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Effects of depth of cut on the redistribution of residual stress and distortion during the milling of thin-walled part

Beizhi Li[a], Xiaohui Jiang[a,*], Jianguo Yang[a], Steven Y. Liang[b]

[a] College of Mechanical Engineering, Donghua University, Songjiang, Shanghai, China
[b] The George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA, USA

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ABSTRACT

The distortion of thin-walled part is significantly affected by the residual stress generated after the material is cut away. During this process, the relations between the redistributed residual stress and the distortion are quite complex; as a result the control of distortion of thin-walled part always is being considered tough issues. In this study, an approach of optimizing the profile and magnitude of residual stress is proposed by analyzing the effects of depth of cut on the redistribution of residual stress. Experiments and simulations are conducted to compare the cutting forces, temperature and residual stress. The results show that, in the roughing, by selection of a subsequent depth exceeding prior depth of maximum compressive residual stress, the material which contains the main machined residual stress can be removed in favor of the subsequent machining. Furthermore, in the finishing, different depths of cut are utilized in different cutting stages, resulting in smaller magnitude of maximum machined residual stress and depth of maximum compressive residual stress. In addition, to verify the approach, an aviation thin-walled part is used as the experimental object. The results demonstrate that the magnitude of distortion and residual stress can be decreased and optimized efficiently by controlling and optimizing the depth of cut in the roughing and finishing.

1. Introduction

The thin-walled parts have been commonly used in a wide variety of industries including automotive, aerospace, and precision machinery sectors. As thin-walled parts are easy to distort due to its weak stiffness, it is quite difficult to control the machining accuracy, often resulting in the high processing costs. In order to ensure the machining accuracy, the distortion needs to be controlled during the working procedure. Otherwise the part will be broken. The distortion of part can be separated into machining distortion and subsequent distortion. The machining distortion is caused when cutting away the material which contains initial residual stress, while the subsequent distortion (usually occurred by the machined residual stress) happens after the fixture is uninstalled. Many cases are reported from the industries about the same issues, the thin-walled parts are scrapped due to the subsequent distortion. Thus, it is necessary to understand the profile of the residual stress in the machining.

Previous investigations on machined residual stress were usually focused on analyzing and predicting the profile of residual stress by considering different processing parameters, tool parameters and other factors. Khabeery and Fattouh (1988) found that the magnitude of the peak residual stress generally increased with an increase in feed rate, the depth of cut and the tensile strength of work material. Kuang and Wu (1995) discovered that the cutting speed, feed rate, tool nose radius and flank wear had the most significant effects on the residual stress. Coto et al. (2011) found that higher feed rate would increase the magnitude of tensile residual stress, however, by increasing cutting speed less tensile residual stress would be generated. Navas et al. (2012) noted that by reducing the feed rate and increasing cutting speed, less tensile residual stress could be achieved for AISI4340 steel. With regard to the influence of the tool parameters on the residual stress, Jeelani et al. (1986) firstly found the change of rake angle had little influence on the distribution of residual stress. Fan et al. (2009) presented the residual stress decreased as the rounded cutting edge increased. The results also had shown the tool parameters had significant effects on the machined residual stress.

In conclusion, it was still difficult to control profile and magnitude of the machined surface and sub-surface residual stress. And no clear relations for them had been summarized when using

* Corresponding author. Tel.: +86 15121029145.
E-mail address: 11xiaoyuyu11@163.com (X. Jiang).

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different materials and processing parameters in the machining. For instance, Mohammadpour et al. (2010) observed the magnitude of maximum machined surface residual stress (MMSRS) was 680 MPa, and the depth of maximum machined compressive residual stress (DMCRS) could be even achieved at 200 μm. Moreover, Muñoz-Sánchez et al. (2011) reported the MMSRS was 1100 MPa, the DMCRS was 200 μm. Liang and Su (2007) measured the MMSRS was 900 MPa, the DMCRS ranged from 25 μm to 100 μm. However, Ulutan et al. (2007) found the MMSRS was 1200 MPa, and the DMCRS could be even less than 10 μm.

