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# A Physically Based Model to Predict Microstructural Modifications in *Inconel 718* High Speed Machining

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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. Despite of its good mechanical performance, this alloy is extremely difficult to be machined. Moreover, high speed machining processes can radically affect the products quality in terms of surface integrity, because of metallurgical modifications induced by severe thermo-mechanically induced loads. Physics based computational analysis is an excellent technique to analyze the micro-scale phenomena (e.g. dynamic recrystallization, density of dislocation changes, etc.) occurring during the large plastic deformation induced by the industrial processes. Thus, it represents an important tool to optimize the cutting process, allowing to achieve the desired surface integrity on the machined parts. This work employ a physics based model to assess the micro-mechanical behavior of Inconel 718 super alloy subject to severe machining operations at extremely high speed. Results show the good capability of the model to properly deal with the microstructural modifications occurring during the process and to predict the main variables of industrial interest.



*Keywords:* High Speed Machining; Inconel 718; Physics Based Model

## 1. Introduction

Inconel 718 is a precipitation hardening nickel-chromium superalloy that shows outstanding thermo-mechanical properties at extremely high temperatures, such as strength, creep resistance and good fatigue life. These properties allow to use this superalloy to manufacture aeronautic components that are subjected to critical working conditions such as cyclic mechanical loads under high temperatures [1].

Despite of its performance, this superalloy shows extremely poor machinability due to its low thermal conductivity, significant adhesion with the cutting tools and the presence of abrasive particles on the microstructure. Consequently, the proper design of high speed machining processes, still represents a very tough challenge in order to increase the productivity in the involved industries [2].

In this context, the numerical simulations play a central role, because they can be easily implemented to study the manufacturing process, allowing to optimize the working parameters leading to a drastic reduction of the number of experiments with a subsequent saving of the production costs. These models also provide important feedback information on the effects of the manufacturing processes on the final product, allowing to achieve the desired productivity and quality of the final products [3].

In the numerical modeling of the material plastic behavior, the phenomenological models cover an important role for a large variety of metallic materials under high strain, strain rate and temperature. Among these models, the most used in machining simulations is that proposed by Johnson and Cook (JC), because of its simplicity of implementation and because it is straightforwardly obtainable through experimental data

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interpolation [4]. Despite of its versatility, the JC model frequently needs to be re-tuned considering the various working conditions, moreover the obtained numerical constants have not physical meanings [5].

To overcome these limitations, dislocations dynamic based models have been developed. These models allow to physically describe the plastic flow behavior of the metals when they are subjected to large deformations. Although the computational complexity, these numerical models guarantee a deeper knowledge of the microstructural phenomena occurring during the manufacturing process and the material behavior is modified accordingly with the metallurgical modifications that occur during the material deformation process [6].

In this paper, a physics based modeling procedure able to simulate the plastic behavior of *Inconel 718* under high speed machining conditions is proposed. The numerical analysis was carried out to predict the main variables of industrial interest and deeper information about the evolution of the microstructure during the process. The obtained results also allow to predict the main microstructural modifications that can be employed to improve the final product surface quality.

## 2. Experimental Procedure

The experimental tests were performed under dry cutting conditions. The workpiece material was an *Inconel 718* tube of outer diameter of 102 mm and inner diameter of 89 mm. The tube was solution annealed and aged to a surface hardness of 40 HRC. Orthogonal turning trials were performed (three repetitions for each case analyzed) on a Starrag STC 1250 lathe, with the workpiece stationary and tool revolving around its spindle (Figure 1). A standard Sandvik Coromant SiC, whisker reinforced aluminium oxide based ceramic insert SNGN 120712 T01 020 of grade CC670 was used for the machining tests. The cutting speeds set for the experimental test were 200, 300 and 400 m/min at a constant feed rate of 0.1 mm/rev. Cutting force measurements were conducted using a Kistler 9255B dynamometer.

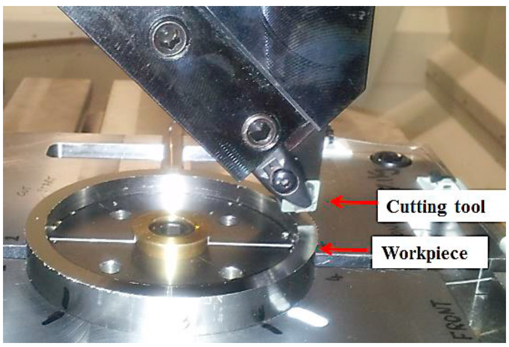


Fig. 1. Experimental set-up for orthogonal machining [7].

