Journal of Materials Processing Technology 209 (2009) 4515–4520

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

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

An FEM study on residual stresses induced by high-speed end-milling of hardened steel SKD11

J.L. Li*, L.L. Jing, M. Chen

School of Mechanical Engineering, Shanghai Jiao Tong University, 800 Dong Chuan Road, Shanghai 200240, PR China

ARTICLE INFO

Article history:
Accepted 6 October 2008

Keywords:
Residual stresses
FEM
Variable undeformed chip
Effective rake angle
Continuous feed

ABSTRACT

Milling of Hardened steel SKD11 is usually a finishing process, therefore stable cutting process must be guaranteed at first. Residual stresses (RS) were studied in this paper with the help of finite element method (FEM) for its significant influence on the quality of machined part. A two-dimension (2D) fully thermo-mechanical coupled finite element (FE) model was employed to evaluate RS remaining in a machined component. The model was developed based on the effective rake angle and the variable undeformed chip layer. Johnson–Cook plasticity model was introduced to model the workpiece material. Coulomb friction was assumed at the tool–chip interface. Two same cutting tools were employed to model continuous feed milling process. RS profiles were obtained after the cutting and stress relaxation stages. The predicted RS profiles were in reasonable agreement with the experimental results.

1. Introduction

Hardened steel SKD11 has wide applications in the molds and dies industry. However, it is also a difficult-to-cut material due to its high strength and hardness. In the current work, the workpiece hardness ranges from 60 to 62 HRC. With the development of cutting tool, hard milling is becoming a feasible approach to instead of traditional grinding and electron discharge machining (EDM) for its high machining efficiency. However, hard milling is often used as a finishing process, stable cutting process should be guaranteed to obtain satisfied machining precision (El-Wardany et al., 2000; Chen et al., 2003). Residual stresses (RS) existing in a machined product have a major influence on the quality of the machined part, in particular, its fatigue life and corrosion resistance (Brinksmeier et al., 1982; König et al., 1993). Hence, predicting the distribution of RS induced by cutting process is very important.

Development of analytical model is slow due to the inherent complexity of machining process. The finite element method (FEM) has been widely used since 1980s. FEM has played an important role in simulating and understanding the metal cutting process by having an insight looking at what is going on during cutting, which might not be achieved by experimental or analytical method. Shet and Deng (2003) proposed a FE model to study RS when orthogonal cutting of AISI 4341 steel. A modified Coulomb friction law was used to model frictional interaction along the tool–chip interface. Chip separation was modeled by the nodal release technique based on a critical stress criterion. Outeiro and Umbrello (2006) employed the commercial FEA software DEFORM-2D and experimental method to evaluate RS induced by orthogonal cutting of AISI 316L steel. In their researches, effects of feed rate, tool coating on RS distribution in the machined surface and subsurface were experimentally and numerically studied. Mohamed and Ng (2007) proposed an Arbitrary–Lagrangian–Eulerian (ALE) FE approach to estimate the effects of cutting edge radius on the RS profile when orthogonal dry cutting of austenitic stainless AISI 316L with continuous chip formation.

However, from the literature review of RS induced by machining process, it is clear that the major of the prior works on RS focused on turning, which could be easily performed as two-dimension (2D) orthogonal cutting process. Few researches have been done in milling process which is regarded as a typical three-dimension (3D) oblique cutting due to its complex milling tool and undeformed chip layer. In the present paper, a 2D fully thermo-mechanical coupled FE model based on the effective rake angle and the variable undeformed chip layer was proposed to study RS induced by high-speed end-milling of Hardened steel SKD11.

2. Experimental procedure

Hardened steel SKD11 milling experiments were carried out on DMU70V high-speed machining centre. The uncoated commercial carbide insert was used under dry condition. The main chemical components of SKD11 and cutting parameters used in tests are shown in Tables 1 and 2, respectively. RS were measured by X350A X-ray diffraction system in these experiments.

* Corresponding author. Tel.: +86 13641604837; fax: +86 2134206317.
E-mail address: lijunli@sjtu.edu.cn (J.L. Li).

0924-0136/$ – see front matter
doi:10.1016/j.jmatprotec.2008.10.042

Table 1
Chemical components of hardened steel SKD11.

SKD11	
C	1.4–1.6
Cr	11.0–13.0
Si	0.4
Mn	0.6
Mo	0.8–1.2
P	<0.03
S	<0.03

Table 2
Cutting conditions in SKD11 milling experiments.

Cutting speed [m/min]	75.36
Feed rate [mm/min]	1450
Depth of cut (mm)	5
Width of cut (mm)	0.25
Rake angle (°)	0
Clearance angle (°)	8
Helix angle (°)	45

3. Finite element modeling

A plane strain thermo-mechanical FE model was built to simulate dry cutting of Hardened steel SKD11 and study RS distribution in the subsurface.

