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Finite element simulation of machining Inconel 718 alloy including microstructure changes

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ABSTRACT

Inducing thermo-mechanical loads during the machining of hard materials lead to the severe grain refinement and hardness variation into the machined surface. This variation significantly affects the performance and the service quality of the products. Inconel 718 superalloy is one of the difficult-to-machine materials employed widely in aerospace industries and its surface characteristics after final machining process is really important. The main objective of this study is to implement a reliable finite element (FE) model for orthogonal machining of Inconel 718 alloy and prediction of the microstructure changes during the process. At first, experimental results of cutting forces, chip geometry and maximum temperature were taken into account to identify the most suitable material model out of the seven models found in the literature. Then, the FE numerical model was properly calibrated using an iterative procedure based on the comparison between simulated and experimental results. Moreover, a user subroutine was implemented in FE code to simulate the dynamic recrystallization and, consequently, to predict grain refinement and hardness variation during the orthogonal cutting of Inconel 718 alloy. Zener–Hollomon and Hall–Petch equations were employed to respectively predict the grain size and microhardness. In addition, the depth of the affected layer was controlled using the critical strain equation. As overall, a very good agreement has been found between the experimental and simulated results in term of grain size, microhardness and depth of the affected layer.

1. Introduction

Nickel-based superalloys were created in the 1940s to be used in gas turbine applications because of their excellent performance and service quality. Inconel 718 superalloy is one of the hard materials among other nickel based alloys which are also used extensively in many industries. Inconel 718 has superior properties such as wear resistance, high melting temperature, high corrosion and creep resistance and maintaining strength and hardness at high temperatures. Consequently, this alloy finds a wide range of applications in the aerospace industry and in the rotary parts of gas turbine engines such as blades, shafts and disks. The mentioned properties are responsible for poor machinability of the Inconel 718 from various points of view such as surface integrity [1–3].

Surface integrity of a machined workpiece is one of the most specified customer's requirements. It becomes more essential in machining of difficult-to-cut materials (such as Inconel 718) because of the severe thermo-mechanical loads induced during the process. Surface and subsurface alterations including microstructural and microhardness changes are significant factors of the surface integrity [4,5]. Machining is known to be a fast chip formation operation where a workpiece material is exposed to high temperature, strain and strain rate during the process. When the amount of these dislocations exceeds a critical value, dynamic recrystallization (DRX) occurs and leads to the grain refinement in the machined surface. Microstructural changes and consequently microhardness variation during the finish turning process are much more important than most of the manufacturing processes, since these phenomena occur near the machined surface and directly influence the performance and service quality of the final products [5,6]. However, experimental investigation of the surface integrity in machining processes is very expensive and time-consuming.

Recently, the finite element method (FEM) has been developed as a beneficial and efficient tool in order to simulate the machining processes [6,7] and to investigate the mechanical and thermal variables as well as the some parameters related to the surface integrity avoiding, at the same time, unnecessary experiments [6]. Unfortunately, it should be highlighted that various indicators of the surface integrity, such as residual stresses and microstructural changes, are difficult to model and required accurate inputs [6,8].

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Therefore, reliability of the machining simulation is a very important task, especially when valuable outputs such as the surface integrity parameters are modeled.

In this regard, the material constitutive model is the most important prerequisite for simulation of the cutting process and plays a significant role on the FE numerical results. In other words, the identification of the most reliable material model is the first step for an accurate simulation of the machining process. In general, the Johnson–Cook's (*J–C*) constitutive equation is used to model the behavior of the workpiece material during the cutting simulation [6,9]. Furthermore, the reliability of the numerical models drastically depends on the fracture criterion, frictional and thermal parameters between the chip, tool and workpiece interfaces [6]. Therefore, a suitable selection of these parameters is also an essential step to obtain a reasonable accuracy for the prediction of the cutting forces, temperature fields, and chip geometry [6,9,10]. As overall, it is evident that, the correct selection of the mentioned parameters is truly beneficial for predicting the surface integrity on the machined workpiece by FE analysis.

Currently, significant improvements have been reported for machining simulation of difficult-to-cut materials [11,12], especially for the machining of nickel and titanium based alloys [3,13–15]. Recently, Ahmed et al. [16] modeled the distribution of thermal strain in the machined surface during conventional and ultrasonically assisted turning of Inconel 718. Courbon et al. [17] investigated the effect of high-pressure coolant on the thermal and mechanical loads induced during the machining of Inconel 718. Ozel et al. [18] conducted an experimental and numerical investigation in order to evaluate the effect of the tool nose radius on the cutting forces and residual stresses in the machining of Inconel 100 alloy.

So far, several *J–C* material models have been introduced for aged and annealed Inconel 718 superalloy, although the degree of success of these material constitutive models has not been compared with various machining experiment tests to identify the most reliable material model for the simulation of the cutting process (e.g., a sort of benchmark). In addition, only few works are found in literature to simulate the microstructural changes during the machining of other materials [3,19], but also it has been never conducted for machining of Inconel 718 alloy.