The chips and the machined surface samples obtained by each cutting test were collected and processed for chip morphology and microstructural analysis. The samples were polished and etched using Kalling's reagent No 2.

The optical analysis was conducted using a LEICA DFC 320 microscope and the surface hardness was measured by means of a Vickers indenter. The overall details regarding the experimental tests are available in a previous work [7].

## 3. Physically Based Model

In order to understand the plastic behavior of the material under different strain, strain rate and temperature conditions and to simulate the metallurgical phenomena related to the microstructural modification that occurred during the machining process, a material plastic flow stress model based on dislocation dynamic and grain refinement was implemented in a commercial Finite Element (FE) software via FORTRAN user subroutines (SFTC Deform®). The flow stress model was proposed by in a previous work [3] and the main details about it are resumed below.

The employed 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).

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

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

The interaction between mobile and immobile dislocations is the physical basis of the mechanical strengthening of a metal material and is described by the well-known Taylor equation (Eq. 2) [3].

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

Where $\alpha$ is a proportional constant, $M$ is the Taylor factor, $\rho_i$ is the density of immobile dislocations, $G$ is shear modulus and $b$ is the Burger's vector (2.56E-10 $m$) [3].

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

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

The strengthening phenomena 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 [3].

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

Where $Kc$ is a calibration constant.

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

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

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

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

$$D_v = D_{v0} exp(-Q_v/k_b T) \quad (8)$$

Where $D_v$ is the material self-diffusivity, while $\Omega_0$ and $\Omega_{r0}$ 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 [3].

The $\sigma^*$ 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.

$$\sigma^* = \sigma_0 \left( 1 - \left( \frac{k_b T}{\Delta f_0 G b^3} ln \left( \frac{\dot{\varepsilon}_{ref}}{\dot{\varepsilon}^p} \right) \right)^{1/q} \right)^{1/p} \quad (9)$$

Where $\Delta f_0$, $q$ and $p$ are calibration parameter and $\dot{\varepsilon}_{ref}$ is typically taken as $10^6\ s^{-1}$ [3].

The recrystallized grain size *D*, due to the dynamic recrystallization phenomena, has been calculated considering Equation 10 [7],

$$D = b\, Z^m \quad (10)$$

where *b* and *m* are two material constants. The numerical expression of the recrystallized grain size depends on Zener-Hollomon parameter (*Z*). The Zener-Hollomon equation proposed by Abbasi et al. [7], was used to predict the dynamic recrystallization effect and is calculated by this Equation 11:

$$Z = \dot{\bar{\varepsilon}}^p e^{\frac{Q}{RT}} \quad (11)$$

where *R* is the universal gas constant expressed in *J/(K mol)* and *Q* is the apparent activation energy for mechanical deformation process (*kJ/mol*).

Another important parameter for predicting the grain refinement is the critical strain value ($\varepsilon_{cr}$) that represents the minimum value that strain have to reach in order to trigger the dynamic recrystallization phenomena. The value of $\varepsilon_{cr}$ is calculated from the Equation 12 [7]:

$$\varepsilon_{cr} = \left( 0.00234\, \dot{\varepsilon}^{0.1293} e^{\frac{5759.863}{T+273}} \right) / c \quad (12)$$

Where *c* is a calibration constant.

The Hall-Petch stress ($\sigma_{HP}$) depends on the mean grain size of the investigated material and represents the contribution to the material strengthening given by the grain boundaries and its expression is given by Equation 13.

$$\sigma_{HP} = \alpha_{HP} G \sqrt{b/_D} \quad (13)$$

Where $\alpha_{HP}$ is a calibration constant.

Moreover, to predict also the variation of the hardness, experimentally observed, the Hall-Petch equation has been implemented (Equation 14),

$$HV = C_0 + \frac{C_1}{\sqrt{d}} \quad (14)$$

The terms $C_0$ and $C_1$ are constants that need to be calibrated.

Figure 2 shows the strategy used to predict the microstructural changes consequent to the orthogonal cutting process of *Inconel 718*.

