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Physics based modeling of machining *Inconel 718* to predict surface integrity modification

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Abstract

Inconel 718 nickel-based super alloy is widely used in aerospace, nuclear and marine industries due to its important thermo-mechanical properties and excellent corrosion resistance. However, the possibility to produce parts with a superior surface quality (e.g. enhanced surface integrity) still represents a challenge for manufacturing industry since the standard processing parameters are not suitable when difficult-to-cut materials are involved. Thus, predictive models represent a useful tool to simulate the material behavior during machining. Physics based computational analysis is an excellent technique to analyze the micro-scale phenomena (e.g. dynamic recrystallization, density of dislocation changes) taking place during the plastic deformation processes. Thus, it represents an important tool to optimize the cutting process achieving the desired characteristics of the machined surface. This work presents a physics based model developed to assess the micro-mechanical behavior of Inconel 718 super alloy subject to severe machining operations. Results show the good capability of the model to properly deal with the main physical phenomena taking place during the process and to correctly predict the main surface modifications which affect the final product performance.

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Keywords: Physics Based Modeling; Hard Machining; Inconel 718; Surface Integrity

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1. Introduction

Due to its superior thermo-mechanical properties, *Inconel 718* superalloy is extensively used to manufacture rotating components for turbine engines. These latter, are subject to extreme working conditions due to the cyclic mechanical loads under high temperatures, that critically affect their fatigue and corrosion resistance [1].

The most significant properties exhibited by *Inconel 718* are the capability of maintaining high stiffness and strength at high temperature, high dynamic shear strength and extremely low reactivity in highly corrosive environment. Although the *Inconel 718* has these beneficial properties in hostile working conditions, it shows poor workability due to its high work hardening, low thermal diffusivity and high reactivity with tool materials [2].

In this context, the numerical simulations play an important role because such material is still considered as a hard-to-cut one. Thus, numerical analysis can be successfully implemented to optimize the process parameters drastically reducing the experimental time and cost needed. Numerical simulation provides feedback information on process parameters, in order to achieve the desired efficiency together with the quality of the machined product [3].

In numerical modeling of the material plastic behavior, the phenomenological models always covered a fundamental role for a large variety of metallic materials under high strain, strain rate and temperature. Among these models, the most widely used in machining simulations is the Johnson-Cook (JC) model,

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because of its simplicity of implementation and because it is easily calculated through experimental data interpolation [4]. Furthermore, the versatility of the JC model is reinforced by the possibility to be coupled with microstructural dependent semi-empirical models, allowing to obtain information about the microscale modifications of the material. On the other hand, this model frequently needs to be re-tuned considering the various working conditions; furthermore, the obtained numerical constants have poor physical meanings [5].

To overcome these limitations, dislocation based models have been developed in order to physically describe the plastic behavior of the materials. Despite the computational complexity, these numerical models guarantee a deeper knowledge of the inner metallurgical phenomena occurring during the manufacturing process and the material behavior is modified based on microstructural modifications [6].

This paper proposes a physics based model able to simulate the plastic behavior of *Inconel 718* under large strain deformations induced by machining process. The numerical analysis was carried out to obtain deeper information on the microstructural evolution mechanism that can be employed to improve the surface integrity of the machined products. The obtained results involve processing (forces and temperatures) and surface integrity (dislocation density evolution, micro-hardness, etc.) variables, providing a deeper knowledge on the phenomena occurring during high speed machining of *Inconel 718* components.

2. Experimental tests

Orthogonal machining tests were conducted on *Inconel 718* disks (429 HV) under dry conditions. Disks were characterized by a thin wall geometry (10 mm depth and 2 mm thick) using a CNC turning center. Coated DNMG Sandvik tools (ISO SDNMG150616) were selected and mounted on a Sandvik DDJNR/L tool holder. The tool holder was held in a Kistler 9257 three component piezoelectric dynamometer to measure the forces. Furthermore, a thermocouple (K-type) was embedded into the tool-holder and the tool interface in order to measure the local temperature at the cutting tool during machining. This temperature was used to determine the temperature on the cutting tool edge by an inverse numerical methodology. Disks were machined investigating three cutting speeds and three feed rates as reported in Table 1.

Table 1. Experimental machining test conditions.

Cutting Speed [m/min]	Feed Rate [mm/rev]
50	0.05/0.075/0.100
60	0.05/0.075/0.100
70	0.05/0.075/0.100

After the experimental tests, the machined surfaces and chips samples were collected, mounted and then polished in order to analyze the effects of the machining process. The overall details regarding the experimental tests are available in a previous work [7].