In this study, orthogonal cutting process of Inconel 718 was modeled using the FE method in order to improve the knowledge on the *J–C* material constitutive model for Inconel 718, to highlight advantages and drawbacks of different set of material constants and to enhance the FE analysis when surface integrity parameters need to be predicted. To do that, the process was firstly simulated using different *J–C* material models and the results were compared with experimental data to identify the most reliable material model. The effective parameters of simulation including thermal and frictional conditions and fracture criterion were calibrated and then validated with several experimental data. Once the most suitable *J–C* material constitutive equation was found, a user subroutine was implemented in the FE software to simulate microstuctural and microhardness changes. Zener–Hollomon parameter and Hall–Petch equation were taken into account to simulate the grain refinement and hardness variation, respectively. In addition, the depth of the affected layer was controlled using the critical strain considered as a function of the temperature and strain rate. At the end, a very good agreement was reported between predicted results and corresponding experimental data.

2. Literature review on material model of Inconel 718

Johnson–Cook (*J–C*) model describes the plastic deformation of materials at the different range of strain, strain rate and temperature. Therefore, this model is mostly utilized for the modeling of the material behavior in the simulation of cutting process where large plastic deformations are occurred during the chip formation. In this study, different *J–C* material models were employed to simulate the thermo-visco plastic behavior of Inconel 718 superalloy. This equation is presented using the following equation:

$$\sigma=(A+B\varepsilon^{n})\left(1+Cln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right)\left(1-\left(\frac{T-T_{room}}{T_{melt}-T_{room}}\right)^{m}\right) \quad (1)$$

where σ is the flow stress, ε the plastic strain, $\dot{\varepsilon}_0$ the reference plastic strain rate (s^{-1}), $\dot{\varepsilon}$ the strain rate (s^{-1}), T (°C) is the workpiece temperature, T_{melt} is the melting temperature of the workpiece material (1300 °C for Inconel 718), and T_0 is the room temperature (25 °C). *A*, *B*, *C*, *n*, and *m* are the *J–C* constants where *A* (MPa) is the yield strength, *B* is (MPa) the hardening modulus, *n* is the hardening coefficient, *C* is the strain rate sensitivity coefficient, and *m* is the thermal softening coefficient. In fact the first, second and third bracket in *J–C* equation are taken into account for the strain hardening, strain-rate hardening, and thermal softening effect, respectively. In the literature, different combinations of *J–C* parameters have been reported for Inconel 718 alloy which some of them were found for the aged Inconel 718 in 45 HRC (models M_1–M_7).

Demange et al. [20] conducted SHPB experimental tests to identify a new combination of *J–C* material constants (model M_1) for both annealed and aged samples. The experiments were measured in strain rate up to 1000 s^{-1} and temperature in the range of 72–400 °C. The constitutive equation related to the aged samples was implemented in the FE model. Recently, Wang et al. [21] proposed a modified *J–C* model (model M_2) where the strain rate softening effect (*C* constant in *J–C* equation) was found to be dependent of the temperature and strain rate. Then, the *C* parameter was proposed using the following equation:

$$C=0.0232-\left(0.00372+0.0021\ \mathrm{Sin}\left(\frac{\dot{\varepsilon}-5000}{3000}\pi\right)\right)\mathrm{Sin}\left(\frac{T-500}{150}\pi\right) \quad (2)$$

They also conducted the SHPB tests at high range of strain rate and temperature to access a suitable model for the simulation of cutting process. The SHPB tests were performed at the strain rate of 5000–11,000 s^{-1} and the temperature of 500–800 °C.

Klocke et al. [22] carried out an inverse methodology to identify the *J–C* parameters (model M_3) using finite element simulation of orthogonal cutting process. The constants *A*, *B* and *n* in Eq. (1) were obtained by using the quasi-static tests taken from Issler's work [23]. They implemented different values of *C* and *m* in the *J–C* equation for the simulation of the process. Then, the most suitable values were obtained by comparison between the predicted and experimental results of cutting forces and chip geometry. Pereira et al. [24] conducted SHPB tests for annealed and aged IN718 to determine the *J–C* material model. The experiments were performed at room temperature and at the strain range of 1600–5000 s^{-1}. A new set of the constitutive model was suggested by Mitrofanov et al. [25]. The *A* and *B* constants in *J–C* equation were calculated from the quasi-static material property data while *C* and *n* parameters (strain hardening constants) were adopted from the Pereira's material model [24]. Unfortunately, it should be note that the thermal softening effect was neglected in Pereira's model [24].

Afterwards, Lorentzon et al. [26] developed a new *J–C* material model (model M_4) by adding the thermal softening effect to the Mitrofanov equation [25]. In fact, they adopted the parameter related to the thermal softening effect (*m* constant in *J–C* equation) equal to that found by Sievert et al. [27] although in this latter work the derivation of the *m* parameter was obtained for annealed samples, while model M_4 was introduced for aged Inconel 718. Ozel et al. [28] proposed a modified *J–C* equation for Inconel 718 in which the dynamic behavior of the material was taken into