Identification of plastic and creep properties of plasma-sprayed coatings by means of macro-indentation and a Levenberg-Marquardt method

N.Kind[a,b], B. Berthel[a], C.Poupon[b], O.Jaubert[b]

a. Laboratoire d Tribologie et Dynamique des Systèmes, UMR CNRS ECL ENISE ENSMSE 5513, Ecole Centrale de Lyon, 69134 Ecully cedex, France ; nora.kind@doctorant.ec-lyon.fr

b. Airbus Operations S.A.S, 316 route de Bayonne, 31060 Toulouse, France

Abstract :

Plasma-sprayed coatings are widely used for thermal protection and wear stability of structural components. These coatings feature an anisotropic porous structure as a result of the thermal spraying process. To our knowledge little research is dedicated to describing the temperature-dependent plastic behavior of these coatings, let alone to identifying the coating's properties when subjected to macro-scale contacts encountered in industrial applications. In this work we present a novel inverse method for the identification of plastic properties of thick plasma-sprayed coatings over a wide temperature range by means of macro-indentation and finite element simulations coupled to a Levenberg-Marquardt optimization. For the description of the coatings' plastic behavior we made use of the Gurson-Tvergaard plasticity criterion coupled to a linear isotropic work hardening of the matrix. The constitutive parameters to be identified include the yield strength $\sigma y_0(T)$ and the work hardening coefficient K(T) of the solid matrix as function of temperature as well as two dimensionless fitting parameters q_1 and q_2 and the initial void fraction f_0 that are proper to the Gurson plasticity criterion. We could show that the proposed method is capable of identifying these parameters after as little as three iterations.

Key words: macro-indentation, inverse identification, Gurson-Tvergaard plasticity criterion, plasma-sprayed coatings, finite element analysis, Leveenberg-Marquardt optimization, creep

1 Introduction

The elastic-plastic properties of materials are commonly identified from the load displacement curve obtained in the course of indentation [1][2][3]. Although this common method is suitable for nano and microindentation, we propose an alternative method in this work. The inverse method proposed here does not require knowledge of the entire loading history but it suffices to provide the geometry of the residual macro-indent. In this work we present a novel inverse method for the identification of plastic properties of thick plasma-sprayed coatings by means of macro-indentation and finite element simulations coupled to a Levenberg-Marquardt optimization over a large temperature range from ambient to up to 500C. This optimization aims to fit numerically generated indentation profiles to the experimentally obtained ones, such as illustrated in figure 1.

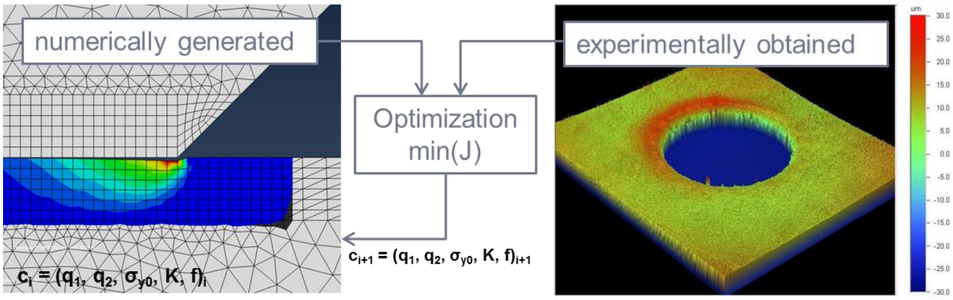

Figure 1 : updating scheme of Levenberg-Marquardt optimization coupled to FEM simulation

For the description of the coatings' plastic behavior we made use of the Gurson-Tvergaard plasticity criterion coupled to a linear isotropic work hardening of the matrix. This criterion is appropriate for ductile porous solids as it takes into account the hydrostatic pressure, and it is readily implementable in commercial finite element software such as Abaqus.