3. Deformation mechanism

Nickel-Iron based superalloys subjected to large plastic deformation, usually show significant metallurgical modifications. Considering the investigated material, the machined surfaces and the chips showed altered areas characterized by grains distortion, dynamic recrystallization (DRX) and intense slip activity. The distorted grains highlight wide regions of slip band concentration; this phenomenon indicates movement of crystalline dislocations towards the regions of higher plastic deformation. Critical process parameters induced high thermo-mechanical loads; therefore, sub-micron grains are formed via reorganization of dislocations within the dislocation cells triggering DRX phenomena [5].

The described phenomena occur both in the worked surface and sub-surface as well as in chips. An intense accumulation of slip bands (altered layers from 60μm to 100μm) was detected beneath the worked surface and in the heavier case studies an ultrafine grain layer of few micron thickness was also detected. Referring to the machined chips, two different zones are distinguishable, namely the Low Shear Strain Zone (LSSZ) and the High Shear Strain Zone (HSSZ). In LSSZ the grains show low deformation, maintaining almost the same size of the bulk material. On the contrary, the HSSZ (shear zone) shows extremely deformed grains frequently culminating in intense dynamic recrystallization phenomena. All the described zones are visible in Fig. 1.

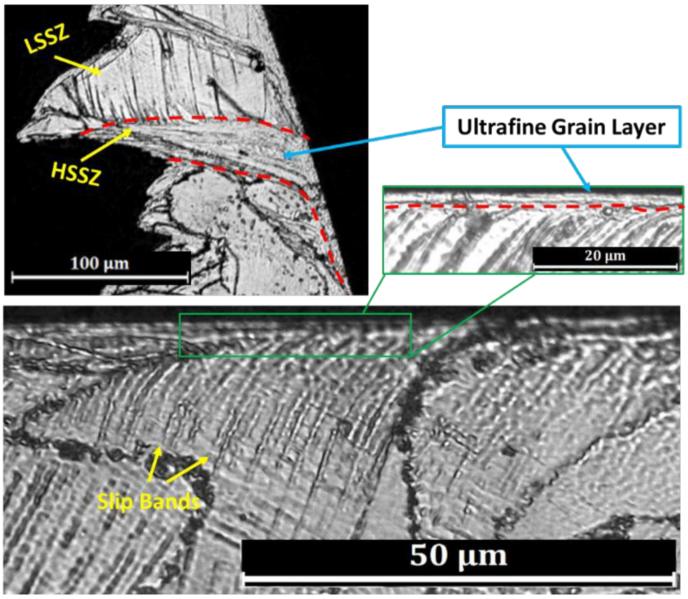

Fig. 1. Different deformation mechanisms in chip and machined surface.

4. Physically based constitutive model

In order to understand the plastic behavior of the material under different strain, strain rate and temperature conditions, the physics based model is an necessary tool because allows to describe the inner phenomena related to the metallurgical modification that usually occur during machining process. The material behavior model used in this work is based on dislocation dynamic and grain evolution and it was implemented in Finite Element (FE) software in order to simulate the machining process. The flow stress model consists of the algebraic sum of different contributions, taking into account the effects of the thermo-mechanical loads on the lattice defects and on the grain size modification (Eq. 1).

$$\sigma_{pl} = \sigma^* + \sigma_{HP} + \sigma_G \tag{1}$$

σ^* represents the resistance of the material to plastic strain where thermal activated mechanisms assist the applied stress in moving dislocations through the lattice. σ_{HP} is the Hall-Petch stress and denotes the contribution of the grain size to the plastic flow, while σ_G designates the strain hardening due to the forest dislocation.

The interaction between the mobile and immobile dislocations is the physical basis of the strengthening of a metal material and is described by well-known Taylor equation (Eq. 2) [8].

$$\sigma_G = M\alpha Gb\sqrt{\rho_i} \tag{2}$$

Where α is a proportional constant, M is the Taylor factor, ρ_i is the density of immobile dislocations, G is shear modulus and b is the Burger's vector (2.56×10^{-10} m) [8].

