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Prediction of surface residual stress after end milling based on cutting force and temperature

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ABSTRACT

Residual stress in the machined surface can significantly influence the performance of machined parts. In recent years many researches have been carried out to measure and predict the machining-induced residual stress, where the machining-induced residual stress is often regarded as the function of machining parameters. Yet it is the combined effect of the thermal and mechanical loads that directly affect the stress field during cutting process. In this research, the cutting forces and cutting temperature were measured during end milling process with different feed rate and depth of cut, and the surface residual stress along peripheral direction was measured after machining. The effect of thermal and mechanical loads on the formation process of residual stress was analyzed, and a new prediction model was proposed, which specifies the effect of thermal and mechanical loads, and which also takes into consideration the influence of feed rate and the depth of cut. Generally the thermal loads drive the surface stress to be more tensile, while the mechanical loads have the opposite effect. Larger feed rate weakens the effect of cutting forces on unit area of machined surface remarkably, while the influence of the depth of but is less significant. Under the cutting conditions in this research, the surface residual stress along peripheral direction is tensile, which indicates that the thermal effect plays the dominant role in forming residual stress. The coefficients in the proposed model were determined with experimental data, and the model was preliminarily verified. It might be a useful method to achieve a real-time prediction and control of machining-induced residual stress by monitoring cutting forces and temperature.

1. Introduction

The residual stress existing in the surface layer is an important aspect of the surface integrity that can influence the performances of the mechanical parts such as fatigue life (Sasahara, 2005) and corrosion resistance (Wan et al., 2013). It has been widely noticed that the machining process, as the last manufacturing procedure for many parts, can significantly influence the surface residual stress. Thus it is important to predict and control the machining-induced residual stress.

During the past decades many researches have been carried out on machining-induced residual stress, covering the influence of a wide range of workpiece materials, tool geometry parameters and machining parameters. Liu et al. (2004) studied the residual stress distribution in hard turning of bearing steel, and in his experiments the surface residual stress tends to be more tensile with the increase of tool nose radius, and the tool wear greatly influences the stress distribution. Hua et al. (2006) investigated the influence of cutting conditions and cutting edge parameters on residual stress in hard turning and concluded that larger feed rate, larger hone radius or chamfer, and higher hardness of material due to heat treatment may help to introduce larger compressive residual stress within subsurface layer. Sun and Guo (2009) carried out a comprehensive study on the surface integrity for milling of Ti-6Al-4V, and the results showed that the influence of cutting speed on surface stress is not monotonic and the maximum compressive stress is achieved around the cutting speed of 80 m/min, while the surface stress tends to be less compressive with the increase of feed. Qin et al. (2012) compared the distribution of residual stress after machining with different coolants, and coolant with better cooling performance makes the distribution of residual stress become more compressive. There are many similar studies, and as concluded by Ulutan et al. (2007), most of these researches treat residual stress as the function of cutting parameters, tool parameters, the properties of the workpiece material, or a combination of these factors.

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Table 1
Chemical composition of workpiece material SCM440H (% in weight).

C	Si	Mn	P	S	Cr	Mo	Ni	Cu
0.41	0.25	0.77	0.021	0.018	1.09	0.16	0.08	0.09

Different prediction models based on experimental data have been proposed, including the second-order polynomial model (Fuh and Wu, 1995) and the exponential model (Yao et al., 2013) for prediction of surface residual stress, the n-order polynomial model for in-depth distribution of residual stress (El-Axir, 2002), and the complicated prediction model specifying the different influence of cutting parameters, tool geometry parameters and the chemical composition of material (Capello, 2005, 2006). These researches and the accumulated data reveal some aspects of the nature of machining-induced residual stress, but as a matter of fact, it is with great limitation to predict the distribution of residual stress with several selected parameters, as all the cutting parameters, tool parameters and material properties work synergistically in the metal cutting process.

On the other hand, in most empirical models, usually some form of monotonic function expression is used to specify the influence of a single machining parameter, which might not be proper. As a matter of fact, the influence of machining parameters on surface residual stress is usually not monotonic, as has been shown in some researches like El-Khabeery and Fattouh (1989) and Wan et al. (2013). Thus the data in different researches might lead to different understandings, or sometimes opposite conclusions, on the effect of some parameter on residual stress. For example, to address the influence of cutting speed on surface residual stress in turning of AISI 316 steel, Outeiro et al. (2002) set the range of cutting speed as 75–125 m/min and the results indicated that the surface residual stress grow more compressive with the increase of cutting speed, while the data measured by M'Saoubi et al. (1999) showed different trend when the range of cutting speed was set as 100–200 m/min. Processing the measured data with intelligent algorithm might be one way to more comprehensively reveal the influence of technical parameters on residual stress, which, to some extent, evades the limit of function expression. Jafarian et al. (2014) applied the hybrid technique of artificial neural network (ANN) and genetic algorithm (GA) to find optimal machining parameters to minimize the tensile residual stress and surface roughness. However, it is still difficult to build an ANN that can cover the influence of all important parameters at ranges wide enough for the prediction of residual stress, as the measurement of residual stress is expensive and time costing for the time being. To solve this problem, new methods might be needed.

