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Simulation analysis and experimental study of milling surface residual stress of Ti-10V-2Fe-3Al

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ABSTRACT

Nowadays, Ti-10V-2Fe-3Al is widely used in aerospace field because of its high specific strength, good breaking property, low forging temperature, and excellent stress corrosion resistance. However, these properties render Ti-10V-2Fe-3Al a hard-to-cut material. Moreover, the low thermal conductivity of Ti-10V-2Fe-3Al results in high temperature on the tool face, which causes the wear of cutting tool. This paper presents a simulation analysis and an experimental validation on the milling surface residual stress of Ti-10V-2Fe-3Al. The formation mechanism and influence of cutting parameters on the residual stress in the end milling of Ti-10V-2Fe-3Al are investigated through orthogonal experiments. The interaction effect of cutting parameters on forming residual stress is studied by analyzing the finite element (FE) simulation results. Moreover, relevant experiments are carried out to validate the accuracy of FE simulation. On the basis of these data, a formulation describing the interaction effect is proposed.

1. Introduction

Titanium alloy is considered a industrial high-strength material because of its high specific strength, good breaking properties, low forging temperature, and excellent stress corrosion resistance. Hence, titanium alloy is widely used in aerospace field. However, titanium alloy is difficult to be milled because of the excellent properties mentioned above. Machining titanium alloy is expensive. Thus, many studies have investigated the milling process and surface integrity of titanium alloy to improve milling efficiency. Some studies focused on the effect of milling tool. Wagner et al. [1] studied the tool wear mechanisms of Ti-1023 milling by using toroidal tool and established the relation among cutting conditions, milling tool geometry, and tool life. Rao et al. [2] performed experimental and numerical studies on the face milling of Ti-6Al-4V titanium alloy to characterize tool performance and surface integrity. Thepsonthi et al. [3] proposed an integrated method in selecting toolpath and optimized the process parameters to improve the performance of micro-milling Ti-6Al-4V alloy. Pan et al. [4] investigated the performance of polycrystalline diamond tools in the end milling of titanium alloys and analyzed the relationship between cutting force and cutting parameters. Li et al. [5] presented a 3D finite element method (FEM) of Ti-6Al-4V milling for the design and optimization of solid carbide end milling. Thepsonthi et al. [6] carried out experiments and finite element (FE) simulation to show that the cBN-coated carbide tool outperforms the uncoated carbide tool in generating tool wear and cutting temperature during Ti-6Al-4V micro-milling. Nouari et al. [7] studied the effect of third-body particles on the tool-chip contact and tool-wear behavior during the dry cutting of aeronautical titanium alloys. Thepsonthi et al. [8] conducted the 3D FE modeling and simulation of micro-end milling for Ti-6Al-4V titanium alloy to characterize chip flow and tool wear. The simulation results agreed with the experimental data. Rao et al. [9] focused on the measurement of specific cutting energy, surface integrity and tool performance with the experimental and numerical study of face milling of Ti-6Al-4V titanium alloy. Some studies focused on the deformation and cutting chip in the milling process. Bajpai et al. [10] studied the cutting forces and chip morphology through 3D FE simulation and experiments. Wu et al. [11] developed a 3D FE model for the complex milling of titanium alloy Ti-6Al-4V with ABAQUS and compared the chip formation, cutting force, and milling temperature obtained from simulation with those obtained from experiments. Liu et al. [12] established a 3D FE model of a helical tool and a thin-walled part with a cantilever to predict the cutting deformation of a titanium alloy Ti-6Al-4V thin-walled part during milling. The accuracy of this model can be validated by experimental cutting deformation. Calamaz et al. [13]

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implemented a new material constitutive law in a 2D FE model to analyze the chip formation and shear localization when machining titanium alloys.

Moreover, some studies performed experiments and FE simulations to establish the relationship between milling parameters and face integrity. Ma et al. [14] employed the FEM to investigate the effects of cutting conditions in corner up milling on the temperature of the tool rake face. Wyen et al. [15] studied the influence of the cutting edge radius on surface integrity in terms of residual stress, micro-hardness, surface roughness and optical characterization of the surface, and near surface area in up and down milling of the titanium alloy. Wu et al. [16] presented the effect of machined surface quality and cutting parameters on residual stress distribution in 7075 aluminum alloy. Yao et al. [17] investigated the formation mechanism and influence of cutting parameters on residual stress in the flank milling of Ti-10V-2Fe-3Al through orthogonal experiments. Daymi et al. [18] conducted a series of end milling experiments to characterize comprehensively the surface integrity of titanium alloy Ti-6Al-4V with TiAlN-coated carbide cutting tools under various milling conditions. Mantle et al. [19] studied the surface integrity of a high-speed ball end milled gamma titanium aluminide. Yang et al. [20] utilized a hybrid technique combining the FEM to study the effect of cutting speed and feed rate on the residual stress of Ti-6Al-4V (TC4). Miguélez et al. [21] investigated the influence of cutting speed on the induced machining residual stresses of TC4. Wu et al. [22] determined the effects of machined surface quality and cutting parameters on the residual stress distribution in a silicon carbide particle-reinforced metal matrix composite through FEM and experiments. Xin et al. [23] numerically analyzed the impact of cutting factors on residual stress. Li et al. [24] adopted non-dominated sorting genetic algorithm-II to established empirical models of tool life, residual stress and roughness according to TC4 milling parameters. The empirical models were utilized for optimization of production cost and surface quality. Yang et al. [25] developed a hybrid technique combining the finite element method and the statistical model for residual stress prediction in peripheral milling of TC4. The sensitivity to cutting speed and feed rate of four key features of the residual stress profile including surface residual stress, compressive stress peak value and location, response depth were investigated.