The evolution of the dislocation density is described by the two terms of Eq. 3. In detail, $\rho_i^{(+)}$ represents the strengthening effect, while $\rho_i^{(-)}$ represents the softening due to the recovery effects.

$$\dot{\rho}_i = \dot{\rho}_i^{(+)} - \dot{\rho}_i^{(-)} \tag{3}$$

The motion of the dislocation can be obstructed by the presence of obstacles causing a hardening effect in the material flow stress. This phenomenon is described by Eq. 4.

$$\dot{\rho}_i^{(+)} = \left(\frac{1}{s} + \frac{1}{D}\right)\left(\frac{M}{b}\right)\dot{\bar{\varepsilon}}^p \tag{4}$$

Where $\dot{\bar{\varepsilon}}^p$ is the equivalent plastic strain rate, D is the initial grain size and s represents the crystal cell size, that is described by Eq. 5 [8].

$$s = K_c/\sqrt{\rho_i} \tag{5}$$

Where K_c is a calibration constant.

The material softening due to recovery effect is described by Eq. 6.

$$\dot{\rho}_i^{(-)} = \Omega\rho_i\dot{\bar{\varepsilon}}^p \tag{6}$$

Where Ω is the recovery function and its expression is described by Eq. 7 and Eq. 8.

$$\Omega = \Omega_0 + \Omega_{r0}\left(\frac{1}{\dot{\bar{\varepsilon}}^p}\frac{D_v}{b^2}\right)^{1/3} \tag{7}$$

$$D_v = D_{v0}exp(-Q_v/k_bT) \tag{8}$$

Where D_v is the diffusivity, while Ω_0 and Ω_{r0} are two calibration parameters, D_{v0} is a numerical constant, Q_v is the activation energy for self-diffusion. k_b is the Boltzmann constant and T the absolute temperature [8].

The σ^* term represents the material resistance to plastic deformation due to the short-range interactions where thermal activated mechanisms assisting the applied stress in moving dislocations and is described by Eq. 9.

$$\sigma^* = \sigma_0\left(1 - \left(\frac{k_bT}{\Delta f_0 Gb^3}ln\left(\frac{\dot{\varepsilon}_{ref}}{\dot{\varepsilon}^p}\right)\right)^{1/q}\right)^{1/p} \tag{9}$$

Where Δf_0, q and p are calibration parameter and $\dot{\varepsilon}_{ref}$ is typically accepted as 10^6 [8].

The grain size D was predicted taking into account the common mixture law (Eq. 10):

$$D = D_{DRX}X_{DRX} + D_0(1 - X_{DRX}) \tag{10}$$

Where D_0 is the average initial grain size (18µm), D_{DRX} is the dynamically recrystallized grain size (Eq. 11) and X_{DRX} is the volume fraction of the recrystallized grains [5], this latter is described by the Avrami model (Eq. 12) [9].

$$D_{DRX} = 3054.62Z^{-0.13871} \tag{11}$$

$$X_{DRX} = 1 - exp\left(-0.693\left(\frac{\varepsilon-\varepsilon_{cr}}{\varepsilon_{0.5}-\varepsilon_{cr}}\right)^3\right) \tag{12}$$

As showed by Eq. 12, the X_{DRX} depends on strain ε, critical strain for the nucleation of the recrystallized grains ε_{cr} (Eq. 13), $\varepsilon_{0.5}$ (Eq. 14) that is the strain referred to the 50% of recrystallized grains and Z is the Zener-Hollomon parameter described by Eq. 15 [9].

$$\varepsilon_{cr} = 0.0015Z^{0.11741} \tag{13}$$

$$\varepsilon_{0.5} = 0.00146Z^{0.14299} \tag{14}$$

$$Z = \dot{\bar{\varepsilon}}^p exp\left(\frac{474000}{RT}\right) \tag{15}$$

To obtain the correct value of the numerical constants, a fitting procedure of experimental stress-train curves was carried out. The value of the constant obtained via calibration and by literature analysis [8-10] are reported in Table 2.

Table 2. Numerical constants identified.

Numerical Constant	**Value**	**Numerical Constant**	**Value**
α	0.15	τ_0	0.017
M	3.06	Δf_0	1.7
D_{v0} [m^2/s]	8.8e-5	p	1.2
Q_v [J/mol]	283000	q	1.5
Ω_0	3.4	d [µm$^{-0.5}$]	1
Ω_{r0}	0.2135	υ	1.4
K_c	36	α_G	0.9
ρ_0 [m^{-2}]	1.0e12		

5. Finite element model

A FE physics-based model of the orthogonal machining process was developed using the commercial software SFTC Deform®. A 2D plane-strain multi-physics analysis was performed via Update-Lagrangian code coupled with a remeshing technique.

