

# Numerical simulation of the thermo-mechanical behaviour of thermally sprayed abrasible coatings

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The newly designed abrasible coatings are usually validated by rig tests, where samples are rubbed by the contact of a dummy blade with given running speed and incursion rate, simulating actual working conditions in an aircraft engine.

The aim of this work was to develop a model of abrasible coating rig tests, allowing extensive studies of the influence of coating properties and test conditions on the thermal behaviour of the system.

The proposed model includes several steps implementing different numerical tools. Firstly, a relevant structural description of an abrasible coating is obtained from micrographs, using an original image analysis route. FE (Finite Element) calculations based on this description allow then to estimate the coefficients of an anisotropic elastic law of mechanical behaviour. Furthermore, a plasticity law is deduced from a FE simulation of the material HR15Y hardness. These parameters are used as input of a FE simulation of a single blade-to-coating rubbing hit, resulting in calculated stresses and temperatures. Finally a global approach of the complete abrasibility test, based on the results obtained from the simulation of a single hit and on various assumptions, provides predictions of the blade and coating temperature variations versus time during a complete abrasibility test.

## 1 Introduction

In aerospace applications, abrasible coatings are used to control the over-tip leakage of air in the compressor between rotor blades and casings. Abrasible seals allow the blade to cut a track but this has to be achieved with minimum wear.

The abrasible materials must not erode otherwise sealing effectiveness is lost. To gain the combination of properties required, these are generally combustion or plasma sprayed to give a distribution of matrix, dislocator and porosity.

So far, this strategically important area has developed largely empirically with thermally sprayed seal coatings generally made up from a range of simple two-phase powder mixtures. Manufacturers currently have a suite of abrasible seal coatings that are functional but they are perfectible [1] [2] [3].

The aim of this work was thus to gain a better and more fundamental understanding of abrasibility. To achieve this, it appeared necessary to develop first a numerical model for abrasible seal coatings and then to set up a predictive simulation package for abrasibility as a design tool for future applications. The model presented here is a first approach toward these objectives.

## 2 Overview of the modelling process

The proposed model includes several steps implementing different numerical tools, **Fig. 1**.

- LEG (LERMPS Ellipses Generator) and LATS (LERMPS Abrasibility Test Simulator) were in-house developed.
- ImageJ (Image Analysis) [4] and OOF (Object-Oriented Finite Element Analysis) [5] are freeware.
- ANSYS is a well-known FE (Finite Element) code [6].

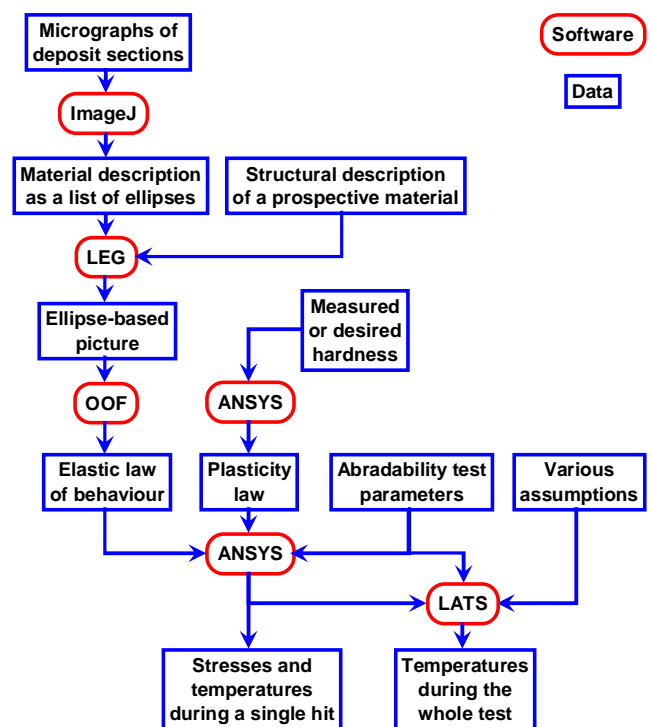


Fig. 1. Simulation package chart.

The starting point of the modelling process is metallography. An image analysis route has been implemented to achieve a relevant structural description of an abrasible coating. This method can also be used to describe a prospective material before its manufacturing.

