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2D FE prediction of surface alteration of Inconel 718 under machining condition

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Abstract

Nickel-based super alloys such as Inconel 718 are widely employed in extremely hostile applications owing to their superior thermo-mechanical properties. On the contrary, these latter lead the industries to adopt conservative process parameters (e.g. low cutting speed) resulting in lower production rates. The possibility to increase the cutting parameters could lead to higher material removal rates and drastic reduction of the machining time of the process. The aim of this study is to investigate the effects of extreme cutting parameters on the surface and subsurface alterations such as grain size and hardness changes by developing a finite element (FE) numerical model. The Zener-Hollomon and Hall-Petch equation were implemented to predict the grain size and micro hardness variations due to the cutting process. In addition, the depth of the affected layer due to machining was predicted using the critical strain equation. The obtained results proved the accuracy and reliability of the proposed FE model showing a good agreement between the simulated and the experimental results.

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Keywords: Hard Machining; Inconel 718; Finite Element Method (FEM); Surface Integrity.

1. Introduction

Amongst the super alloys used in aero engine manufacturing, nickel-based alloys stand out particularly; in fact they are the most used in terms of weight percentage for aerospace applications. This wide usage is attributed to their extremely high thermo-mechanical properties such as high resistance to corrosion, high strength to weight ratio, high fatigue and creep resistance, etc.

Within nickel-based alloys, *Inconel 718* super alloy is one of the most used for artefacts that work in high temperature conditions, such as the critical components of the aircraft engines, nuclear power plants and marine equipment. This super alloy is considered one of the most difficult-to-machine material because of its rapid work hardening and low thermal diffusivity [1]. The mechanical and thermal loads imposed on the workpiece by the machining process could cause some microstructural and metallurgical alterations on the machined surface and sub-surface layer. These alterations include grain refinement and surface hardness changes that affect the mechanical behaviour of the machined components and impact their fatigue life [2, 3].

Having a numerical model that can predict i) the material thermo-mechanical behavior and ii) the evolution of the microstructure consequential to machining process, is important to obtain feedback information and establish control of the machining process and achieve the desired surface integrity. This will also lead to avoiding many long and expensive experimental trials [4].

In this paper we have investigated for the orthogonal machining tests that involve a range of cutting speeds, exceeding the commonly used speeds within industries for *Inconel 718* alloy. Subsequently, the development of a customized numerical model is shown and the numerical

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results in terms of cutting forces, chip morphology and surface integrity (hardness and grain variations) are compared with the experimental ones. Zener-Hollomon and Hall-Petch equations are implemented to simulate the grain refinement and the hardness variation both on the worke subsurface and along the depth.

2. Experimental procedure

The experimental tests were performed under dry cutting conditions at the Advanced Manufacturing Research Centre with Boeing, The University of Sheffield. The workpiece material used was an *Inconel 718* tube of outer diameter 102 mm and inner diameter 89 mm, with a nominal chemical composition of 53.9% Ni, 18.5% Cr, 5.11%Nb, 5.11% Ta, 3.03% Mo, 0.49%Al, 1.01%Ti, 0.09% Co, 0.05% Si, 0.05% Mn, 0.03% Cu, 0.022% C and Fe balance (all weight percent). The tube was solution annealed and aged to a surface hardness of 40 HRC.

Orthogonal turning trials were performed (three repetition for each case analysed) under dry cutting conditions on 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 machining. The cutting speeds set for the cutting 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.

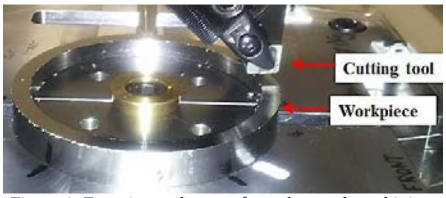

Figure 1: Experimental set-up for orthogonal machining.

