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Numerical simulation of surface modification during machining of nickel-based superalloy

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Abstract

The main objective of this study is to implement a reliable FE model of the orthogonal machining of a Nickel based superalloy for the prediction of microstructural changes occurring during the process. A FE numerical model was properly calibrated using an iterative procedure based on the comparison between simulated and experimental results. A user subroutine was implemented in the FE code to simulate the dynamic recrystallization and consequently the grain refinement and hardness variation when orthogonal cutting of Nickel based superalloy is performed. Thus, Zener-Hollomon and Hall-Petch equations were implemented to predict the grain size and micro hardness, respectively. In addition, the depth of the affected layer was predicted using the critical strain equation. The obtained results proved the adequacy of the proposed model showing a good agreement between the simulated and the experimental results.

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1. Introduction

Nickel-based alloys are the most widely used superalloys, accounting for about 50 wt.% of materials used for aerospace applications [1]. In particular, due to their superior properties (e.g., higher strength to weight ratio, high resistance to corrosion, high mechanical and thermal fatigue resistance, high mechanical and thermal shock resistance, superior endurance to creep and corrosion at elevated temperatures, etc.) nickel-based alloys are generally employed by the aerospace or marine industries to develop mechanical components (shaft, blades or exhaust systems) designed to operate in extreme service conditions [2, 3]. Within the commercially available nickel-based superalloys, *Inconel 718* is employed for many applications such as aircraft gas turbines, nuclear power plants, chemical industries and heat exchanger. Nevertheless, *Inconel 718* is generally known to be one of the most difficult-to-machine materials because of its high hardness, high strength

at high temperature, tendency to react with the tool materials, and low thermal diffusivity [4-6].

The severe thermo-mechanical loads, induced during the processing of this material, lead to a reduction of the cutting-tool life and the generation of a poor surface and subsurface integrity. Among the several aspects related to the surface integrity, microstructural and microhardness changes are meaningful factors to take into account during the machining process. Work hardening and dynamic recovery usually take place during the machining process affecting the resulting workpiece microstructure. When the amount of the total existing localized dislocations exceeds a critical value, dynamic recrystallization (DRX) occurs in the corresponding region of the deforming workpiece leading to a grain size modification in the machined surface. This phenomenon occurs near the machined surface influencing the performance and service quality of the final products [7, 8]. For this reason, knowledge about microstructural alteration and consequently

microhardness variation in the surface and subsurface layer become critical for predicting product quality and optimizing the machining conditions. In this context the finite element method (FEM) represents an efficient tool to better understand and simulate the machining process of Inconel 718. In fact, numerous researches in this field involve FEM to investigate the mechanical and thermal variables as well as some parameters related to the surface integrity avoiding, at the same time, expensive and time-consuming experimental investigations.

In this study, the orthogonal cutting process of *Inconel 718* is modeled by using a grain-size based flow stress material. The effective parameters of the simulation, including thermal conditions, friction model and fracture criterion are validated by comparing the numerical results with those experimentally measured. Zener-Hollomon parameter and Hall-Petch equation are implemented to simulate the grain refinement and hardness variation both at the surface and along the depth during the cutting process. A very good agreement is observed between predicted results and corresponding experimental data.

2. Numerical model

2.1. FE modeling of the orthogonal cutting process

The commercial FEA software DEFORM-2D™ is used to simulate the orthogonal cutting process of *Inconel 718* (429 HV). A plane-strain coupled thermo-mechanical analysis is performed. Updated Lagrangian model with remeshing technique is applied to achieve the mechanical and thermal steady state conditions during the simulation. The tool is modelled as a rigid body and meshed with 8000 elements. The workpiece is initially designed with 15.000 isoparametric quadrilateral elements with very fine elements near the cutting zone (1 μm element size), in order to obtain more accurate results and a better chip geometry. A hybrid model based on the sticking-sliding friction condition is used at the tool-chip interface. Sticking-sliding model is governed by the shear friction factor (*m*) and the Coulomb constant (*μ*), respectively. The global heat transfer coefficient (*h*) is also set up to control the heat transfer at the tool-chip interface. In particular, the following values were used for the mentioned coefficients: shear friction factor (*m*=1), Coulomb constant (*μ*=0.3) and global heat transfer coefficient (*h*=100.000 kW/m²K) [9].