FE calculations based on this description allow then to estimate the coefficients of an anisotropic elastic law of mechanical behaviour.

Furthermore, a plasticity law is deduced from a FE simulation of the material HR15Y hardness. Using hardness measurements on coating samples of different thicknesses, a bilinear elastic-plastic law was determined with a good accuracy.

These parameters are used as input of a FE simulation of a single blade-to-coating rubbing hit, resulting in calculated stresses and temperatures. A comparison with previous test data showed some consistency between these results and the measured blade wears.

Finally a global approach of the complete abrasability test has been implemented, based on the results obtained from the simulation of a single hit and on various assumptions. It allows to take account of the cooling phases between the hits. The influence of the rig environment can also be considered.

The results are predictions of the blade and coating temperature variations versus time during a complete abrasability test. It appeared that the adjustment of the inlet parameters allows to reproduce some observed variations.

### 3 Topological characterization of the abradable coating

An innovative route has been developed to model very porous or heterogeneous materials as abradable deposits [7] [8].

SEM (Scanning Electron Microscopy) micrographs of coating sections give information about the different phases present in the structure (matrix, dislocator and porosities) and their morphology. Equivalent images are then produced, replacing particles and porosities in the metallic matrix by equivalent ellipses, **Fig. 2**.

This model has several advantages:

- To simplify the picture, making the computing of a mesh easier,
- To characterise geometrically all inclusions, allowing statistics on them,
- To restore in some manner the effective three-dimensional geometry of the coating (during the process, the narrow gaps between matrix sections are filled, simulating the solid connections existing in planes close to the micrograph plane).

### 4 Generation of a virtual micrograph of a porous or heterogeneous material

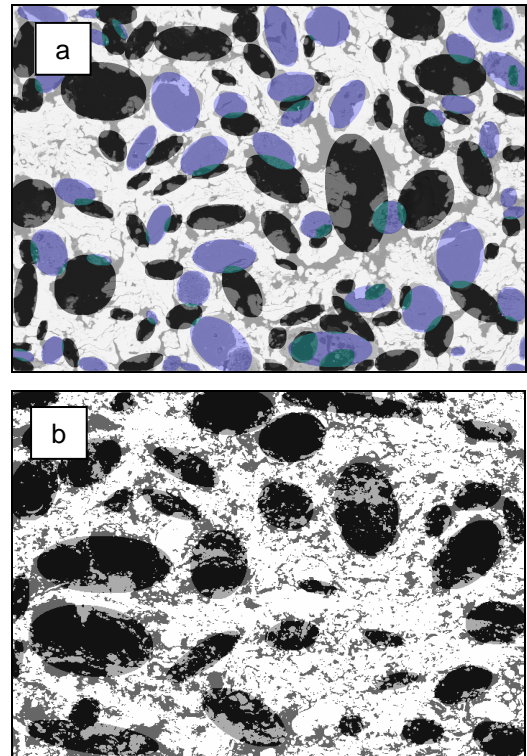
The LEG program has been developed to produce images equivalent to microstructures and well adapted to finite element analyses.

It can be used in two cases:

- Case 1: The material to be modeled exists and micrographs have been analyzed and characterised by a set of ellipses. To eliminate unrealistic ellipses' overlapping, LEG is used to redistribute them randomly in the picture, saving the initial matrix % by an adjustment of the picture size.
- Case 2: The material to be modeled does not exist yet, but can be described by a set of ellipses equivalent to the pores and particles of additional

phases included in a metallic matrix. Assuming some limits for the areas, shapes and angles of these ellipses, LEG can generate a random set of ellipses and distribute them with a given density to produce the same kind of images as those deduced from real micrographs.

The mechanical properties were computed as explained below on several images resulting from different random distributions of the same set of ellipses and it was shown that the different results were almost the same. That validates the process of random distribution. The only condition is to have a sufficient number of ellipses in the considered area, which is of about 100.



**Fig. 2.** Equivalent image generation for NiCrAl-Bentonite (a) and AlSi-hBN (b) coatings.

### 5 Determination of the linear thermoelastic parameters by virtual tests

The software OOF is used to create a mesh from an ellipse-based picture representing the microstructure of a coating and to simulate mechanical and thermal tests [9]. The meshing process produces elements of decreasing sizes close to the interfaces between two different materials, **Fig. 3**.