The chips and machined surface samples obtained by each cutting test were collected and processed for chip morphology (in terms of peak, valley and pitch) and microstructural analysis. The samples were polished and etched using Kalling's reagent No 2. The optical analysis was conducted with the microscope *LEICA DFC 320*. The grain size has been measured as specified in "ASTM E112 – 12 Standard Test Methods for Determining Average Grain Size" referring to "*Planimetric Procedure*" [5]. The microhardness was measured by means of a Knoop indenter at a load of 50 g for 15s on polished samples (four to five indentation for each different depth).

3. Numerical Model

Once obtained and defined all the results coming from the experiments, a finite element model was used to predict all the important variables of interest. A FE-based thermo-mechanical model formulation of the orthogonal cutting process has been developed using the commercial FE software SFTC Deform 2D®. A plane-strain multi physics analysis was performed by using orthogonal assumption, the Update-Lagrangian code with remeshing technique was utilized. The workpiece was meshed with 5000 isoparametric quadrilateral elements (the elements size is nearly 160 μm) and a very fine elements size was defined near the cutting zone (the elements size is nearly 8 μm), in order to obtain more accurate results and a better chip geometry, the tool was modelled as a rigid body.

In the simulation the tool was totally deprived of all displacement, while the workpiece was able to move only along the X direction. The temperatures at the bottom and left sides of the workpiece as well as the top and right sides of the cutting tool were set to equal to the room temperature, T_{room}, which was assumed of 20 °C. The top and right sides of the workpiece as well as the left and bottom sides of the cutting tool were allowed to exchange heat with the environment. The global heat transfer coefficient, h_{int}, at the tool-chip-workpiece interfaces was set equal to 10^5 kW/(m^2K) according to the guidelines and literature results [6, 7].

In order to simulate as real as possible the orthogonal cutting process the mechanical and thermo-physical properties for the workpiece and the tool were defined taking into account the software database. In this work, Cockroft and Latham's damage criterion [7] was considered in order to predict the chip segmentation during the orthogonal cutting. The equation 1 shows this criterion:

$$\int_0^{\varepsilon_f} \sigma_1 \, d\varepsilon = D \tag{1}$$

Where σ_1 is the principal stress, ε_f is the effective strain and D is a material constant. The value of D has been calibrated comparing the numerical chip morphology with the ones evaluated through optical micrographs.

As demonstrated by Özel [9], different friction definitions can lead to obtain different simulation outputs. For this reason, to properly simulate the cutting process, a hybrid friction model, based on sticking-sliding model was implemented and calibrated (μ = 0.8, m = 1 for 200 and 300 m/min; μ = 0.6, m = 1 for 400 m/min).

The material constitutive model and the different laws about grain size modification and hardness evolution have been implemented via user subrutine. The flow stress behaviour was defined using Johnson-Cook (J-C) model that describes the plastic deformation of materials at different ranges of strain, strain rate and temperature. Several J-C models with different set of coefficients are available in literature, according to Jafarian et al. [3]. In the current study the model used is as shown in Equation 2:

$$\sigma = (1290 + 895\varepsilon^{0.526}) \times \left(1 + 0.016 ln \frac{\dot{\varepsilon}}{0.03}\right) \times \left(1 - \left(\frac{T - T_r}{T_m - T_r}\right)^{1.55}\right) \tag{2}$$

where σ is the flow stress, ε is true strain, $\dot{\varepsilon}$ is true strain-rate, $\dot{\varepsilon}_0$ is reference true strain-rate and T, T_m, T_r, are work, material melting and room temperature respectively ($T_m = 1300$ °C; $T_r = 20$ °C).

The recrystallized grain size d, due to the *DRX* phenomena, has been calculated considering the Equation 3 [10],

$$d = b\dot{Z}^m \tag{3}$$

where b and m are two material constants. This numerical expression depends on Zener-Hollomon parameter ($\dot{Z}$). In the user routine, Zener-Hollomon equation proposed by Abbasi et