Although each of above studies has its features and merits, only a few of them focus on the empirical formula about residual stress and milling parameters. And they mostly focus on the titanium of TC4. Besides, cutting depth, which is one of the four key milling parameters, is less investigated. The purpose of this paper is to provide an empirical formula about the relationship between residual stress and cutting speed, feed rate and cutting depth. In this work, several experiments were performed to acquire the specific parameters of the Johnson–Cook material model of Ti-10V-2Fe-3Al. Then, the Johnson–Cook material model was applied into FE software DEFORM to validate its accuracy. FE simulations and relevant experiments under various end milling conditions were conducted to explore the relationship between the residual stress and milling parameters of Ti-10V-2Fe-3Al. After comparing the results obtained from FE simulations and experiments, a good agreement between the two data was found. Furthermore, the variation tendency of residual stress with the changes in feed speed, cutting depth, and cutting speed was discussed and analyzed. The results of this study may serve as a reference for future studies to improve the milling efficiency of Ti-10V-2Fe-3Al.

2. Johnson–Cook material model

In this study, the Generalized Johnson–Cook model was adopted to simulate Ti-10V-2Fe-3Al in FE software DEFDORM. To obtain an accurate simulation result, several experiments were carried out to obtain the relevant parameters of the Generalized Johnson–Cook model for the Ti-10V-2Fe-3Al. Moreover, we appropriately modified the parameters to fit the data from experiments, and the following is the process.

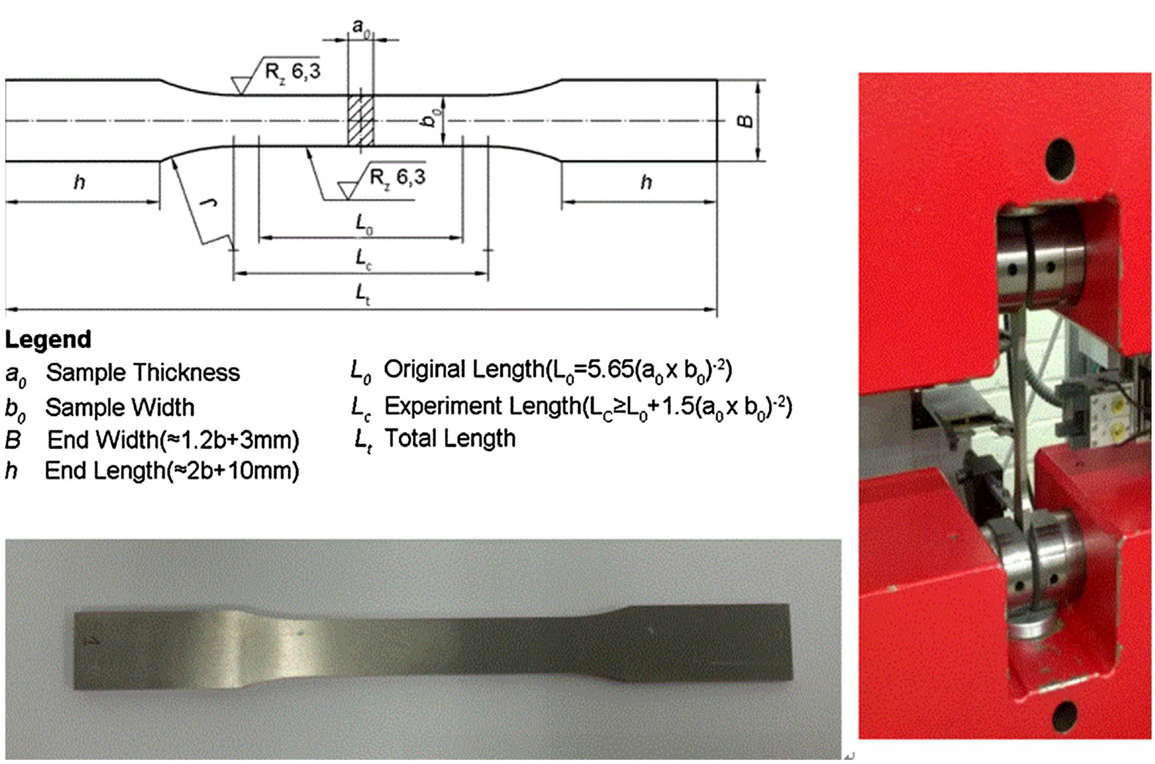

Fig. 1. Tensile test.