FORTRAN subroutines were coded to integrate the numerical model explained in Section 4 in the FE software allowing the stress and metallurgical phenomena evolution prediction.

The workpiece was meshed with 20000 isoparametric quadrilateral elements, with a severe mesh refining near the cutting zone, reaching a mean element size of 2μm, in order to obtain an accurate prediction of the surface integrity close to the machined surface. The workpiece was considered as a plastic body, while the cutting tool was modeled as rigid body and its geometry was obtained using a non-contact profilometer. The physical interaction between the cutting tool and the workpiece was modeled considering the hybrid friction model that takes into account the sticking and sliding effects occurring at the interface. The friction coefficients m and μ were chosen as 1 and 0.3 respectively, while the global heat transfer coefficient (h) was imposed to be 100000 kW/m^{2}K. The values used for global heat transfer coefficient and friction constants refers to previous studies on the same process [7].

6. Results and discussion

6.1. Machining forces and temperatures

Fig. 2 reports a comparison between the numerical predicted cutting forces (main cutting and thrust forces) and temperatures and the experimental results. The predicted main cutting forces are in good agreement with those measured during the experiments, with an overall average absolute error of nearly 6%.

The predicted feed forces showed a mean absolute error equal to 8.32%, while cutting temperatures prediction exhibits an average absolute error of nearly 15%. These errors are higher than the error on the main cutting force, however, due to the very complex deformation process simulated, this specific entity of error was considered acceptable. Moreover, it is important to point out that, during machining of hard materials, the tool geometry unavoidably changes, due to the wear effect. This aspect was not modelled because of higher computational time, therefore the higher error in feed forces and temperatures was also attributed to the absence of tool wear that introduces significant non-linearity in the friction and contact modeling, which are unavoidably present in the machining of superalloys [11].

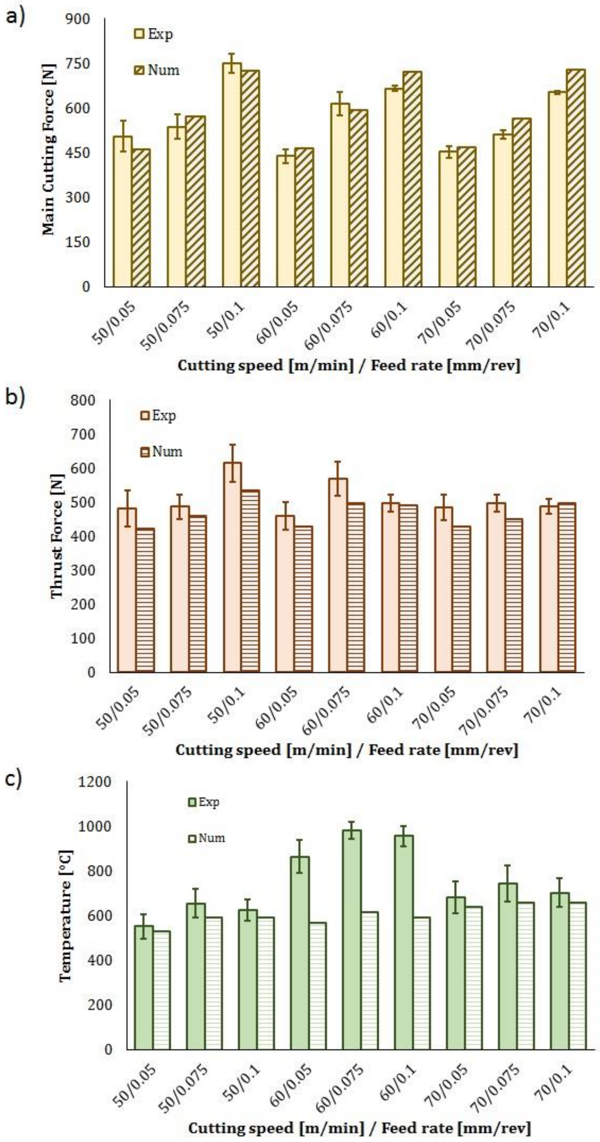

Fig. 2. Mean and variation of experimental (EXP) and numerical simulated (NUM) cutting forces (a), thrust forces (b) and temperatures.

6.2. Surface integrity analysis

The metallurgical modifications experimentally observed were deeply investigated through the numerical model. Depending on the machining parameters, different phenomena may occur on the worked surface, sub-surface and chip. Areas of intense slip activity behave as preferred site for grains nucleation, causing DRX.