During the machining of *Inconel 718*, adiabatic shear bands with low thermal conductivity are developed at the chip leading to the serrated chip formation. In this case, tensile stress plays an important role on the fracture of the material and the starting of the chip segmentation. In this research, Cockcroft and Latham’s criterion is applied in order to predict the chip segmentation during the orthogonal cutting. It can be described as reported in Equation (1):

$$D = \int_0^{\epsilon_f} \sigma_1 d\epsilon \tag{1}$$

Where σ_1 is the principal stress, ϵ_f is the effective strain and *D* is a material constant and often called the critical damage value. The damage value (*D*) is defined as a function of the cutting speed (*V_c*) and the feed rate (*a_f*) [9] as illustrated in the

following equation (2):

$$D = 939.3 - 1040a_f - 22.87V_c + 30400a_f^2 - 36a_fV_c + 0.19V_c^2 \tag{2}$$

User subroutines are implemented in DEFORM-2D software to define the material models. A grain-size based flow stress model is introduced for Inconel 718 as follows:

$$\sigma_{eq} = (A + B\epsilon^n) \left(1 + C \ln \left(\frac{\dot{\epsilon}}{\dot{\epsilon}_0} \right) \right) \left(1 - \left(\frac{T - T_{room}}{T_{melt} - T_{room}} \right)^m \right) \tag{3}$$

The values of the parameters *B*, *C*, *n*, *m* are defined as reported in [9]; while the influence of grain-size reduction on the mechanical behaviour of material is taken into account into the Johnson - Cook (J-C) material model according to equation (4):

$$A = a + \frac{k}{\sqrt{d}} \tag{4}$$

where *d* is the average grain size, and *a* and *k* are two constants calibrated from literature [10-12].

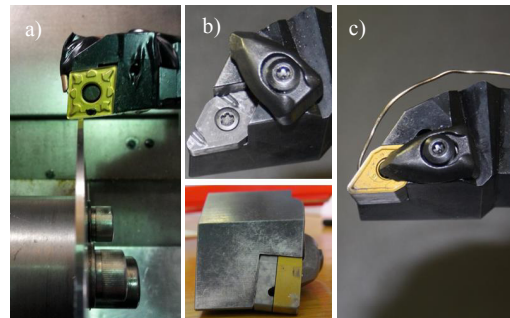


Fig. 1. a) Scheme of the orthogonal machining; b) seat of the thermocouple made on the tool holder; c) embedded thermocouple for measuring the temperature.

Experimental results on cutting forces, chip morphology and temperature are used to validate the results of the orthogonal cutting simulation of *Inconel 718*. The experiments are performed on a CNC turning center. A bar sample with an initial diameter of 347 mm is gently machined in order to create several disks. The *DNMG150616 Sandvik* grooved tools are used for radial cutting operation, as shown in Figure 1. The inserts are mounted on a *Sandvik DDJNR/L* tool-holder to provide rake and clearance angles of -6° and 4°, respectively. A piezoelectric dynamometer (*Kistler 9257*) is employed to measure cutting forces. Furthermore, a thermocouple (K-type) is also embedded between the tool-holder and tool, as shown in Figure 1. The maximum machining temperature at the tool edge location is evaluated by using inverse numerical methodology [12]. After the machining operation, the geometrical parameters of the chips (peak, valley and pitch) are observed and measured by using an optical microscope (1000x). The experiments are carried out at different cutting speed and feed rate, as shown in Table 1.

Table 1. Experimental test conditions.

Testing Number	Cutting Speed [m/min]	Feed Rate [mm/rev]
ID_1	50	0.050
ID_2	50	0.075
ID_3	50	0.100
ID_4	60	0.050
ID_5	60	0.075
ID_6	60	0.100
ID_7	70	0.050
ID_8	70	0.075
ID_9	70	0.100

2.2. FE model and strategy for predicting grain size and hardness

The grain refinement and hardness variation are predicted by implementing a user subroutine in the selected software. Thus, the evolution of material grain size generated by the dynamic recrystallization (DRX) is predicted by implementing the Zener-Hollomon relationship since it is able to combine the working temperature and the strain rate that are the two most important machining parameters for DRX. In addition, the Hall-Petch equation is employed to predict the micro-hardness variation induced on the surface and the subsurface of the machined workpiece. The Zener-Hollomon parameter is defined as follows:

$$Z = \dot{\epsilon} * \exp\left(\frac{Q}{RT}\right) \quad (5)$$

where:

- $\dot{\epsilon}$ is the strain rate;
- $R = 8.3145 \text{ J/(K}\cdot\text{mol)}$, is the universal gas constant;
- $Q = 386 \text{ kJ/mol}$, is the apparent activation energy for the mechanical deformation process [9];
- T is the absolute temperature K.

