International Journal of Mechanical Sciences 133 (2017) 426–437

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

Theoretical prediction of machining-induced residual stresses in three-dimensional oblique milling processes

Min Wan*, Xiang-Yu Ye, Yun Yang, Wei-Hong Zhang*

School of Mechanical Engineering, Northwestern Polytechnical University, Xi'an, Shaanxi 710072, China

ARTICLE INFO

Keywords:
3D milling process
Oblique cutting
Residual stress
Theoretical model
Thermo-elasto-plastic loading

ABSTRACT

Residual stress not only has great influence on the fatigue life of a machined component, but also can cause serious distortion in machining of large components, and thus, it is an important characteristic needed to be studied deeply. Previous researches on theoretical calculation of machining-induced residual stresses were mainly carried out for two-dimensional (2D) orthogonal cutting processes, and analytical prediction of residual stresses in three-dimensional (3D) milling is seldom reported.

This paper presents a theoretical model to predict the machining-induced residual stresses in 3D milling processes by taking the 3D instantaneous contact status between the mill and part into consideration. A 3D contact model of oblique cutting is established to predict the stress distributions by integrating the cutting effect in shear zone with the ploughing effect in the honed zone of the cutting edge. Instantaneous machining stresses produced by shearing effects are predicted based on the basic principles of cutting mechanism, contact mechanics and J-C constitutive model; while the stresses in the honed zone are evaluated by using slip line theory. Complicated geometrical relationships in both zone are detailed in the model formulation. Instantaneous cutting temperature fields during milling process are predicted to study the influences of thermal loads on residual stresses. Incremental thermo-elasto-plastic method is adopted to predict the thermo-elasto-plastic constitutive behavior of the workpiece in elastic-plastic cyclic loading process. 3D relaxation procedures are proposed to calculate the final residual stresses after the loading process of the cutting edges. Validity of the proposed model is demonstrated by the good agreements between the theoretical predictions and the results by using finite element methods and experimental means. Furthermore, it is also verified that the computation efficiency of this model is significantly higher than that of finite element method.

1. Introduction

Machining residual stresses, which mainly come from the uneven plastic deformation during the contacting process between the tool and workpiece, play a crucial role in the mechanical characteristics, such as fatigue life, corrosion resistance and static strength. Values of residual stresses are concerned with cutting tool geometry, cutting parameters, material properties and lubrication conditions, and so on. This paper presents an analytical model to predict the machining residual stresses in three-dimensional (3D) milling processes.

Relatively early studies on residual stresses were mainly carried out in rolling field. For example, Merwin and Johnson [1] proposed an approximate numerical method to analyze the plastic deformation condition in rolling contact, and pointed out that complex stress and strain cycles are the main sources of the forward surface displacements. Later, Hearle and Johnson [2] estimated the subsurface plastic shear strain rate in rolling line contact by treating orthogonal shear strain component as the only plastic strain. Bower and Johnson [3] introduced strain hardening into line contact model to consider its influence on plastic deformation. Sehitoglu and Jiang [4] investigated the influence of normal and tangential loads on residual stress distribution by approximating the elastic-plastic rolling contact as an elastic problem. McDowell [5] introduced a blending function to predict residual stress in a two-dimensional (2D) elasto-plastic rolling line contact. Foletti and Desimone [6] took full non-linear kinematical hardening into account for high values of plastic loading by using non-linear finite element method.

It should be pointed out that above analytical models [1–6] for the study of residual stresses in rolling are established by using 2D contact theory, and also constitute the theoretical basis to predict residual stresses in 2D machining process [7–9]. Ulutan et al. [7] utilized finite difference method to study the residual stresses under the combined

* Corresponding authors.
E-mail addresses: m.wan@nwpu.edu.cn (M. Wan), zhangwh@nwpu.edu.cn (W.-H. Zhang).

http://dx.doi.org/10.1016/j.ijmecsci.2017.09.005
Received 17 May 2017; Received in revised form 19 August 2017; Accepted 6 September 2017
Available online 8 September 2017
0020-7403/

effects of mechanical cutting forces and thermal fields. Liang and Su [8] assumed that the stresses produced by both shearing and ploughing effects are in the same working way, and established a residual stress model for 2D orthogonal machining by considering cutting force and cutting temperature. Saurabh and Suhas [9] took the tool face rubs into account in the prediction of residual stresses, and studied the shape of contact regions and residual stress distributions in orthogonal machining.