It has been concluded that mechanical loads, thermal loads and microstructure transformation are the main sources of the machining-induced residual stress (Yao et al., 2013). Denkena and Biermann (2014) concluded that the thermal and mechanical stresses create a superposed residual stress state. Cutting forces and cutting temperature, which are also influenced by many factors but are much easier to measure and track, might be useful in predicting the machining-induced residual stress. Jacobus et al. (2000) studied the rationale for interpretation of residual stress distribution profile, which considers mechanical and thermal loads. Tang et al. (2009) studied the influence of tool flank wear on milling forces, temperature and residual stress, and the results indicated that the changes in the distribution of residual stress may result from the increase of milling forces and temperature due to the growing tool wear. Maranhão and Davim (2010) measured cutting forces and temperature in the machining of AISI 316 steel and the data were used to validate the finite element model built in this research, which shows acceptable accuracy, but the relation between cutting loads and residual stress was not specified. Köhler et al. (2012) studied the correlation between residual stress distribution and cutting forces, the results showed that the cutting loads influence the value and the influencing depth of residual stress. Wyen et al. (2013) analyzed the changing law of surface residual stress with changing cutting edge radius in both up milling and down milling sides created in slot milling, and it was supposed that the edge radius influences the process kinematics and cutting temperature, and then further affect the residual stress.

Table 2
Machining parameters for Group A and Group B.

Test No. (Group A)	A1	A2	A3	A4	A5	A6	A7	A8	A9
Feed per tooth [10^{-2} mm]	4.17	5.00	5.83	6.67	7.50	8.33	9.17	10.00	10.83
Other parameters	spindle speed = 3000 rpm; depth of cut = 0.35 mm								
Test No. (Group B)	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**	**B9**
Depth of cut [mm]	0.1	0.2	0.3	0.4	0.6	0.8	1.0	1.3	1.6
Other parameters	spindle speed = 3000 rpm; feed per tooth = 0.05 mm								

Yet though cutting forces and temperature are measured besides residual stress in some experimental studies, they are mainly used as a reference for analysis and few publications pay attention to the direct link between the thermal-mechanical loads and the machining-induced residual stress. In one research carried out by Outeiro et al. (2002) the components of surface residual stress were plotted versus three directional cutting forces, respectively, which showed that cutting forces have significant influence on residual stress but if cutting forces are being taken alone without considering the influence of thermal effects, it is still difficult to predict residual stress. It is a pity that few later publications go further along this meaningful clue. One aspect which was not specified by Outeiro et al. (2002) and which might hinder the direct link between cutting loads and residual stress might be that only part of measured cutting loads really act on the machined surface, where residual stress exists.

To directly analyze the role of thermo-mechanical loads might be a good clue, which might bring about more intuitionistic understanding on the formation mechanism of machining-induced residual stress, and maybe a more universal prediction model can be established. In this study, we chose 18 sets of cutting parameters for end milling, and the relation between cutting forces, temperature and residual stress was analyzed, and a new prediction model was proposed to predict the surface residual stress.

2. Experiment procedures

The workpiece material used in this research was SCM440H, a low alloy steel in Japanese Industrial Standard, and its chemical composition is listed in Table 1.

The dimensions of the specimen are 100mm × 30mm × 10 mm, and 9 tests were performed on each specimen. The machining parameters are listed in Table 2. The cutting speed was kept constant for all tests, and changing feed rate was set for Group A and changing depth of cut (DOC) was set for Group B.

The milling experiments were performed on a DMG machining center. The specimen was fixed onto a fixture with melt adhesive and then the fixture was bolted to a Kistler 9257B dynamometer, as shown in Fig. 1. The cutting forces signal from the dynamometer was amplified by Kistler 5070A amplifier and then processed with data processing software Dynoware and Matlab. A 10 mm diameter, two teeth end mill made by SECO was chosen, with R217.69-1010.0-06-2 cutter arbor and XOMX 060208R-M05 inserts (with F40M composite coatings, Ti(CN) + (TiAl) N + TiN). Dry cutting conditions were kept in all experiments. New inserts were used for each group of tests to avoid the influence of tool wear. The cut-