. doi:10.1016/0043-1648(80)90277-X.
- [2] R.C. Hendricks, B.M. Steinetz, M.J. Braun, Turbomachine Sealing and Secondary Flows. Part 1 - Review of Sealing Performance, Customer, Engine Designer, and Research Issues, NASA, 2004.
- [3] R.K. Schmid, New high temperature abrasives for gas turbines, theses, Diss. Techn. Wiss. ETH Zürich, Nr. 12223, 1997. Ref.: Ludwig J. Gauckler ; Korref.: Eduard H. Freitag, 1997. [https://e-collection.library.ethz.ch/view/eth:40776?q=\(keywords\\_en:GAS%20TURBINES\)](https://e-collection.library.ethz.ch/view/eth:40776?q=(keywords_en:GAS%20TURBINES)) (accessed May 25, 2016).
- [4] Y. Maozhong, H. Baiyun, H. Jiawen, Erosion wear behaviour and model of abrasible seal coating, *Wear*. 252 (2002) 9–15. doi:10.1016/S0043-1648(01)00681-0.
- [5] X. Ma, A. Matthews, Evaluation of abrasible seal coating mechanical properties, *Wear*. 267 (2009) 1501–1510. doi:10.1016/j.wear.2009.03.044.
- [6] M. Dorfman, U. Erning, J. Mallon, Gas Turbines Use “Abradable” Coatings for Clearance-Control Seals, *Sealing Technology*. 2002 (2002) 7–8. doi:10.1016/S1350-4789(02)80002-2.
- [7] A. Dadouche, M.J. Conlon, W. Dmochowski, B. Liko, J.-P. Bedard, Experimental Evaluation of Abradable Seal Performance at High Temperature, Volume 5: Structures and Dynamics, Parts A and B. (2008) 143–150. doi:10.1115/GT2008-51228.
- [8] J. Stringer, M.B. Marshall, High speed wear testing of an abrasible coating, *Wear*. 294–295 (2012) 257–263. doi:10.1016/j.wear.2012.07.009.
- [9] N. Fois, M. Watson, J. Stringer, M. Marshall, An investigation of the relationship between wear and contact force for abrasible materials, *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*. 229 (2015) 136–150. doi:10.1177/1350650114545139.
- [10] H. Xuan, N. Zhang, Y. Hu, J. Shen, H. Weirong, Evaluation of an AlSi-polyester abrasible seal coating performance using high-temperature and high-velocity abrasion tests, *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*. 0 (2015) 1–10. doi:10.1177/1350650115619150.
- [11] S. Gao, W. Xue, D. Duan, S. Li, Tribological behaviors of turbofan seal couples from friction heat perspective under high-speed rubbing condition, *Friction*. 4 (2016) 176–190. doi:10.1007/s40544-016-0114-x.
- [12] U. Rathmann, S. Olmes, A. Simeon, *Sealing Technology: Rub Test Rig for Abrasive/Abradable Systems*, (2007) 223–228. doi:10.1115/GT2007-27724.
- [13] A. Millecamps, J.-F. Brunel, P. Dufrénoy, F. Garcin, M. Nucci, Influence of Thermal Effects During Blade-Casing Contact Experiments, (2009) 855–862. doi:10.1115/DETC2009-86842.
- [14] R. Mandard, J.-F. Witz, X. Boidin, J. Fabis, Y. Desplanques, J. Meriaux, Interacting force estimation during blade/seal rubs, *Tribology International*. 82, Part B (2015) 504–513. doi:10.1016/j.triboint.2014.01.026.
- [15] M. Cuny, S. Philippon, P. Chevrier, F. Garcin, Experimental Measurement of Dynamic Forces Generated during Short-Duration Contacts: Application to Blade-Casing Interactions in Aircraft Engines, *Experimental Mechanics*. 54 (2014) 101–114. doi:10.1007/s11340-013-9780-z.
- [16] J. Vincent, S. Philippon, A. Cappella, J. Meriaux, S. Selezneff, Enhancement of an experimental method to measure accurately the evolution of forces during short-lived interactions: Application to blade-abradable material contacts in turbomachines, *Measurement*. 98 (2017) 167–178. doi:10.1016/j.measurement.2016.11.034.
- [17] A. Cappella, J. Vincent, S. Philippon, L. Faure, High-Speed Contact Study between a Ti-6-Al-4V Tool and an Abradable Coating Using Ballistic Benches and a Dynamic Compensation Approach 1, *Journal of Friction and Wear*. 38 (2017) 444–449. doi:10.3103/S1068366617060022.
- [18] This technology is subject to filling a patent at the INPI (French National Institute of Industrial Property) under the reference B-022174 FR.

- [19] R. Mandard, Y. Desplanques, G. Hauss, J. Fabis, J.-F. Witz, J. Meriaux, Mechanisms of incursion accommodation during interaction between a vibrating blade and an abradable coating, *Wear*. 330–331 (2015) 406–418. doi:10.1016/j.wear.2015.01.014.
- [20] M. Cuny, S. Philippon, P. Chevrier, F. Garcin, Experimental Measurement of Dynamic Forces Generated during Short-Duration Contacts: Application to Blade-Casing Interactions in Aircraft Engines, *Exp Mech*. 54 (2013) 101–114. doi:10.1007/s11340-013-9780-z.
- [21] M.A. Guler, F. Erdogan, The frictional sliding contact problems of rigid parabolic and cylindrical stamps on graded coatings, *International Journal of Mechanical Sciences*. 49 (2007) 161–182. doi:10.1016/j.ijmecsci.2006.08.006.