3.1. 2D model derived from milling process

Compared to turning process, it is more difficult to establish a 2D model for milling process due to the more complex cutting process, especially the milling tool and undeformed chip layer. On the other hand, because of the complex cutting process and current computer technology, adopting a 3D FE model to simulate milling process is a catastrophic time-consuming work. Hence, developing a feasible and efficient model to study RS induced by milling process is very necessary. Compared with turning process, the obvious characteristic of milling process is the milling tool with helix angle, which leads milling process to be a complicated 3D oblique cutting process (as shown in Fig. 1). From Fig. 1, it could be easily found that the cutting edge does not perpendicular to the cutting direction OC. The actual rake angle does not equal to the rake angle α_n because of the inclination angle i (which is equal to helix angle ω (Le, 1992)). Indeed, the actual rake angle which is also called effective rake angle (labeled α_e as shown in Fig. 2) is larger than the rake angleα_n. The effective rake angle α_e could be determined as follow by Shaw (2005):

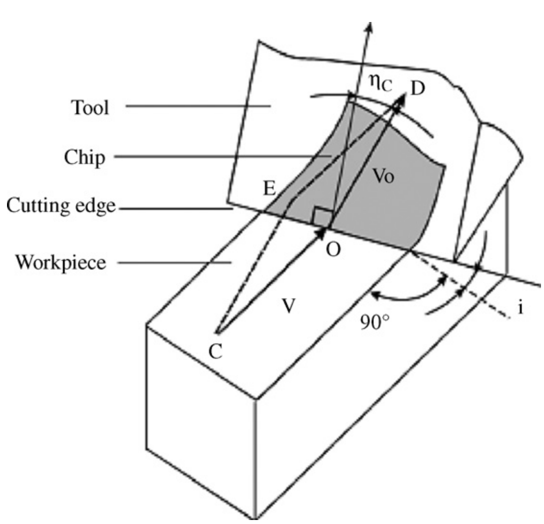

Fig. 1. Schematic diagram of oblique cutting.

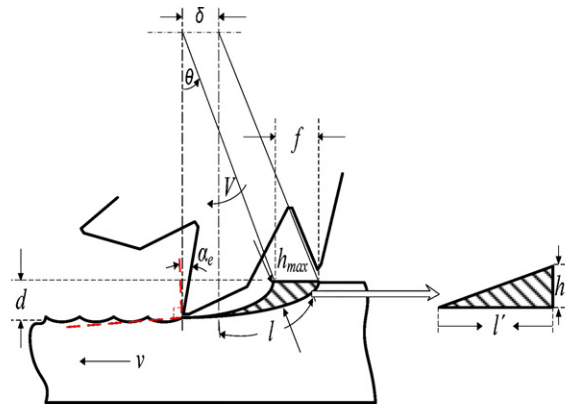

Fig. 2. Schematic diagram of down-milling process.

$$\sin\,\alpha_e = \sin\eta_c \sin i + \cos\eta_c \cos i \sin\alpha_n \tag{1}$$

where η_c is the angle between the chip-flow direction and the normal to the cutting edge (as shown in Fig. 1), α_n is the rake angle and i equal to helix angle ω, respectively. Stabler (1951) reported that angle η_c was approximately equal to the inclination angle i for a variety of tools and work materials, rake angles, and speeds. When Eq. (1) is simplified by using of Stabler's rule and Eq. (2) is obtained:

$$\sin\,\alpha_e = \sin^2 i + \cos^2 i \sin\alpha_n \tag{2}$$

It has mentioned that the other difficult to model milling process is the variable undeformed chip layer. Seen from Fig. 2, the actual shape of the undeformed chip is rather complex as the cutting edge traverses a trochoidal path. Modeling the complex undeformed chip is extremely difficult and time-consuming so that it is worth developing a feasible approach. Fig. 2 indicates that the most important indexes are the maximum undeformed chip thickness (h_{max}) and the undeformed chip length (l), which have been developed by Martellotti (1941) as expressed:

$$h_{max} = \left[2f\sqrt{\frac{d}{D}}\right]\cos\ i \tag{3}$$

$$l = \sqrt{Dd} - \frac{v}{2nN} \tag{4}$$

where f, d, D, i, v, n and N are feed rate, depth of cut, tool diameter, helix angle, cutting speed, number of teeth and spindle speed, respectively.

It is known that power required to perform machining operation is almost determined by cutting area when the other conditions are invariable. In this paper, a triangle undeformed chip was proposed to instead of the trochoidal path based on the effective cutting area. Here the height of the triangle h was assumed to have the same value with h_{max}, and the other index l' could be determined relatively.

3.2. Workpiece and material modeling

Physical properties of Hardened steel SKD11 (60-62HRC) are shown in Table 3. The workpiece material was modeled by Johnson–Cook plasticity model. This model is suitable for modeling cases with high strain, strain rate, strain hardening, and non-linear material properties, which represent the main numerical challenges when modeling metal cutting. Besides, it has been widely used in modeling cutting process and has proved its suitability