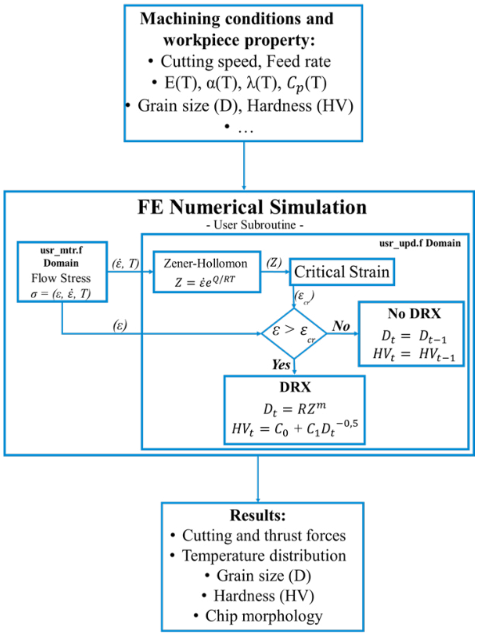


Fig. 2. Implemented strategy for simulation the cutting process.

## 4. 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 that permit a good prediction of the large geometry modifications that are typical of machining processes.

The workpiece was meshed with 20000 isoparametric quadrilateral elements, with a severe mesh refining near the cutting zone, reaching a mean element size of 2 *μm*, in order to obtain an accurate prediction of the surface integrity parameters occurring on the machined surface.

The workpiece was considered as a plastic body, while the cutting tool was modeled as rigid body. The physical interaction between the cutting tool and the workpiece was modeled considering the hybrid friction model that considers the sticking and sliding effects at the tool-workpiece interface. As suggested by previous studies on the same process, the hybrid friction coefficients *m* and *μ* were set as 1 and 0.3

respectively and the global heat transfer coefficient ($h$) was imposed to be 100000 $kW/(m^2K)$ in accordance with [3].

In order to simulate as real as possible the orthogonal cutting process the mechanical and thermo-physical properties of the workpiece and the tool were defined taking into account the software libraries.

Moreover, Cockroft and Latham's plastic failure criterion was considered to predict the chip segmentation during the orthogonal cutting. The Equation 15 shows this criterion:

$$\int_0^{\varepsilon_f} \sigma_1 \, d\varepsilon = D_{C\&L} \quad (15)$$

Where $\sigma_1$ is the principal stress, $\varepsilon_f$ is the effective strain and $D_{C\&L}$ is a material constant and its value was taken from [7].

## 5. Results and Discussions

### *5.1. Machining Forces and Temperatures*

In Fig. 3 is reported the comparison between both the numerically predicted cutting forces and the experimentally obtained ones.

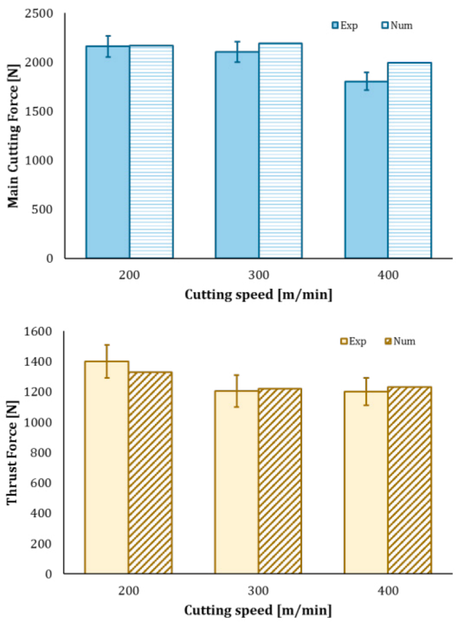


Fig. 3. Mean and variation of experimental (EXP) and numerical simulated (NUM) cutting forces and thrust forces.

The predicted forces are in good agreement with those measured during the experiments, with an overall average absolute error of 4.79% on the main cutting force and an absolute error of 3.03% on the thrust forces. Thus, an overall total absolute error of 4% is noticeable on the all simulated forces, remarking the correct prediction capacities of the numerical model.

### *5.2. Chip Morphology*

In Figure 4 is shown a comparison between the numerically predicted chip serrated morphology and the experimental results. Here it is possible to notice a good qualitative matching between the experimentally analyzed serrated shape of the machined chip and the numerically predicted one.