Virtual experiments are then conducted on the meshed structure to generate the parameters of an anisotropic linear elastic law of behaviour.

Calling respectively  $x$  and  $y$  the horizontal and vertical directions of the micrographs and pictures ( $x$  being also the direction parallel to the substrate and  $y$  the direction perpendicular to it), five parameters describe the coating mechanical behaviour:

- Two Young's moduli  $E_x$  and  $E_y$ .
- Two Poisson's coefficient  $\nu_{xy}$  and  $\nu_{yx}$ .
- A shear modulus  $G_{xy}$ .

Based on these parameters, the classical two-dimensional Hook's law gives the relationship between the stresses and the strains in the coating.

$$\begin{pmatrix} \epsilon_{xx} \\ \epsilon_{yy} \\ \gamma_{xy} \end{pmatrix} = \begin{pmatrix} 1 & -\nu_{yx} & 0 \\ E_x & E_y & 0 \\ -\nu_{xy} & 1 & 0 \\ E_x & E_y & 0 \\ 0 & 0 & 1 \\ & & G_{xy} \end{pmatrix} \times \begin{pmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{xy} \end{pmatrix} \text{ with } \frac{\nu_{xy}}{E_x} = \frac{\nu_{yx}}{E_y}$$

Two different values of the CTE (Coefficient of Thermal Expansion), in both directions x and y, can also be computed by the same model after the simulation of a temperature step.

A key point to obtain realistic results is to use relevant inlet data, particularly the mechanical properties of the different phases considered.

An experimental study was conducted to assess the weakening effect of the spraying process on the Young's Modulus of the metallic phase.

The coated sample which was used was plasma sprayed NiCrAl-hBN with very low BN% thus dense and representative of the metallic matrix of a porous coating. This sample was submitted to a cantilever bending test, giving a value of the coating Young's modulus. Comparing this value to the Young's modulus of the bulk alloy, it was possible to estimate a reduction factor of about 4 between the rigidities of the bulk alloy and the rigidities of the same alloy as sprayed.

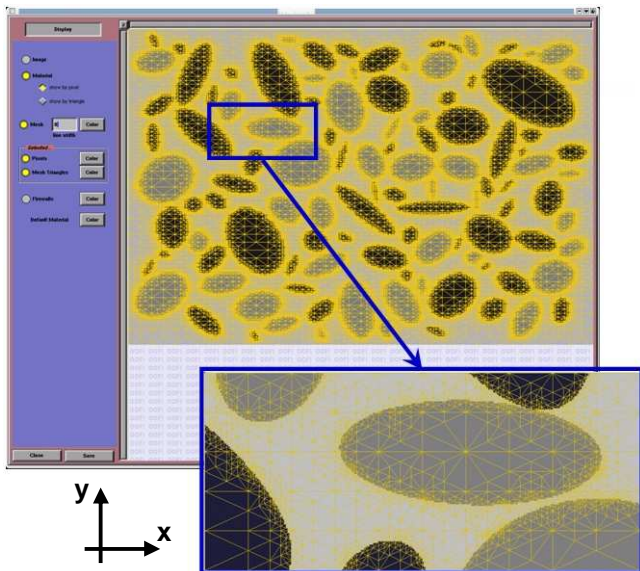


Fig. 3. Generation of an adaptive mesh by OOF, from an ellipse-based picture.

## 6 Determination of the plastic behaviour of an abradable material by simulating the HR15Y hardness test

The HR15Y hardness test, which is widely used to characterize abradable coatings, is based on the measurement of the permanent residual deformation remaining after the application of a load through a spherical indenter [10].

Thus it is clearly dependent on the plastic properties of the material.

Estimates of the 2 parameters of a bi-linear plastic law (yield stress and tangent modulus) were deduced from the simulation of the hardness test on 2 deposits of the same material, but having different thicknesses [11].

This model was developed using ANSYS software, with a mesh including two-dimensional axisymmetric elements and contact elements, Fig. 4.

An optimization process allowed to determine a bi-linear plastic law in good agreement with experimental data.

