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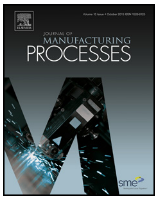

Evolution and empirical modeling of compressive residual stress profile after milling, polishing and shot peening for TC17 alloy

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ABSTRACT

Compressive residual stress is important to improve the fatigue life of components. This paper proposed an empirical model to predict the compressive residual stress profile induced by the integration manufacturing processes (firstly milling, then polishing, finally shot peening). An exponential decay function was used to describe the compressive residual stress profile induced by milling process. Moreover, a sinusoidal decay function was proposed to describe the compressive residual stress profile induced by shot peening process. The integration manufacturing processes model was a deterministic function of the combination of exponential decay function, sinusoidal decay function, and their interaction term. Additionally, an impact coefficient was introduced to describe the influence of polishing process on compressive residual stress profile. The coefficients of the proposed models were related to the input machining parameters. Experiments of TC17 alloy were carried out utilizing response surface methodology and full factorial design to construct these models. Flank wear, tool inclination angle, axial depth of cut, shot peening intensity, and shot peening coverage were selected as five input machining parameters. According to the experimental results obtained, the evolution of compressive residual stress profile after the integration manufacturing processes was investigated, and the proposed models had been developed. The empirical model was validated by two extra experiments and a significantly good prediction was achieved.

1. Introduction

Titanium and its alloys are widely used in aerospace, automotive, marine, and biomedical parts, due to their superior properties. TC17 alloy is an important portion of titanium alloys and widely used to machine the aero-engine fan and compressor blades because of the high specific strength, good coordination of the strength and toughness, low specific gravity, and high hardenability [1]. However, TC17 alloy is very difficult to machine due to the increased high chemical reactivity with high temperature, as well as the low thermal conductivity. Thus, the tools are damaged in short time, resulting in poor surface integrity of components and high production cost. In addition, the deteriorated surface integrity may decrease the fatigue life significantly and affect the safe reliability of aero-engine. Therefore, an integration manufacturing processes, which is usually described as firstly milling, then polishing, finally shot peening, is employed to remove the tool marks and induce compressive residual stress of TC17 alloy components.

The compressive residual stress can improve the fatigue life of components significantly. When the components endure the alternating loads, residual stress can be superposed with the applied load, and compressive residual stress may reduce the amplitudes of the applied load. Moreover, the crack initiation can be moved from surface to subsurface, crack propagation is prevented because of the high level of crack closure effect [2]. Compared with compressive residual stress, the profile of compressive residual stress gives a more comprehensive understanding of crack initiation, propagation, and fatigue failure of components. For this purpose, a large number of researchers studied on the methods of predicting residual stress as well as residual stress profile. The finite element (FE) method, analytical and empirical modeling are the principal techniques used to analyze and investigate residual stress.

The simulation technique of FE method can provide much comprehensive knowledge to realize the formation mechanism of residual stress without the necessity of doing lots of experiments. Chen et al. [3] studied the prediction of residual stresses using ABAQUS software when orthogonal cutting Ti-6Al-4V, and found that modeling the chip formation mechanism and tool wear correctly was a prerequisite to obtain accurate results. Additional,

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Nomenclature

A_1	Amplitude of exponential decay
A_2	Amplitude of underdamped oscillation
a_p	Axial depth of cut
C	Shot peening coverage
CRSP	Compressive residual stress profile
f_A	Shot peening intensity
h	Depth beneath surface
h_{actual}	Actual value of depth beneath surface
$h_{\mathrm{normalized}}$	Normalized value of depth beneath surface
m_i	Impact (or interaction) coefficient of X_i and Y_i on controlling factors
n_i	Impact (or interaction) coefficient of X_i and Y_i on weighting coefficients
VB	Flank wear
W_1	Weighting coefficient of milling process
W_2	Weighting coefficient of shot peening process
W_3	Weighting coefficient of interactive item between milling and shot peening process
X_i	Coded value of input milling parameter
x_i	Actual value of input milling parameter
x_{i0}	Actual value of input milling parameter at center point
x_{i+1}	Actual value of input milling parameter at high point
Y_i	Coded value of input shot peening parameters
y_i	Actual value of input shot peening parameter
y_{i0}	Actual value of input shot peening parameter at center point
y_{i+1}	Actual value of input shot peening parameter at high point