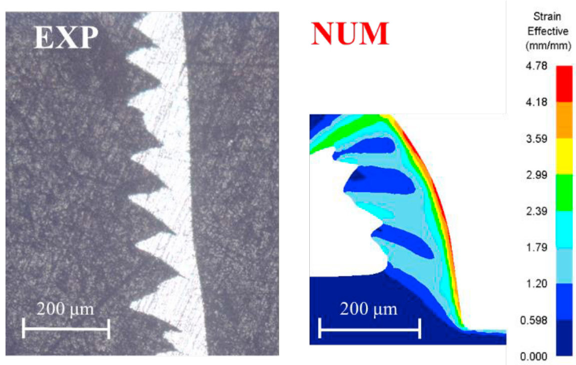


Fig. 4. Graphical comparison between the measured and numerical chip morphology at 300 m/min and 0.1 mm/rev.

On the other hand, in Figure 5 is reported the comparison of the experimental and numerically predicted chip morphology under quantitative terms of peak, valley and pitch. These terms permit a quantitative evaluation of the chip morphology and a proper estimation of the goodness of prediction of the implemented numerical model.

The numerical predicted values are in good agreement with the experimental ones showing a maximum absolute error of nearly 11% highlighting a substantial accordance between experimental and numerical predicted data.

### *5.3. Surface Integrity*

Depending on the severity of the involved machining parameters, different metallurgical phenomena can be promoted on the worked surface and sub-surface.

Zones of intense slip activity are the preferred site for grains nucleation, causing dynamic recrystallization phenomena. In detail, grain refinement layers were noticed on the machined surfaces, where the thermo-mechanical loads were more prominent and consequently a more intense energy is given to the workpiece in terms of plastic work and thermal flux.

In Figure 6 the effects of cutting speed on the worked surface and subsurface are shown (Figure 6b) and these are compared with the as received material (Figure 6a).

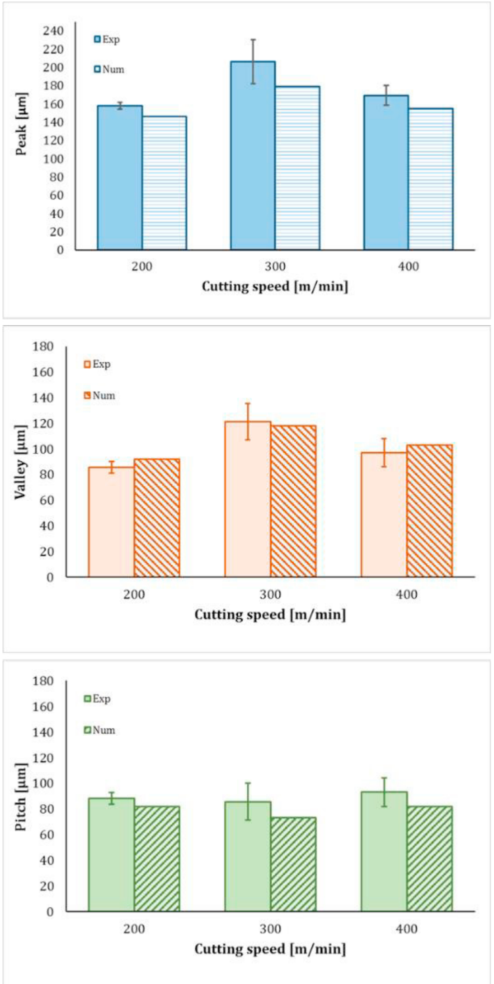


Fig. 5. Comparison between the experimental (Exp) and the numerical predicted (Num) chip morphology at different cutting parameters in terms of peak, valley and pitch.

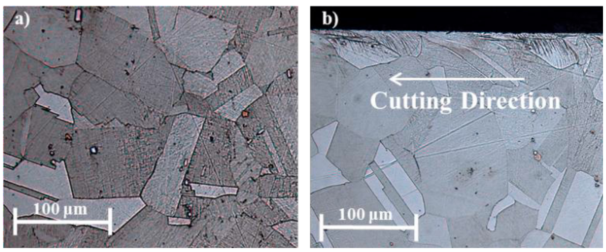


Fig. 6. Comparison between the grain size of the raw material (a) and at the parameters of 300 m/min and 0.1 mm/rev (b).

Figure 7 shows the comparison between the numerical and the experimental grain size values measured on the workpiece machined surface and subsurface. It can be noticed that there is tendency for grain refinement when the cutting speed increases from 200 to 400 m/min. on the other hand, moving from the machined surface until a depth of 100 $\mu m$ the grain size tends to reach the value of the as received material.