The ultrafine grain regions noticed in the chip analysis are visible in all the investigated cases due to the intense shear activity during the chip serration phenomena (Fig. 3a). Also, the ultrafine grain layers produced on the machined surfaces were detected when higher feed rates were employed, due to the heavier thermo-mechanical loads on the worked surface. In detail, the thicknesses of these layers are always lower than 2 μm and the numerical predicted ones are always comparable (Fig. 3b). As highlighted by M'Saoubi et al. [12], taking into account the high density of grain boundaries, the ultrafine grain

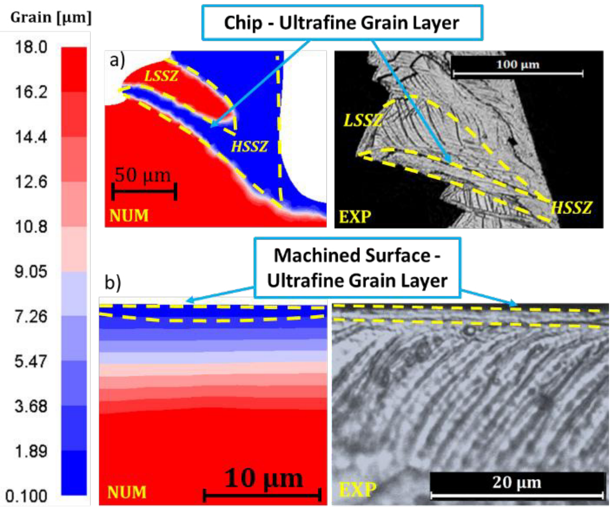

Fig. 3. Microstructural modifications measured (EXP) and numerical predicted (NUM).

layers are particularly difficult to be analyzed without using complex analysis systems (such as electron backscattered diffraction technique) and consequently the grain dimensions are extremely difficult to be evaluated. Therefore, a validated physics based numerical model offers a valid instrument to deeply investigate this phenomenon. The FE simulation was able to easily predict the grain size changes phenomena induced by cutting process previously described in Section 3.

Fig. 4 shows the comparison between the numerical and the experimental distribution of grain size measured on the machined subsurface and along the depth. The grain refinement is more significant as the cutting parameters became severer. Referring to Fig. 5 is possible to observe that the fraction of recrystallized grains is predominant beneath the machined surface. Consequently, taking into account that dynamically recrystallized grains are poor of dislocations [13], the main contribution in micro-hardness increasing was attributed to the grain refinement effect. Therefore, the Hall-Petch model (Eq. 16) was used to predict the hardness increment beneath in the affected layer [7].

$$HV = HV_0 + \frac{k_{HP}}{\sqrt{D}} \tag{16}$$

Where HV_0 and k_{HP} are calibration constants. The comparison between measured micro-hardness and the predicted one is reported in Fig. 6.

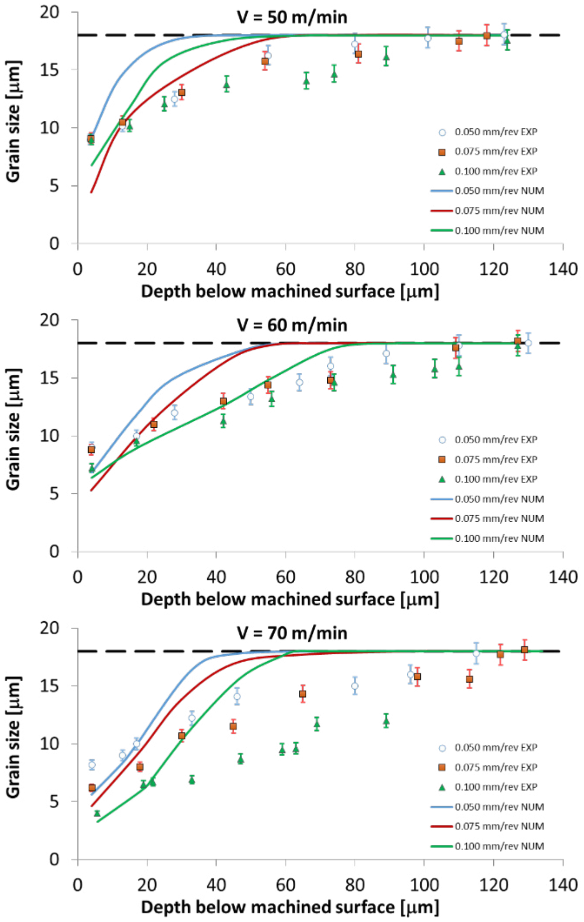

Fig. 4. Comparison between the measured (EXP) and the predicted (NUM) grain size.