The recrystallized grain size is related to the Zener-Hollomon parameter as reported below:

$$d = ad_0 Z^m = bZ^m \quad (6)$$

where d_0 is the initial grain size, a and m are two material constants, commonly $d_0 * a$ is identified by one parameter (b in Equation 6).

In particular, a value equal to 0.01 [9], is set for m while b is defined as a function of the feed rate (a_f) as shown in the following equation [9]:

$$b = 600a_f^2 - 139.8a_f + 10.2 \quad (7)$$

Another important parameter to take into account for the grain size prediction is the critical strain ϵ_{cr} , that represents a guard parameter for starting the microstructural changes during the plastic deformation. In fact, the strain should reach ϵ_{cr} to

start the DRX process. Therefore, when the induced strain in the workpiece is below the critical strain ϵ_{cr} , the grain refinement and the onset of DRX do not occur. In this study, the critical strain equation is calculated according to the following equation [9]:

$$\epsilon_{cr} = \left(0.00234 \dot{\epsilon}^{0.1293} \exp\left[\frac{5759.863}{T+273}\right]\right) / 10^7 \quad (8)$$

The hardness variation is also related to the new grain size by using the Hall-Petch equation as follows:

$$HV = C_0 + C_1 d^{-0.5} \quad (9)$$

where C_0 and C_1 are two material constants set respectively equal to 378 and 298.4 [9].

Figure 2 shows the employed strategy to predict the microstructural changes during the orthogonal cutting process of Inconel 718.

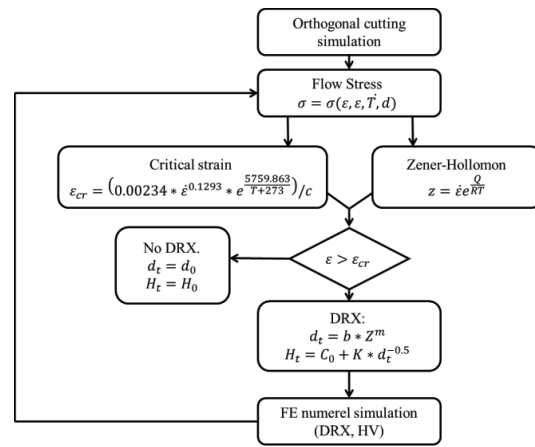


Fig. 2. Implemented strategy for simulation of dynamic recrystallization, grain refinement and hardness variation during cutting process.

At each step of the simulation the Zener-Hollomon parameter and the critical strain are calculated for each element of the mesh. Only when the calculated strain exceeds the critical value, the dynamic recrystallization occurs and a new grain size (Eq. (6)) is calculated replacing the value of the previous step and the microhardness variation is computed according to the Eq. (9). Otherwise, both grain size and hardness do not change keeping the value of the previous step.

2.3. FE validation and FE analysis

The FE developed model has been then validated by comparing the predicted and the experimental data. More in detail, the cutting and thrust forces (Figure 3 and Figure 4) have been compared as well as the chip morphology in terms of peaks height, depth of chip valley and distance between consecutive peaks or valleys as shown in Figure 5.

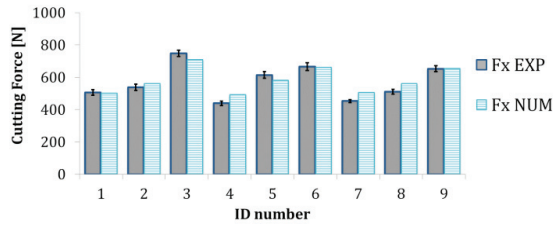


Fig. 3. Comparison of the measured and predicted cutting force (F_x).

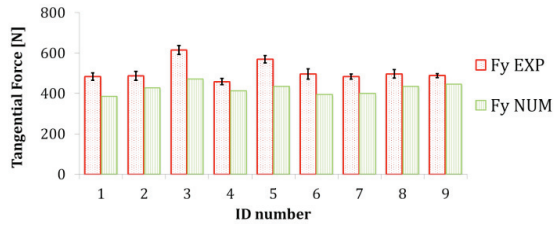


Fig. 4. Comparison of the measured and predicted tangential force (F_y).