As is known, milling is one of the most common 3D machining processes, and its residual stress status cannot be predicted by simply using the contact model of 2D orthogonal cutting. Thus, residual stresses in milling were mainly studied by finite element methods and experimental means. Fu and Wu [10] experimentally established an empirical residual stress model for milling of aluminum alloy, in which the influences of the cutting conditions and the tool geometries on residual stresses were considered. Jacobus et al. [11] used experimental results to statistically develop a thermo-elasto-plastic model for the prediction of residual stresses in turning process with inclined cutting edge. Based on the measured data, Tan et al. [12] also fitted an exponential decay function to predict the compressive residual stresses in milling process. Jiang et al. [13] employed finite element simulation to study the residual stress distributions in high-speed circular milling, and found that the influence of uncut chip thickness on tangential residual stress is obvious. Yao et al. [14] did some experiments to observe the effects of cutting parameters on surface residual stresses. Grove et al. [15] experimentally investigated the machining residual stresses in milling of β-annealed Ti6Al4V, and analyzed the influence of the tool wear on residual stress distributions. Beizhi et al. [16] used both finite element methods and experimental tests to study the effects of depth of cut on residual stresses in milling, and pointed out that the residual stresses can be decreased by optimizing the depth of cut in milling of thin-walled part. Nejah et al. [17] investigated the residual stress in side milling by usage of finite element analysis, and concluded that the mechanical loads are the main factor that influences residual stress distributions comparing to the thermal loads.

Above literature review shows that most of the previous researches [10–17] on residual stresses in milling were mainly carried out by experimental means and finite element methods, which are difficult to quantitatively reveal the relationship between residual stresses and milling parameters from the perspective of theoretical aspect. That is, analytical works in this field are very limited. Some scholars tried to use the two-dimensional contact model to predict the residual stress of three-dimensional milling process by ignoring the effect of the mill's helix angle [18,19]. However, this kind of treatment will lead to deviations between predictions and actual statuses since the mechanism of 3D oblique milling is greatly different from that of 2D orthogonal cutting [20], and thus, analytical means is greatly desired to detect the underlying mechanism of residual stresses in milling process.

This paper aims at establishing a theoretical model to predict the residual stresses in 3D milling processes. The key advantage over previous efforts lies in that a new contact model suitable for revealing the 3D oblique cutting status is effectively developed by combining the basic milling principle with typical contact mechanics. Expressions for predicting the internal residual stresses caused by mechanical loads and thermal loads are derived in detail by considering the thermo-elasto-plastic loading and relaxing effects of cutting edges. Influence of helix angle is included in the model formulation. The theoretical model is verified by both finite element simulations and experimental measurements.

2. Contact model of milling

Based on the basic principle of Hertz contact theory, an analytical model of milling process is established to predict the internal stress directly caused by mechanical load, which is the main contribution source of new produced stresses for most widely used cutting speeds [19,21,22].

2.1. Contact model of oblique cutting

As shown in Fig. 1, milling process can be treated as a series of oblique cutting processes along the main cutting edges. Figs. 1(c), (d) and Fig. 2 show the geometric relationship of a basic oblique cutting. The angles indicated in Fig. 2 hold the following relationship according to Altintas's research [20].

$$\begin{aligned} &\sin\theta_{\mathrm{i}} = \sin\beta_{\mathrm{a}}\sin\eta_{\mathrm{flow}} \\ &\tan(\theta_{\mathrm{n}}+\alpha_{\mathrm{n}}) = \tan\beta_{\mathrm{a}}\cos\eta_{\mathrm{flow}} \end{aligned} \tag{1}$$

where β_a is the friction angle. The relation between shear direction and chip flow direction is defined as follows [23].

$$\tan\eta_{\mathrm{flow}} = \frac{\tan\beta\cos(\phi_{\mathrm{n}}-\alpha_{\mathrm{n}}) - \cos\alpha_{\mathrm{n}}\tan\phi_{\mathrm{i}}}{\sin\phi_{\mathrm{n}}} \tag{2}$$

