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Numerical and empirical modelling of machining-induced residual stresses in ball end milling of Inconel 718

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Abstract

Machining induced residual stresses can be crucial for the performance and life of the end product. In this paper, a 3D numerical model and an empirical model for residual stresses prediction were built to evaluate the near-surface residual stresses in Inconel 718 under ball end milling conditions. A series of ball end milling experiments of Inconel 718 have been conducted and X-ray diffraction measurements have been utilized to obtain the test residual stress profiles. The comparison results reveal that the numerical model can give an efficient estimation of the residual stress state beneath the machined surface, but the accuracy of the simulation model still needs to be improved. On the basis of the measured residual stresses, an exponentially decaying cosine function was fitted using a particle swarm optimization method. For the purpose of predicting machining induced residual stresses with different cutting parameters, a prediction model based on cutting parameters was developed. A good correlation was observed between the experimental and the predicted results derived from the empirical model.

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Keywords: Numerical model; Empirical model; Residual stresses; Ball end milling; Inconel 718;

1. Introduction

Ball end milling of Nickel-based superalloy Inconel 718 has been broadly applied in the field of aerospace, automotive, energy, and biomedical industries due to its superior properties. These properties are its high strength at high operation temperatures, good anti-corrosion property and low heat transmit rate. Also because of these properties, Inconel 718 falls into the category of very-hard-to-machine materials. In the process of machining, high machining forces and cutting temperatures are observed while the cutting tools wear rapidly, decreasing productivity. As a result, relatively high residual stresses are obtained in the machined near surface layers. The residual stress distribution on a component may cause distortion after machining. What's more, the machining induced residual stresses may lead to fatigue failure due to crack initiation and propagation. Hence, it is essential to give a better understanding of the near surface residual stresses of ball end milled Inconel 718 in order to control the finish machining process and obtain desired surface qualities.

So as to better understand the generation mechanisms of residual stresses and obtain the favorable residual stresses, various research methods have been adopted. In experimental studies, Outeiro and his cooperators [1] studied the residual stresses induced in turning of two major difficult-to-machine materials: Inconel 718 and stainless steel AISI 316L. Their studies show the appearance of high tensile residual stresses at the machined surface and compressive residual stresses in the sub-surface. However, different distributions were reported in hard machining of AISI 52100 steel(compressive stresses obtained) [2] and in orthogonal cutting of AISI 316L steel(tensile stresses obtained) [3], which indicates that the nature of machining induced near surface residual stresses is highly affected by the materials of workpiece and cutting conditions. Schlauer et al. [4] investigated the near surface residual stress distributions in Inconel 718 that originate from the

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machining operation turning experimentally. Cutting speed and feed rate have been varied to investigate their effects on the residual stress state. Tensile residual stresses with a maximum of 1300MPa were found at the surface that turn rapidly into compressive residual stresses of up to -800MPa. Waseem Akhtar [5] found that compressive residual stresses were observed at low cutting speeds and an increasing trend toward tensile direction was found as the cutting speed increased on the machined surface for high speed milling of Inconel 718 with carbide inserts. Residual stresses also showed an increasing trend with the feed rate. Sharman et al. [6] conducted adequate experiments and found that the residual stress profile was tensile at the surface with varies values depending upon the cutting parameters employed. With increasing depth beneath the machined surface the tensile stress rapidly drops and quickly reaches compressive levels (within 50um) before slowly returning to bulk values (within 200um). In these studies, researchers aim to understand and analyze residual stress profiles mostly using X-ray diffraction (XRD) measurement method.

Researchers have tried to evaluate the residual stresses induced by machining using Finite Element-based models. Liu and Guo [7] proposed an FE model to investigate the effect of sequential cuts and tool-chip friction on residual stresses in a machined layer of AISI 304 steel. They reported a reduction in the superficial residual stresses when the second cut is performed. Outeiro built several FEM models based on deform software [1, 3, 8]. Both the 2D and 3D FEM models were reported for turning process. The predicted results were nearly of the same magnitude as those obtained experimentally, and therefore the FEM model can be applied to study the influence of cutting parameters on residual stresses. Ee [9] used a 2D finite element model to evaluate the residual stresses remaining in a machined component. A material model which reflects a rate-sensitive, work hardening material that is temperature-sensitive is used. Case studies are performed to establish the influence of a sequential cut, cutting conditions. However, few papers focused on 3D FEM models for milling processes because of its complex cutting mechanism. Moreover, the main short comings of FEM models are time consuming and the inaccuracy of results induced by the inaccurate inputs of environmental variables.

Empirical model has also been used to model and predict the residual stress profiles. Statistically fitted polynomial function is a frequently used function type [10, 11]. Yet the profile does not necessarily resemble a polynomial fit, particularly when only few terms are used. Exponentially decaying cosine function fitting has been proved to be possible to represent the residual stress profile induced by shot blasting. Also a few researchers use it to represent the residual stress profile induced by cutting process. Ulutan [12] used the sinusoidal decay function to fitting the residual stresses in turning IN-100 and milling GTD-111. However, no predictive function was given in the paper. Yang [13] also used the sinusoidal decay function to fitting the residual stresses in peripheral milling on the basis of the simulation results.

In the present study, a 3D FEM model and an empirical model will be developed for predicting the near surface residual stresses in Inconel 718 subject to ball end milling. The FEM model was built with the simulation software Advantedge and the statistical model empirically fitted the residual stress profiles using an exponentially decaying cosine function. Particle Swarm Optimization (PSO) method was used to minimize the difference between the measurements and the fitting model, and therefore obtain the coefficients that fit the model. Finally, an empirical prediction model was developed based on cutting parameters.

2. Numerical modelling

Due to the high cost and complexity of residual stresses measurement, one aim of this work is to determine whether the residual stress profiles of ball end milled Inconel 718 could be estimated by FEM models. The FEM software Advantedge was used to simulate the three dimensional cutting process of Inconel 718 alloy. A finite element model was developed for the ball end milling operation, and it was composed of the workpiece and tool. The cutting model can be seen in Fig.1.

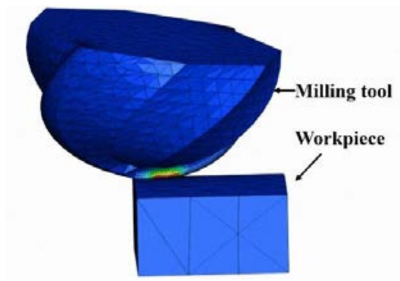

Fig. 1. FE geometry of the ball end milling operation.

The dimensions of the workpiece are 6mm x 4mm x 2 mm. A plane-strain coupled thermo-mechanical analysis was performed. Inconel 718 was defined for the workpiece material and carbide-grade-K was defined for the tool material. The physical properties of the Inconel 718 and the thermal conductivities of the cutting tool were defined based on Advantedge database. The cutting tool geometry parameters were given according to the design drawings acquired from the tool manufacturers. The cutter diameter was 10mm. The helix angle was 40°. The rake angle was 5°. The radius of the cutting edge was 0.04mm. Both the workpiece and the cutting tool were meshed with adaptive elements, while the minimum element size was 0.05mm. The cutting conditions were modeled at cutting speed (v_c): 60m/min, feed rate (f_z): 0.06mm/rev, depth of cut (a_p): 0.1mm, width of cut (a_e): 0.2mm, lead angle: 10º, tilt angle: 0º. The water-based cutting fluid was applied in the simulation.