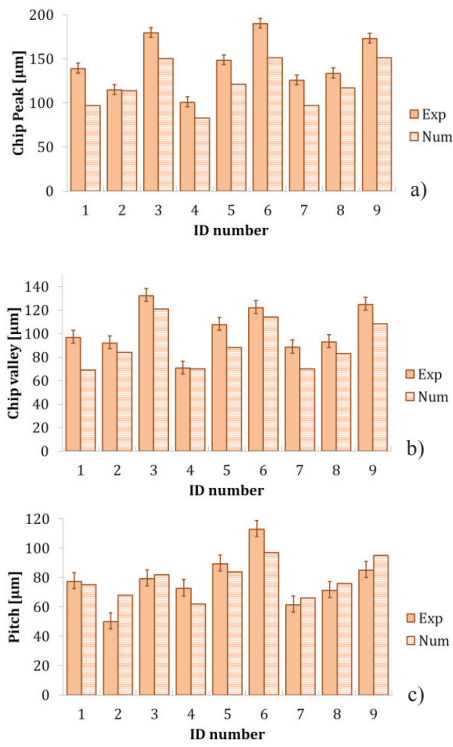


Fig. 5. Comparison of the measured and predicted a) chip peak, b) chip valley and c) pitch.

Both Figures 3 and 4 show a very good agreement between the predicted and experimental results of the cutting and tangential forces as well as the results reported in Figure 5 for chip morphology. Furthermore, the measured temperatures

reached during the experimental process have also been compared with those predicted by the software (Figure 6). The predicted temperatures satisfactory match those experimentally measured with the only exception of those referring to a speed of 60 m/min. This misalliance can be related to the inverse numerical methodology used to estimate the experimental values [12].

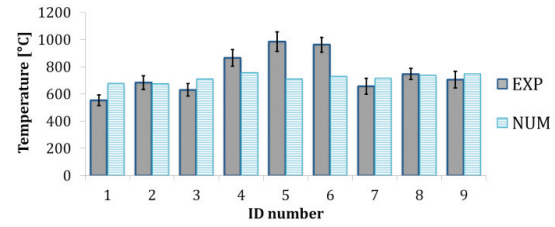


Fig. 6. Comparison of the measured and predicted results of maximum temperatures.

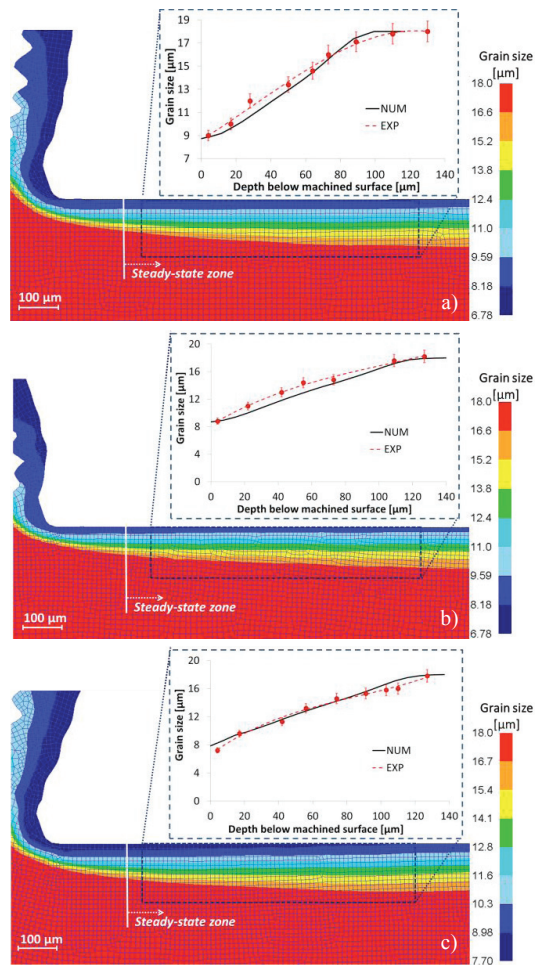


Fig. 7. Results of the implemented user subroutine for predicting the grain size at the cutting parameters of a) 60m/min and 0.05mm/rev; b) 60m/min and 0.075mm/rev; c) 60m/min and 0.1mm/rev.

Figure 7 shows a steady-state step of the FE simulation at 60 m/min varying the feed rate. The implemented user routine gives stable and almost uniform data prediction outside of the transient phase, near the tool tip, where the temperature are still not stationary. Thus, the valid results are those related to the steady state region that also has a proper mesh configuration. The results of the simulations generally confirm an orthogonal cutting process of the *Inconel 718* alloy causes severe alterations in the surface and subsurface of the machined workpiece. It can also be noticed that a bigger refinement (smaller grain size in machined surface) leads to the higher hardness at the corresponding location (Figure 8). These alterations (including the depth of the affected layer, microhardness and grain size changes) increase when machining at higher cutting speeds and feed rates.