θ_i, θ_n, ϕ_n, ϕ_i and η_{flow} are calculated by maximum shear stress criterion, which assumes that the angle between the shear velocity direction and the direction of the resultant cutting force is 45°. As a result, the following relationships hold.

$$\begin{aligned} &\sin\phi_{\mathrm{i}} = \sqrt{2}\sin\theta_{\mathrm{i}} \\ &\cos(\phi_{\mathrm{n}}+\theta_{\mathrm{n}}) = \frac{\tan\theta_{\mathrm{i}}}{\tan\phi_{\mathrm{i}}} \end{aligned} \tag{3}$$

Now, θ_i, θ_n, ϕ_n, ϕ_i and η_{flow}, some of which are used in the following derivations, can be solved by reviewing Eqs. (1) to (3) together.

Loads during cutting process mainly come from two sources of forces, i.e. chip formation force and ploughing force. Chip formation force is in the shear zone, while ploughing force comes from the contact between the tool edge and the workpiece [24]. In orthogonal cutting, the two sources are acting on the same plane, as shown in Fig. 3. Thus, for any point in the workpiece, e.g. P_n in Fig. 3, its stress condition can be computed by using the relationship in one plane, as detailed in Fig. 3(b). But in oblique cutting, the two forces acting on the workpiece are in different planes, as shown in Fig. 4. Therefore, the stress distribution caused by the two forces must be separately calculated in different planes, and thus, different local coordinate systems are required. Then, the stresses predicted by the two local coordinate systems are transformed to the total coordinate system to obtain the final stress status. Following the geometrical relationship shown in Fig. 1(d), normal force F_n on the shear plane can be calculated by

$$F_{\mathrm{n}} = F_{\mathrm{t}}\cos\beta\sin\phi_{\mathrm{n}} + F_{\mathrm{f}}\cos\phi_{\mathrm{n}} \tag{4}$$

The force components in the direction of cutting (F_t) and perpendicular to the machined surface (F_f) are calculated as follows.

$$\begin{aligned} &F_{\mathrm{t}} = K_{\mathrm{tc}}\mathrm{d}a_{\mathrm{p}}t_{\mathrm{c}} + K_{\mathrm{te}}\mathrm{d}a_{\mathrm{p}} \\ &F_{\mathrm{f}} = K_{\mathrm{fc}}\mathrm{d}a_{\mathrm{p}}t_{\mathrm{c}} + K_{\mathrm{fe}}\mathrm{d}a_{\mathrm{p}} \end{aligned} \tag{5}$$

where K_{te} and K_{fe} are the ploughing force coefficients, which can be determined from experiments or finite element models. Cutting force coefficients K_{tc} and K_{fc} are expressed as the following equations by using the orthogonal-to-oblique transformation method [20].

$$\begin{aligned} &K_{\mathrm{tc}} = \frac{\tau_{\mathrm{s}}(\cos\theta_{\mathrm{n}} + \tan\theta_{\mathrm{i}}\tan\beta)}{[\cos(\theta_{\mathrm{n}}+\phi_{\mathrm{n}})\cos\phi_{\mathrm{i}} + \tan\theta_{\mathrm{i}}\sin\phi_{\mathrm{i}}]\sin\phi_{\mathrm{n}}} \\ &K_{\mathrm{fc}} = \frac{\tau_{\mathrm{s}}\sin\theta_{\mathrm{n}}}{[\cos(\theta_{\mathrm{n}}+\phi_{\mathrm{n}})\cos\phi_{\mathrm{i}} + \tan\theta_{\mathrm{i}}\sin\phi_{\mathrm{i}}]\cos\beta\sin\phi_{\mathrm{n}}} \end{aligned} \tag{6}$$

in which τ_s is the flow shear stress, which is calculated by Johnson-Cook's constitutive model as follows [25].

$$\tau_{\mathrm{s}} = \frac{1}{\sqrt{3}}\left(A + B\varepsilon^{\vartheta}\right)\left(1 + C\ln\frac{\dot{\varepsilon}}{\varepsilon_0}\right)\left[1 - \left(\frac{T-T_0}{T_{\mathrm{m}}-T_0}\right)^{\zeta}\right] \tag{7}$$

where A, B, C, ζ and ϑ are the constitutive parameters of the workpiece material. T_m is the melting temperature. T_0 is the room temperature.