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MPM simulations of high-speed machining of Ti6Al4V titanium alloy considering dynamic recrystallization phenomenon and thermal conductivity

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A B S T R A C T

Ti6Al4V titanium alloy is often used in the aircraft industry due to its good strength and toughness etc. However, it is very difficult to simulate high speed machining of titanium alloy using the finite element method (FEM). The reason is that the high speed, large deformation and high strain rate of metal material at high temperature etc. will lead to the element distortions and other numerical difficulties. In contrast with FEM, material point method (MPM) has the advantage of simulating extreme large deformation, fracture and impact problems. Therefore, it is specially suitable for dealing with high speed cutting process. In many existing researches about the high speed cutting process using Johnson–Cook constitutive model, the material dynamic recrystallization softening effect under high pressure and high temperature has not been considered. For this, three modified Johnson–Cook constitutive models for Ti6Al4V titanium alloy are adopted and the parameters for these models were obtained by the split Hopkinson pressure bar (SHPB) test considering the critical strain values, high-temperature range and dynamic recrystallization phenomenon. Furthermore, to ensure the numerical accuracy, the transient heat conduction algorithm is employed in MPM implementation. Finally, comparison and discussion are carried out between the experimental and the simulation data, which show that the high speed cutting process can be better simulated using the modified Johnson–Cook constitutive models.

1. Introduction

For many years, titanium alloys have been widely used in modern manufacturing industry such as aerospace, automotive, marine and biomedical etc. [1]. The attractive properties of titanium alloys are high specific strength at low to moderate temperatures, good chemical resistance, and relatively low densities etc. However, titanium alloys are also known as difficult-to-cut materials, because the characteristics mentioned above and the poor thermal conductivity of titanium alloys lead to an accumulation of heat, especially at the tool/chip interface under the cutting process, which may cause exceedingly early failure of the cutting tool and adversely affect the machined surface quality [2,3]. During the machining process, the microstructure alteration and phase transformation are greatly affected by high temperature and strain during machining

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processes [4]. At high speed cutting stage of titanium alloys, many materials give rise to segmented chips, which severely affect the machining process (cutting forces, temperature and workpiece surface quality). Thus, it is important to have an in-depth study of the microstructure and phase changes of titanium alloys, and have a thorough understanding of the phenomenon of segmented chips during machining process.

The experiments and the numerical simulations are two important methods to study the machining process. The experiments are complex, expensive, time-consuming and difficult to be operated in the cutting process. Compared with experimental methods, numerical methods have some obvious advantages which could not only cover the shortages of the experiments, but also explain the observed phenomena and help define the optimal cutting conditions. Therefore, it is important to employ the numerical models and adequate constitutive laws in the machining process. A correct simulation can show good prediction by considering various factors such as the temperature, strain, stress distribution, dynamic recrystallization phenomenon and thermal conductivity etc. on mesoscopic level. In order to correctly predict the mainly mechanical behavior, thermal variables, chip morphology, cutting force [5], the new materials constitutive laws [6-8] and the simulation strategies [9] have been studied.

Considering the effect of grain size on deformation ununiformity, Zerilli and Armstrong [10] presented a constitutive relation through the use of dislocation mechanics based constitutive relations which considered strain hardening, strain-rate hardening, and thermal softening factors. Lennon and Ramesh [11] proposed a modified Zerilli-Armstrong (mZA) model which considered the coupled effect of strain rate and temperature. It is noteworthy that this model is suitable to predict the flow stress of material at high temperatures. Based on the theory of thermally activated dislocation motion in crystal materials, Gao et al. [12] proposed a new constitutive model for HCP metals which are subjected to high strain, high strain rate and high temperature. This model which is applicable to Ti6Al4V titanium alloy has displayed higher precision compared with the original Johnson−Cook and Zerilli-Armstrong models. Slooff et al. [13] presented a constitutive equation which contains the sine-hyperbolic component and the strain parameter for wrought magnesium alloy, and the calculated results showed good agreement with the measured flow stresses in the relevant temperature range. Lin et al. [14] proposed a revised sine-hyperbolic constitutive equation which considered strain and strain-rate compensation to describe the flow behavior of materials.

In the past few years, numerical methods have successfully been applied to various engineering fields, especially for the fundamental process of machining in manufacturing industry. In machining process, the analytical, numerical and experimental methods are often applied. Most numerical works have been performed to analyze cutting process by FEM. As early as 1945, Merchant explained the cutting process with mechanics, and the plastic behavior of material was considered [15,16]. In 1985, Strenkowski et al. [17] and Carroll [18] presented their numerical work of orthogonal metal cutting. In 1989, Howerton [19] carried out the experimental and numerical investigations of orthogonal machining of aluminum 6061-T6. In 2002, the machining process was modeled with two-dimensional and three-dimensional models by Ng et al. [20,21]. In 2003, Bäker presented the energy dissipation approach to study thermal effects on the chip morphology [22,23]. In 2004, Aurich [24] used FEM to simulate the orthogonal metal cutting process. In 2006, Mabrouki [25] studied the thermo-mechanical effect on the chip morphology with ABAQUS/Explicit software. In 2008, Zhang et al. [26] simulated the serrated chip and analyzed the damage in the chip. Most of researchers studied the machining process by the FEM [27−30], some researchers did not carry out comparison between the FEM solutions and the experimental results [30]. However, there are also many studies that compared experimental results with numerical results [6,26,31−33], and some theoretic results were compared with experimental ones from other previous studies [27,28]. As we have known, the numerical results from FEM are sensitive to the meshes [34], and the severe deformation of material always leads to heavy mesh distortion in the machining process. The mesh distortion diminishes accuracy of the numerical results, and the severe mesh distortion even terminates the computational process. Later, the arbitrary Lagrangian-Eulerian method (ALE) have been applied for cutting process simulation to reduce element distortion of FEM [35−37], but some severely distorted meshes could not be rezoned effectively in the local region. Hence, it is necessary to develop new methods to eliminate the element distortion problem thoroughly and apply these techniques to simulate the large deformation processes.

The element free methods can be applied to study high deformation problems (e.g. high speed machining simulation process) due to its meshless property. The smoothed particle hydrodynamics (SPH) method is the earliest element free technique which is applied to high deformation problems [38,39]. However, SPH was more suitable for the fluid field. Material point method (MPM) is another element free method which is suitable for solving solid mechanics problems. As a meshless method, MPM contains no element distortion in the process of numerical simulation, and it is very suitable for the problems which are difficult for the FEM simulations (e.g. high deformation problems [40], crack forming problems [41,42], instantaneous explosion problems [43], contact/penetration/impact problems [44,45], and fluid and solid fluid interaction problems [46] etc.). Based on the FEM, Chen and Schreyer [47] developed MPM from PIC (particle-in-cell). MPM contains the advantages of both Lagrangian and Eulerian schemes which can eliminate the distorted mesh problems. In 2004, Bardenhagen and Kober [48] developed the generalized interpolation material point (GIMP) method to eliminate the numerical noise caused by particles crossing over the background grid. In 2011, Sadeghirad et al. [49] used convected particle domain interpolation (CPDI) method to improve the accuracy and efficiency of the MPM. In 2011, to avoid the numerical noise when particles pass through the background grid, Zhang et al. displayed a new algorithm [47]. Lian et al. [50-52] presented a FEM-MPM coupled algorithm which takes full advantage of their respective advantages. Furthermore, the MPM has been also developed for cutting process simulations successfully. In 2011, Ambati et al. [53] used MPM to simulate the cutting process of AISI4340, the serrated chip was showed clearly, and the comparison between the MPM and FEM results was carried out. In