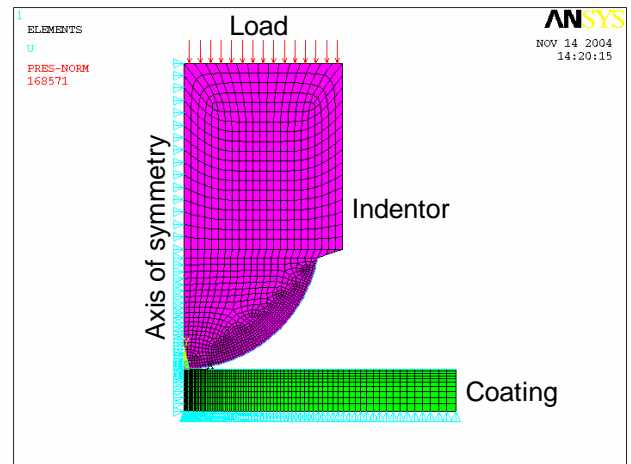


Fig. 4. Mesh of the indenter + coating system.

## 7 Simulation of a blade-to-coating dynamical contact during an abrasibility test

The FE code ANSYS was used to simulate a single contact between a blade and an abradable specimen, Fig. 5.

Located at the interface between the blade and the coating, contact elements allowed to compute the heat generation due to frictional dissipated energy and to take into account the coupling of thermal and mechanical analyses.

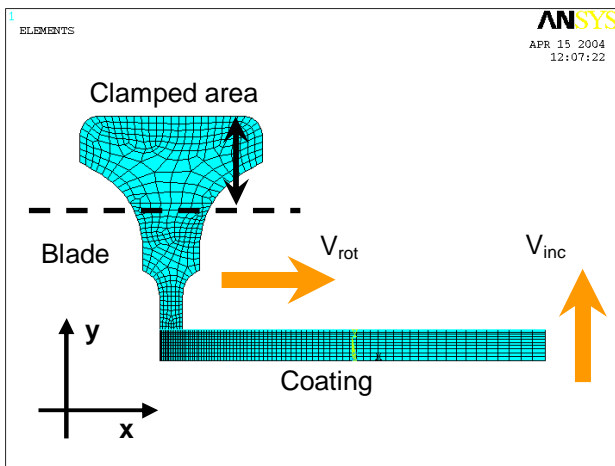
The motions of the two parts during the tests were simulated by dynamical displacements. The coating moved up vertically with an incursion speed  $V_{inc}$ , while the blade moved with a linear speed  $V_{rot}$ .

An initial incursion of the blade into the coating was taken into account by an initial distortion of the mesh, resulting from a preliminary static calculation.

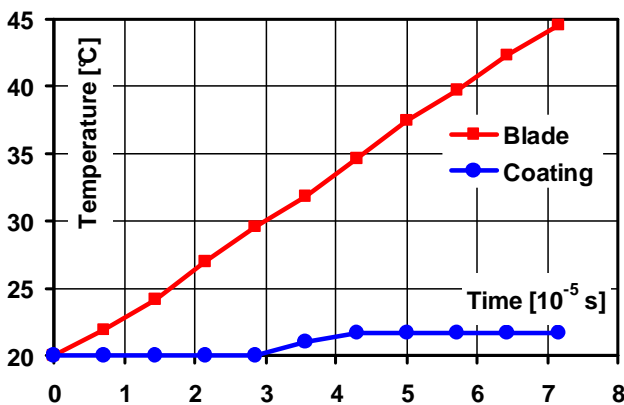
The mechanical properties of the coatings were those evaluated by the previous steps of the model. The results obtained for reference coatings were dynamical fields of stresses and temperatures. Comparisons between the maximum computed values in a set of cases and the corresponding blade wear measurements showed some promising consistency.

Furthermore, these results contribute to explain why different test rigs work sometimes differently. In fact it appeared that the stress field in the blade tip depends a lot on its thickness: for a narrow blade (0,7 mm), the maximum stress level is located on the leading edge, whereas for a wider blade (3 mm), it is located under the blade tip.

Among the results of this simulation, temperatures increases versus time at 2 particular points, the blade leading edge and the coating mid-point, were identified for further exploitation, **Fig. 6**.