Greek symbols

α	Impact coefficient of polishing on CRSP
β	Tool inclination angle
θ	Phase angle
λ_1	Damping coefficient of CRSP induced by milling process
λ_2	Damping coefficient of CRSP induced by shot peening process
σ	Residual stress
σ_{actual}	Actual value of residual stress
$\sigma_{\mathrm{normalized}}$	Normalized value of residual stress
ω_{d}	Damped frequency

Ee et al. [4] used a more realistic FE model, in which material behavior was described as a non-Newtonian fluid, thus the prediction accuracy of residual stresses in 2D machining was improved. Özel and Zeren [5] designed a FE model for high-speed orthogonal cutting to simulate the residual stresses, they pointed out that the residual stress field induced by large cutting edge radius was deeper than that induce by small cutting edge radius. In order to investigate the effect of shot peening parameters on residual stress using FE method, different types of target and shot models have been developed by many scholars. As reported by Miao et al. [6], 2D axisymmetric model, 3D model with four, three, two, one, and without symmetry surfaces had been established subsequently. Moreover, a simulation with an artificially designed multiple impacts was carried out by Kang et al. [7], and the predicted residual stress was compared with that from single impacts. As the rapid development of computational software, numerical simulation is very useful to simulate the residual stress. However, their predictions are generally close to the better material constitutive model, accurate elastic-viscoplastic deformation, small element size or time step, and few assumptions.

Analytical modeling technique is the most difficult method to calculate the residual stress using physical equations, due to the many unknowns to the process which need to be solved through assumptions. Jacobus et al. [8] proposed an incremental thermoplastic model to predict the residual stress of the full in-plane biaxial, results were consistent with the experimental data. An analytical elastic-plastic model was used to simulate the residual stress resulting from thermos-mechanical effect [9], and results were verified with experimental measurements from AISI52100 steel. Su et al. [10] incorporated cutting force and temperature derived for orthogonal/oblique cutting conditions to predict residual stress generated from slot milling and face milling. In addition, a new analytical model was proposed by Huang et al. [11] during flank milling, in which the sequential variable loading was considered for the first time. Despite the complicacy of analytical solution, many attempts were applied to develop the analytical model of residual stresses during shot peening process. The early work of Li et al. [12] proposed a simplified analytical model based on the hertzian pressure, Iliushin's elastic-plastic theory, and reverse yielding and hardening concept to calculate the compressive residual stress profile (CRSP) induced by shot peening process. Shen and Atluri [13] modified Li's model by calculating the plastic indentation using an average pressure distribution and taking the primary shot peening factors into consideration: characteristic of material, diameter and velocity of the shot. Additional, two modifications were adopted by Franchim et al. [14] to develop the analytical model modified by Shen and Atluri, the dynamic load of hertzian pressure and the Ramberg-Osgood and/or Ludwick plasticity models were adopted. Moreover, a simple modification of including the strain rate effect was considered by Bhuvaraghan et al. [15]. The analytical method can describe the real physical phenomenon in the formation of residual stress, while it still has certain distance with the actual conditions during milling or shot peening process, and the accuracy is difficult to guarantee because of the overmuch assumptions and simplifications

The majority of literatures on investigation of residual stresses are experimental and their results can be used for validating and comparing the findings via FE based and analytical predictions. The results of residual stresses in machining are diverse, due to the using of different materials, cutting conditions, and tool parameters. Both tensile and compressive surface residual stress can be obtained. The degree and location of peak residual stress are also various. Mantle and Aspinwall [16] found that compressive residual stresses decreased with the increase of cutting speed during ball nose milling gamma titanium aluminide at cutting speed 70–120 m/min. While, Sun and Guo [17] claimed for end milling Ti-6Al-4V at cutting speed 50–110 m/min that surface residual stresses became more compressive when the cutting speed increased. On the other hand, as reported by Daymin et al. [18], compressive residual stresses decreased slightly with increasing tool inclination angle in high speed end milling Ti-6Al-4V due to the absence of the rubbing and plowing effect which usually occurred at the tip of the cutter. Wyen et al. [19] showed that when up milling Ti-6Al-4V, compressive residual stresses increased as the increase of cutting edge radius, whereas the effect was less significant in down milling. Rao et al. [20] showed another study for face milling Ti-6Al-4V, which suggested that with the increase of flank wear, the maximum residual stress value decreased at each cutting speed. It was in all likelihood due to the increased thermal impact into the machined surface. Feng et al. [21] discussed the influence of shot peening intensity on compressive residual stress field induced in TC4-DT titanium alloy, it was found that the maximum compressive residual stress reduced significantly under large shot peening intensity. Using shot particles with a diameter of 70 μm, the impact