It was noted that the above researches on analyzing the machining residual stress were conducted only for a single cut. Furthermore, there were also many researches investigating on the re-distribution of the residual stress with sequential cuts, which could be traced back to the earliest studies in the 1950s. Treuting and Read (1951) first established a relationship between the stress and the curvature by removing the sheet material layer-by-layer, which laid the foundation for the analysis of the redistribution of residual stress and distortion. In the following study, Liu and Guo (2000) analyzed the regenerated residual stress in the sequential cuts process, and they observed that the machined surface residual stress could be changed from tensile stress to compressive stress by reasonably optimizing the second cutting process. Wang et al. (2005) investigated the redistribution of residual stress and distortion in machining by removing material layer-by-layer for a frame part, and the material thickness of each layer was varied from 2 mm to 3 mm. The model of finite element analysis (FEA) should be further optimized so that it could be closer to the experimental processing. Different geometric shape of the workpiece was selected by Lee and Nikbin (2007). The influence of stress-sensitive factor for different structures during the heat relief was studied and calculated. With the support from the European project (COMPACT), Robinson et al. (2011) discussed the mechanisms of re-distribution of machined residual stress for Al 7449 after heat treatment. By removing the material layer-by-layer, the effect of the re-distribution of the residual stress on the part distortion was discussed. While there were no signs on the stress release, and the model was limited within the rule cube object. In brief, all these studies were mainly based on the thickness of each layer (equal or nearly equal) of machined workpiece material, which made it hard to be applied in the machining areas of thin-walled part where different depths of cut were usually utilized. Therefore, it needs to further analyze the re-distribution of residual stress of thin-walled part with different depths of cut in the machining, which is also expected to decrease the distortion of the thin-walled part.

In this article, an aviation thin-walled part is selected as the machined workpiece, the re-distribution mechanisms of residual stress and distortion are discussed by using different depths of cut. Moreover, the profile of residual stress is measured on the different zones for the machined part, and an approach is proposed to optimize the distortion and the residual stress distribution of thin-walled part in the milling.

2. Methodology

This work consists of three phases: experiment, simulation and discussions. The first phase, experimental phase, was where the physical milling experiments were conducted in order to collect all necessary data in measured residual stress, surface roughness and distortion. In the second phase, the simulated phase was where the cutting force, temperature and residual stress simulated with the same processing parameters to supplement the temperature and evaluate the experimental results. In this phase, the main method was using the professional software to predict the relevant results. Finally, the last phase, discussions phase, was carried out in order to explain the re-distribution of residual stress and its effects on the distortion of the thin-walled part. In this phase, firstly the fundamental experiments were conducted to discuss the effects of the depth of cut on the re-distribution of machined residual stress. Secondly, the case study was made to evaluate the improvement of the real production quality using the proposed method. The following is the detailed procedure and discussions.

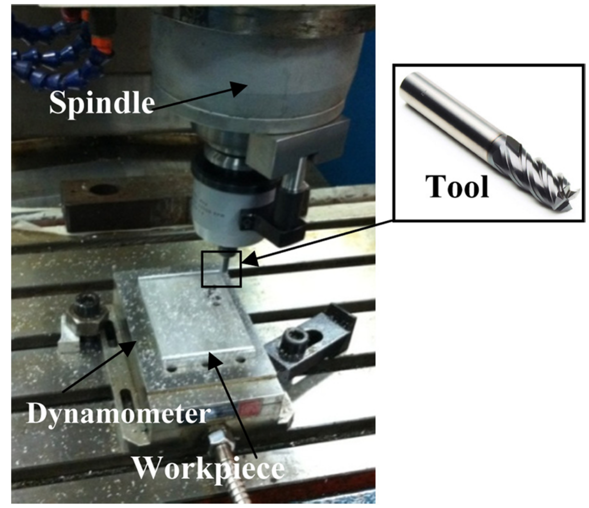

Fig. 1. Machining experiment.

3. Experimental procedure

In this section, the methods are given on the experiments and the way to measure the relevant results such as cutting forces, residual stress and distortion. Since the time consuming and high cost for the machining and measurement experiment, the whole experimental procedure consists of fundamental and industry applied experiments. Aluminum alloy material is widely used in the machining of thin-walled parts such as aerospace industries. The material chosen in this study was Al2024-T3, the chemical composition and main mechanical properties were listed in Table 1. According to the earlier studies and experiences from the industries, in the fundamental experiments, the rectangular workpiece was clamped on the fixture mounted on the table of the milling machine. And the full-immersion slot milling of 6-mm straight grooves was conducted with different processing parameters. In this paper, the different depths of cut (cutting orders range from 0.5 mm to 0.01 mm) were utilized in roughing and finishing, and the processing parameters were given in Table 2. Moreover, in the machining of thin-walled part, in the roughing, using the special fixture to clamping and positioning the machined part. In the finishing, glue clamping was used which had no clamping force. The adhesive dots were designed on the clamping. The specific positions of the dots were not limited but workpiece could be fixed effectively. The processing parameters were the same with fundamental experiments.

3.1. The experimental machining and cutting force measurement

The milling experiments were conducted on Bridgeport machine (model XR1000) (Fig. 1), and the cutting forces were measured with Dalian dynamometer (YDX-III9702) in the fundamental experiments. As presented in Fig. 2, the cutting forces were recorded and analyzed with testing software for different processing parameters. And the professional finite element (FE) cutting software (AdvantEdge^{TM}-3D) was chosen to predict the cutting forces (in X and Y direction) and temperature. Since it was