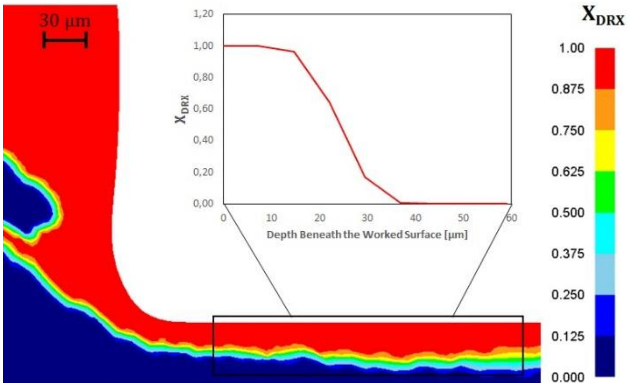

Fig. 5. Volume fraction of recrystallized grain size beneath the machined surface.

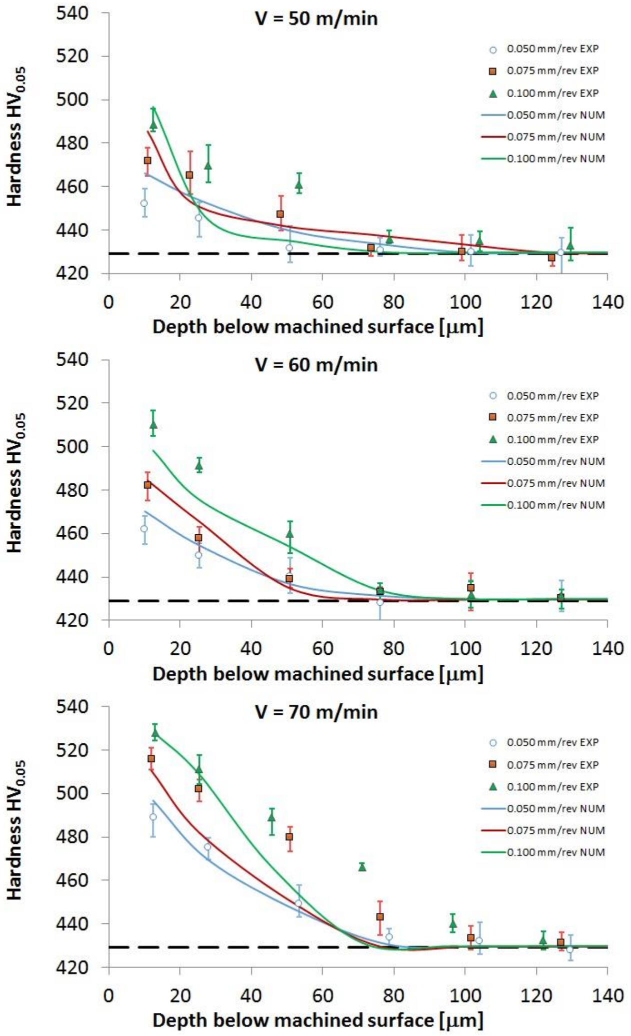

Fig. 6. Comparison between the measured (EXP) and the predicted (NUM) micro-hardness.

7. Conclusions

In this work the physically based constitutive behavior model of machined *Inconel 718* is presented. The main metallurgical phenomena such as dynamic recrystallization and interaction between mobile and immobile dislocation density are taken into account in order to understand their behavior when plastic deformation is induced by the tool. Moreover, the hardness modification was also implemented into the FE model to know its distribution change when different cutting parameters were used. The proposed model was validated through comparison between numerical and experimental results. The numerical data were in good agreement with the experimental ones. The average total error between the predicted and measured cutting forces was not higher than 8.5% while regarding the thermal gradient the error was always lower than the 15%. Through the FE simulation was possible to evaluate the amount of recrystallized grains due to the machining operation at varying cutting parameters.

The application of the numerical model was crucial in order to obtain a more affordable numerical prediction compared with the phenomenological one, with a drastic reduction of numerical error. Moreover, the use of a physics based model allows to get a deeper understanding of the metallurgical phenomena occurring due the large plastic strain induced by machining process, that are of fundamental importance in the design of high performance and reliable industrial processes.

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