The Levenberg-Marquardt algorithm aims to identify the set of material parameters (unknowns) which minimizes the cost function J(c) that can be expressed as the sum of squares of non-linear real-valued functions, representing the error between experimental and numerical results. In other words, c* contains the parameter set for which the computed indent geometry comes closest to the experimental one. This error can be represented as either relative or absolute, depending on the problem at hand. In the numerical implementation this comes down to comparing the residual vertical displacements that are computed numerically to the experimentally obtained ones at different points along the indent and for several indentation loads for a range of temperatures. This concept is illustrated in figure 2. The unknown material parameters for the plasma-sprayed coatings include the yield strength of the solid matrix as a function of temperature σ_y (T), the work hardening coefficient as a function of temperature K(T) as well as the non-dimensional fitting parameters q_1 and q_2 that are proper to the Gurson criterion and finally the porosity volume fraction f_0.

$$J(c) = \sum_{n=1}^{N} j_n^2(c) = \sum_{n=1}^{N} \left(F_n^{calc}(c) - F_n^{exp}\right)^2$$

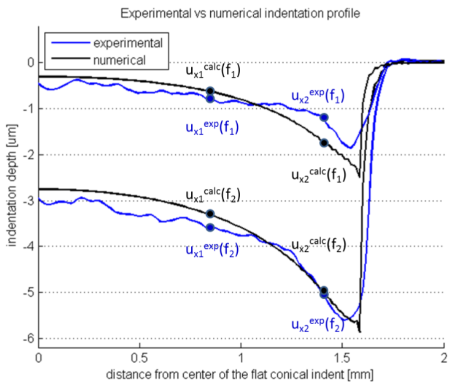

Figure 2 : definition of residual vertical displacements

2 Experimental set-up

2.1 Materials

The materials investigated in this study are Co-based coatings of different chemical compositions that are plasma-sprayed onto steel substrates. These coatings exhibit a thickness of approximately 140µm. The porosity volume fraction of these coatings was estimated by both image binarization of cross-sectional views and mercury intrusion porosimetry.

2.2 Macro-indentation

For the purpose of macro-indentation flat-ended conical indenters with a diameter of 3 mm made of 100C6 steel and Inconel 718 were used. The set-up consists of a servo-hydraulic testing machine with a capacity of 100kN. The indentation loads for the flat-ended conical indenter range between 8-16kN. Macro-indentation was carried out at ambient and elevated temperature of up to 500C. This was achieved by heating the sample holder and surrounding structure by means of heating cartridges and insulating the set-up. The 3D profiles of all indents were obtained by non-contact profilometry. These 3D indentation profiles were averaged around the indent's central axis in order to obtain a representative 2D profile, as illustrated in figure 3.

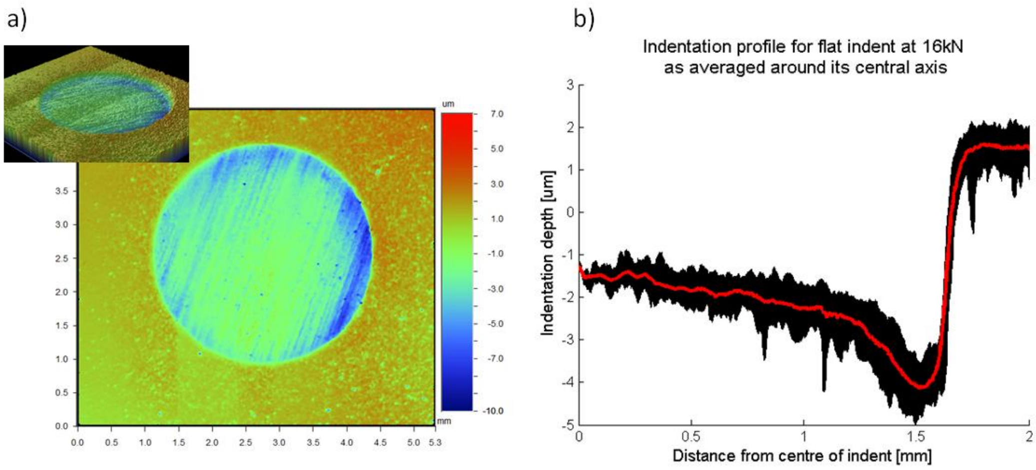

Figure 3 : a) 3D profilometry and b) azimuthal averaging of that profile around its central axis; red: average profile; black: sum of all profiles

2.3 Finite element model

The finite element simulation of the conical indentation configuration was carried out using the commercial Abaqus software. This axisymmetric model consists of the elastic indenter and the substrate-coating system. The coating is modeled as a porous solid obeying the Gurson-Tvergaard plasticity criterion coupled to a linear work hardening of the matrix. For this plasticity criterion the corresponding parameters $q1$, $q2$, $\sigma_{y0}(T)$, $K(T)$ and f_0 are to be determined as part of the Levenberg-Marquardt optimization. The steel substrate is modeled as an elastic-plastic solid. The friction coefficient between indenter and coating was set to a value of 0.5.