**Fig. 5.** Abradable coating + blade. Mesh and boundary conditions.



**Fig. 6.** Example of blade leading edge and coating mid-point temperatures versus time (single hit).

## 8 Thermal modelling of an abrasability test

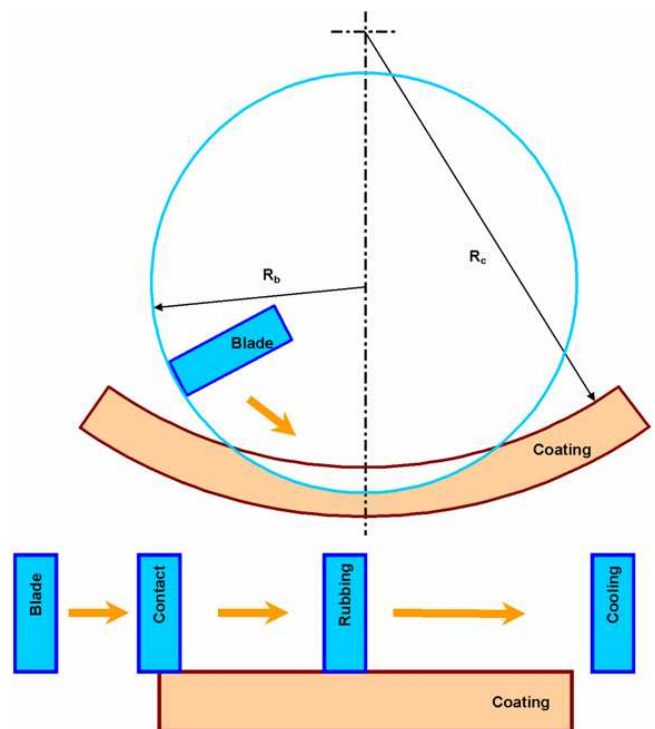
LATS is an approach internally developed to estimate the temperature evolutions during a rig test. It is based on the results given by the simulation of a single blade-to-coating hit, and also on assumptions, which are presently still necessary but should be later replaced by information deduced from extensive exploitation of experimental databases.

LATS considers a large number of revolutions comprising each 3 successive steps, **Fig. 7**.

- Interaction between the blade and the coating at contact instant, unless a gap was generated previously between both parts.
- Heating of both parts by rubbing, as simulated by the blade to coating contact simulation.
- Cooling in air, with the hypothesis of media at constant temperature existing around both the blade and the abradable specimen.

Various options give the possibility to represent particular behaviours of the coating and of the blade, for instance periodic matter transfer to the blade tip.

Using the results of the rubbing simulation described above and making assumptions on the cooling phenomena and environment behaviour, LATS allows to obtain temperatures curves consistent with the available experimental data, **Fig. 8**.



**Fig. 7.** A global sketch of the system and the different steps considered.

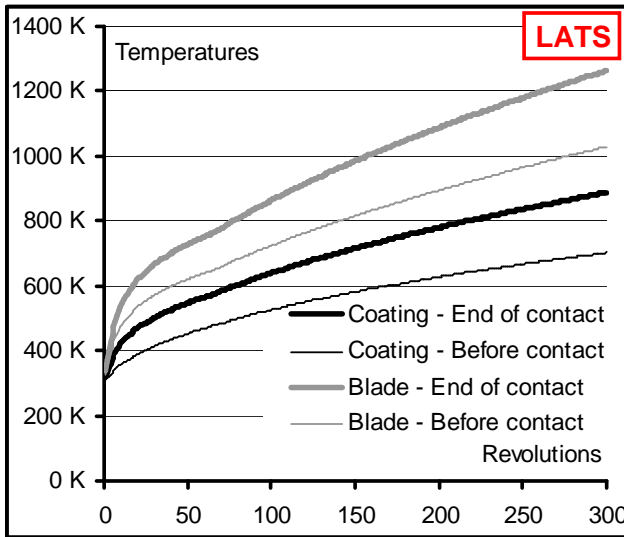


Fig. 8. LATS typical output.

## 9 Conclusion

A complete process to model an abradable deposit and to simulate an abradability test has been set up. Some promising and consistent results were obtained and it appeared that this approach provides interesting information, improving the understanding of the highly complex phenomenon of abradability. Nevertheless, some further work must be undertaken to fully validate a predictive tool able to help for the development of the next generations of abradable materials.

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- Neomet Limited, Manchester, UK
- Institute of Plasma Physics, Praha, CZ
- RALSA, Langreo, ES
- UTBM - LERMPS, Belfort, FR

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