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Identification of new material model for machining simulation of Inconel 718 alloy and the effect of tool edge geometry on microstructure changes

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ABSTRACT

Johnson–Cook (J-C) material model is often used for Finite Element (FE) modeling of cutting processes and it affects significantly the results of simulation. Since experimentally determination of J-C equation parameters is an expensive and time-consuming task, in this paper, a new and efficient methodology was implemented based on the evolutionary optimization algorithm to identify new J-C material constants for Inconel 718 superalloy. Then, orthogonal cutting process of Inconel 718 was simulated using the new material models. The results of simulation were compared extensively with experimental results of cutting forces, chip geometry, and maximum temperature to select and then validate the most suitable material model. After that, a user subroutine was implemented in FE code to model microstructure changes using the dynamic recrystallization mechanism in cutting process of Inconel 718. The Zener–Hollomon and Hall–Petch equations were used to respectively predict the grain size and hardness. The results of simulation were verified successfully with corresponding experiments in terms of near-surface profile. At the end, the effect of tool edge geometry including honed and chamfered tool edge was investigated on microstructure changes.

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1. Introduction

Inconel 718 is one of the most well-known superalloys used widely in different industries because of its excellent properties such as high melting temperature, wear and corrosion resistance, and maintaining hardness at high temperatures. Turning is one of the most frequent manufacturing processes employed for Inconel 718 alloy, since this alloy is mainly used in rotary parts of the components [1,2]. Owing to the fact that experimentally evaluation of machining outcomes is an expensive and time-consuming task, Finite Element Analysis (FEA) of the cutting process can be used to avoid these problems and to better understand the process [3,4]. In order to machining of hard materials such as Inconel718, reliability of the FE results is an important challenge in scientific community. Material model is one of the dominant prerequisite to simulate the machining processes and plays significant role on accuracy of the predicted results.

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Large and fast plastic deformations during the cutting process leads to the generation of high temperature and strain rate into the workpiece. Therefore, Johnson–Cook (J-C) material model is often used for simulation of cutting process, since this model describes the material behavior at different temperature strain and strain rate [5]. Up to now, different combinations of J-C material model have been introduced for Inconel718. Demange et al. identified a new combination of J-C material constants for Iconel718 using Split Hopkinson Pressure Bar (SHPB) tests [6]. Recently, Wang et al. conducted the SHPB tests at high range of strain rate and temperature. The C constant in J-C equation was obtained as a function of strain rate and temperature [7]. Klocke et al. implemented an iterative procedure based on the FE simulation of cutting process to determine some of the J-C parameters, while the other parameters were adopt from literature [8]. The SHPB tests were carried out for annealed and aged IN718 to identify J-C equation parameters by Pereira et al. [9]. Using the quasi-static material property, the J-C material model was developed by Mitrofanov et al. [10]. The effect of thermal softening (m constant in J-C equation) was not taken into account in this model. After that, it was added by Lorentzon [11]. A new J-C material model was introduced by Ozel et al. [12] and dynamic behavior of the material was also added to the model. Recently, an inverse strategy was developed by Malakizadi et al. to identify a new material model [13]. It was implemented using the FE simulation and Response Surface Methodology (RSM). The hardness-based flow stress was developed by Prete et al. to take into account the effect of initial workpiece into the J-C material model [14]. The influence of the mentioned material models on predicted results by machining process was compared together by Jafarian et al. [15].

It should be noted that, suitable determination of J-C material constants is a time-consuming and expensive task. Therefore, development of a new and low-cost strategy for this purpose seems to be necessary. Based on this, at the first section of this study an efficient methodology was implemented to determine new J-C equation parameters for Inconel 718 alloy. Then, the most suitable material model was identified using the FE modeling of orthogonal cutting process and comparing the results with corresponding experiments. Then, it was used for subsequent simulations.

The micro structure change induced by machining process is one of the indications of surface integrity. It affects significantly on surface quality and component life, since physical and mechanical properties of the workpiece are changed drastically near the machined surface [16]. Few studies can be found in literature to numerically model the microstructure changes in machining processes. Firstly, Umbrello used a thermal model (based on the quenching and tempering process) to model hardness modification in machining of AISI52100 steel [17]. Rotella et al. simulated the micro structure changes in machining of AA7075-T651 alloy using the dynamic recrystallization (DRX) mechanism [18]. The Zener–Hollomon parameter was used for modeling the grain size and the Hall–Petch equation was employed for prediction of hardness. Authors at their previous study estimated the surface grain size and hardness value using the DRX mechanism during the machining of Inconel 718 alloy [19].

It should be noted that, not only few studies are found in this regard, but also the effect of process conditions such as tool geometry has not been investigated yet on microstructure changes. Therefore, at the second section of this paper, the microstructure change in machining of Inconel 718 alloy was modeled using the DRX to take into account the effect of tool geometry. After validating the numerical results of grain size and hardness in terms of near surface profile with corresponding experiments, the effect of tool edge geometry including chamfered and honed edge tool was investigated on microstructure changes.

2. Implemented strategy for determination of new J-C material constants

In FE simulation of cutting processes, accuracy of the results are strongly depentent on the material model. The Johnson–Cook constitutive equation is often used for simulation of cutting process because this model describes material behavior at large plastic deformations. On one hand, experimentally determination of J-C parameters using some methods such as Split Hopkinson Pressure Bar (SHPB) is an expensive and time-consuming task, on the other accuracy of these models at high ranges of temperature and strain rate is an important challenge to be used for modeling of the cutting processes. In this paper, a new methodology based on the evolutionary optimization algorithm (Genetic Algorithm (GA)) and FE simulation of cutting process was utilized to identify new J-C material constants for Inconel 718 alloy. It is the efficient and low-cost strategy to determine desirable material model for machining process. The J-C equation is illustrated using the following equation:

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

where σ is the flow stress, $\dot{\varepsilon}_0$ is the reference plastic strain rate (s^{-1}), ε is the plastic strain, $\dot{\varepsilon}$ is the strain rate (s^{-1}) and T_0 (°C), T_{melt}, T are room temperature, workpiece melting temperature, workpiece temperature, respectively. *A, B, C, n*, and *m* are the J-C material constants.

In order to implement the strategy and identify new J-C parameters, firstly, the experimental results of flow stress curves (for Inconel 718 alloy at 45HRC) were used from the literature [7]. The required experiment data were extracted at the given temperature, strain, and strain rate. Then, the J-C equation constants were selected to be optimization variables, and the new variables were used in Eq. (1) to calculate the flow stress. After that, the difference between calculated and experimental flow stress at the corresponding temperature, strain, and strain rate was defined as the objective function of the optimization algorithm. For each generation of GA, the optimization variables were updated so that the objective function is reduced

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