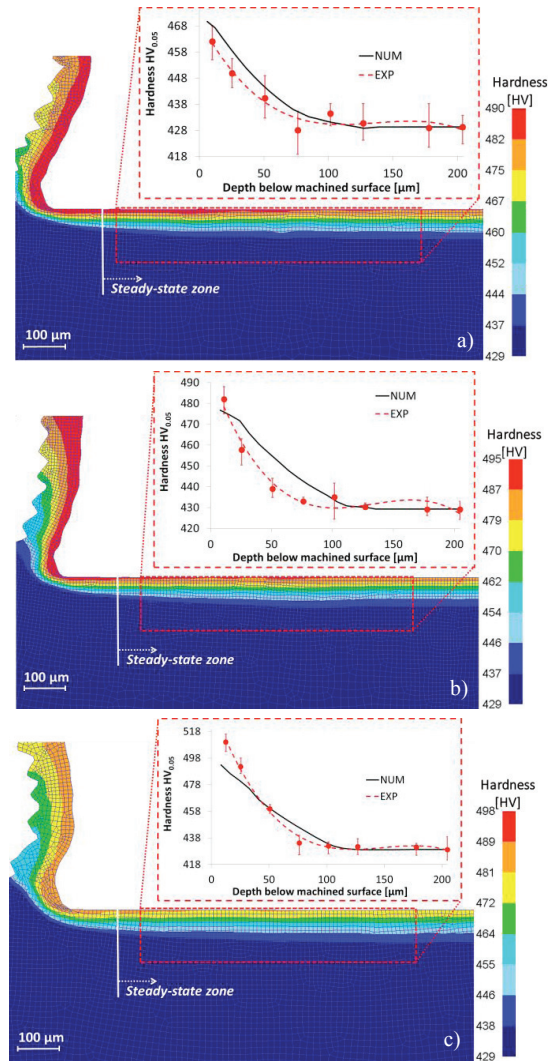


Fig. 8. Results of the implemented user subroutine for predicting the hardness at the cutting parameters of a) 60m/min and 0.05mm/rev; b) 60m/min and 0.075mm/rev; c) 60m/min and 0.1mm/rev.

The overall validation results of microstructural changes are reported in Table 2. Based on these results there is a good agreement between predicted and experimental values, with a maximum average error smaller than 11%.

Table 2. Comparison of measured and predicted results of microstructure and hardness changes.

Testing Condition		Surface Grain size (μm)	Surface Hardness (HV)	Average error (%)
ID_1	Exp	9	452	
	Num	9.1	469	
	Err	1.1 %	3.7 %	2.4 %
ID_2	Exp	9.1	472	
	Num	7.8	485	
	Err	14.2 %	2.7 %	8.4 %
ID_3	Exp	9	489	
	Num	7.2	495	
	Err	20.0 %	1.2 %	10.6 %
ID_4	Exp	9	462	
	Num	8.9	478	
	Err	1.1 %	3.4 %	2.2 %
ID_5	Exp	8.8	482	
	Num	7.1	491	
	Err	19.3%	1.8 %	10.5 %
ID_6	Exp	7.2	510	
	Num	6.2	501	
	Err	13.8 %	1.7 %	7.7 %
ID_7	Exp	8.2	489	
	Num	8.8	488	
	Err	7.3 %	0.2 %	3.7 %
ID_8	Exp	6.2	516	
	Num	6.1	529	
	Err	1.6 %	2.5 %	2 %
ID_9	Exp	4	528	
	Num	3.9	592	
	Err	2.5 %	12.1 %	7.3 %

3. Conclusion

In this paper a modified grain-size based flow stress model is proposed to simulate the surface modification (grain size and hardness change) during the orthogonal cutting of *Inconel 718* alloy. The Zener–Hollomon and Hall–Petch equations have been employed for predicting the grain size and hardness evolution. The simulated results have been validated by comparison with the experimental results and satisfactory agreement between numerical and experimental results was found. Thus, it can be concluded that the proposed FE strategy can be used to properly simulate the cutting process of the *Inconel 718* alloy with particular reference to cutting forces, chip morphology and maximum cutting temperatures. Furthermore, the Zener-Hollomon parameter employed to relate the deformation conditions with the recrystallized grain

size, and the Hall-Petch equation, used for the hardness variation, provided satisfactory results to accurately simulate the grain refinement and the micro-hardness during machining process of *Inconel 718* alloy.

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