$$\Phi = \left(\frac{\sigma_{vm}}{\sigma_y}\right)^2 + 2fq_1 cosh\left(-\frac{3}{2}q_2\frac{\sigma_m}{\sigma_y}\right) - (1 + q_3 f^2) = 0$$

$$\sigma_y = \sigma_{y0} + K\varepsilon_{eq}^p$$

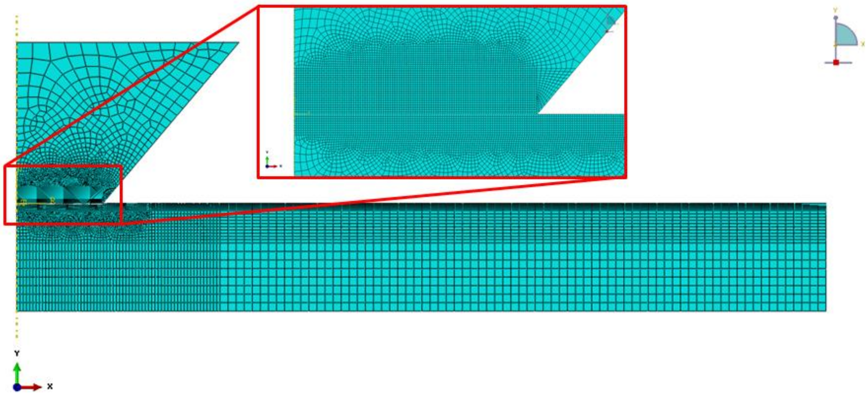

Figure 4 : Finite element model of the conical indenter

3 Results

The coatings' mechanical properties were determined for a wide temperature range from the Levenberg-Marquardt algorithm applied to the flat-ended conical indents. The initial guess for $\sigma_{y0,0}$, K_0, $q_{1,0}$ and $q_{2,0}$ was found by means of a numerical design of experiments whereas the initial guess for f_0 was taken from porosity measurements by means of binarization of optical images and mercury infusion porosimetry. Convergence of the Levenberg-Marquardt algorithm towards a solution was only achieved when absolute errors between the vertical displacements of iteratively generated and experimental curves were considered along the entire surface featuring 168 nodes. Convergence towards a solution was achieved relatively quickly after as little as 3 iterations.

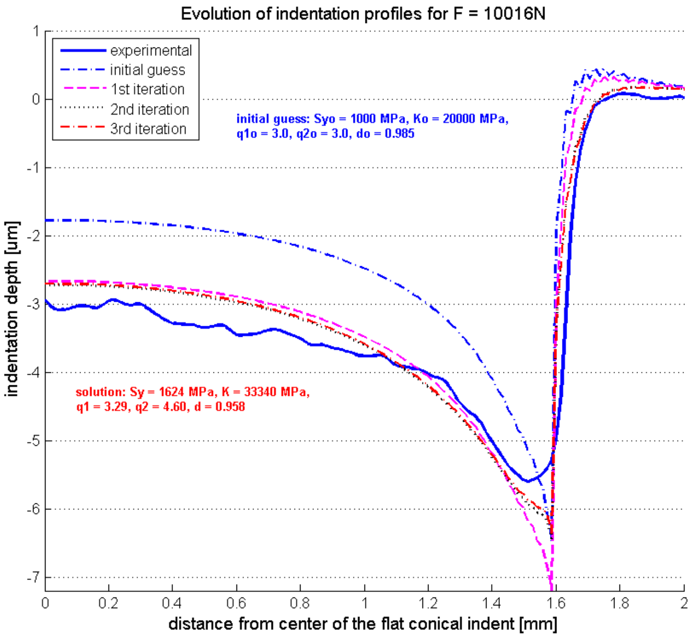

Figure 5 : convergence of indentation profiles for F = 16013N at ambient temperature

Bibliography

[1] Clement, P., Meille, S., Chevalier, J; Mechanical characterization of highly porous inorganic solid materials by instrumented micro-indentation

[2] Gu, Y., Nakamura, T. and Prchlik, L.; Micro-indentation and inverse analysis to characterize elastic-plastic graded materials

[3] Chen, X.; Novel technique for measuring the mechanical properties of porous materials by nanoindentation