In all the investigated cases, extremely near to the worked surface the differences between the numerically predicted values and the experimental ones are lower than the 3% in absolute value. On the other hand, along the depth beneath the worked surface a derive on the difference between numerically predicted and experimentally obtained values is noticeable.

This effect was attributed to the remeshing technique that allows a good prediction of the geometrical variables, but affect also the long range modified variables because of the interpolation of the user variables that occurs at each remeshing step and tends to mediate the grain values extremely near to the worked surface with the bulk value beneath it. This effect causes a shrinkage of the predicted affected layer because of the more prominent presence of bulky dimension grains below it.

However, although the prediction of the grain refinement layer tends to recede along the layer beneath the machined surface, the mean absolute error is in the order of a sole 6% at 50 $\mu m$ of depth where the sub-surface grains were measured.

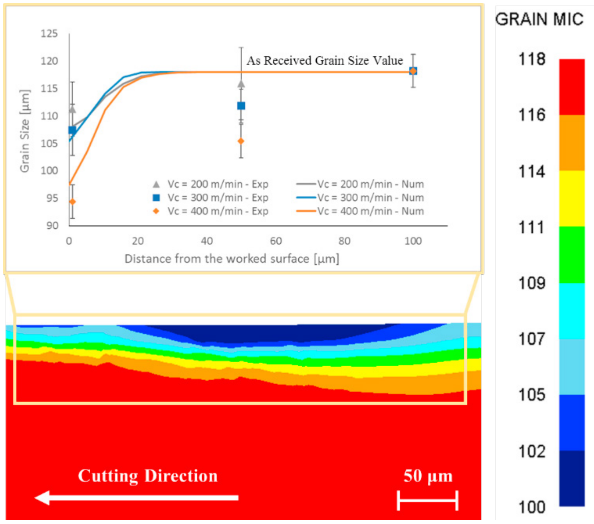


Fig. 7. Comparison between the experimentally measured grain size on the worked surface and beneath it and the numerically predicted ones.

Moreover, in order to predict the experimentally observed variation of the hardness on the worked surface, the Hall-Petch equation has been implemented via user subroutines (Equation 15),

$$HV = C_0 + \frac{C_1}{\sqrt{d}} \qquad (16)$$

The terms $C_0$ and $C_1$ are calibration constants that were taken from [7] and permit to relate the mean grain size dimensions with the hardening increasing on the material.

Figure 8 shows the comparison between numerical and experimentally measured surface hardness values, in all the three investigated cases, the differences between predicted and experimental values are lower than the 3 %, allowing an extremely good prediction of a fundamental index that concerns the finite product surface integrity.

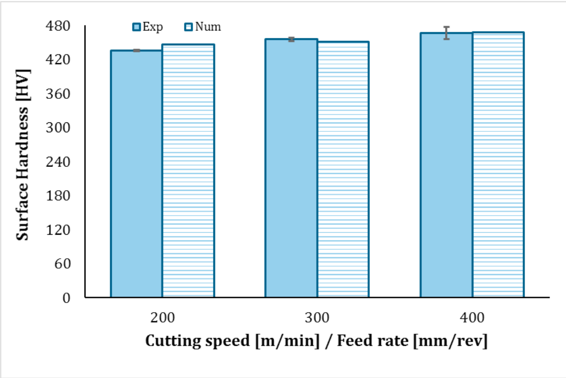


Fig. 8. Comparison between the experimentally measured surface hardness and the numerically predicted ones.

## 6. Conclusions

In this work the physically based constitutive flow stress behaviour model of machined Inconel 718 was used to investigate the main metallurgical phenomena that occur during high speed machining, with particular regard to dynamic recrystallization and Hall-Petch stress.

The dynamic interaction between mobile and immobile dislocations are taken into account in order to understand their effects when plastic deformation is induced by the machining process. Moreover, Hall-Petch hardness prediction model was also implemented into the FE code in order to understand its distribution beneath the machined surface when different cutting parameters are used.

The affordability of the model was verified through comparison between numerical and experimental results and the numerical data were in good agreement with the experimental ones.

The average total error between the predicted and the measured cutting forces was lower than 5% while regarding the grain size prediction it is lower than the 3% with a slight derive along the affected layer. Furthermore, concerning the hardness prediction, the mean absolute error is also of nearly 3%.

The application of the numerical model was crucial to obtain a more affordable numerical prediction compared with the common phenomenological ones, with a consistent reduction of the 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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