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On improving chatter stability of thin-wall milling by prestressing

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ABSTRACT

Some long strip-like thin-walled workpieces such as blades usually need to be manufactured by milling with two ends being clamped on the machine table. This paper presents a stability improvement method in this kind of thin-wall milling by applying tensile prestress to the workpiece. The methodology is described by developing theories to establish the relationship between the needed tensile prestress and the expected critical axial depth of cut. Influence of the workpiece natural frequency on the critical axial depth of cut is theoretically explained for the first time. It is found that increasing the workpiece natural frequency can locally improve the stability in milling, and based on this conclusion, quantitative equations relating the expected critical axial depth of cut to the workpiece natural frequency are theoretically derived and solved in detail. With the aid of modal analysis from finite element simulation, problem on how much tensile prestress should be used to increase the workpiece natural frequency to the expected level is explained. In short, the stability lobe of a thin-wall milling system is shifted to the expected stable zone by manipulating tensile prestress to the clamping areas of long strip-like part. Besides, a prototype device, which has the capacity of fixing and prestressing the workpiece, is originally invented to check the effectiveness of the proposed methodology. The proposed method together with the invented prestressing device is experimentally validated by carrying out a series of milling tests with and without prestress.

1. Introduction

Among thin-walled workpieces, there exist lots of long strip-like parts, such as blades, which are usually manufactured by milling. Here, 'long strip-like' does not means that the workpiece is a real strip, but implies that its external profile can be contoured by a strip. Usually, these kinds of workpieces are fixed on the work table with two ends being clamped (see Fig. 1), while the other two ends are in free status. Such clamping often brings small stiffness to the machining system, and thus, chatter is very easy to occur, and then seriously threatens the quality of the machined workpiece surface and the safety of machine tools (Altintas and Budak, 1995). Thus, it is an urgent need to develop strategies to ensure stable cuts of thin-wall milling of such parts (Giurgiutiu and Bao, 2004). In this paper, a new theoretical method together with a prototype device is presented by using the concept of prestressing to improve the stability of milling process of thin-walled workpiece with two ends being clamped.

In the last century, Taylor (1907) proposed a topic of machining chatter for the first time. Later, Tobias and Fishwick (1958) explained regenerative chatter, while Tlusty (1963) clarified the self-excited vibrations. From then on, numerous scholars got active in studying the problems of chatter stability in machining (Insperger and Stépán, 2004). A review of the literature shows that there exist two types of approaches used for controlling the chatters in milling process.

The first is to avoid chatters by selecting chatter-free parameters based on the dynamic response of the milling system. The most common method is to predict stability lobe diagram (SLD) to show the relationship between critical axial depth of cut and spindle speed, and then choose cutting parameters from the stable feasible region. Many researchers have focused on developing algorithms for obtaining SLD. Lee and Liu (1991) and Yanushevsky (1993) used Nyquist criterion to predict the chatter in milling. Altintas and Budak (1995) proposed a zero-order approximation method (ZOA) to predict SLD. Bayly et al. (2003) adopted temporal finite element analysis to predict the stability for interrupted cutting. Insperger and Stépán (2002) developed a semi-discretization method to predict stability lobe diagram, while Ding et al. (2010) did it by establishing a full-discretization scheme. Wan et al. (2010) developed an unified method to predict the chatter stability with multiple delays.

Studies mentioned above mainly focused on establishing methods to predict the SLDs for rigid milling operations, in which the modes of the cutter-spindle system are dominant. Actually, as Altintas et al. (1992)

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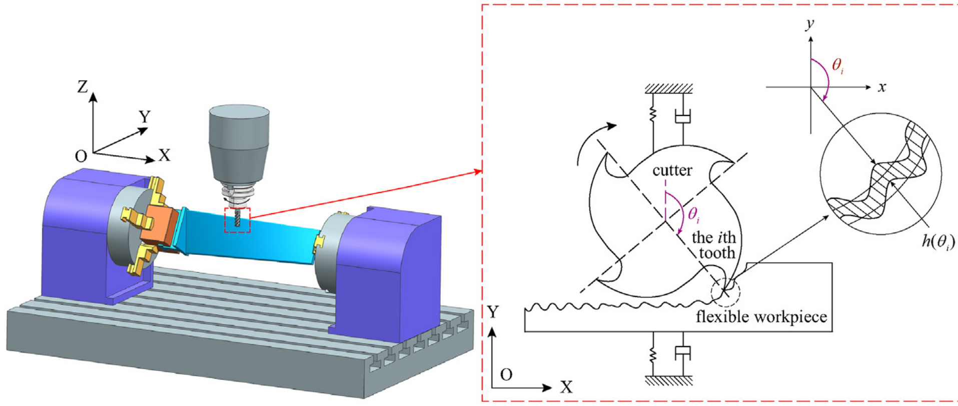

Fig. 1. Dynamic model of thin-wall milling of long strip-like workpiece.

pointed out, in thin-wall milling process, the dynamic parameters of both cutter and workpiece were discrepant along the axial depth of cut. This means that the dynamics of the workpiece should be considered in studying the chatter problems in thin-wall milling. Damir et al. (2011) developed a time domain simulation to predict the SLD by only considering the dynamics of flexible workpiece. Bravo et al. (2005) included the dynamic behaviors of both the cutter and workpiece to predict the stability of thin-wall milling. Eksioglu et al. (2012) considered different dynamics of the cutter and thin-walled workpiece along axial direction, and presented a discrete-time modeling method to accurately predict the stability.

The second approach for controlling chatter is to improve the stability of the milling process by using either soft-intelligent method or additional hardware. The former mainly focuses on optimally choosing the geometrical parameters of the cutter such as the pitch angle and helix angle or the process parameters such as spindle speeds. Altintas et al. (1999) realized the improvement of critical axial depth of cut by using milling cutters with variable pitch angles, and increased the chatter-free region by optimizing the tooth space angles. Sellmeier and Denkena (2011) studied the influence of unequal pitch angle on the stability of milling process, while Dombovari and Stepan (2012) investigated the influences of helix angle on the linear milling stability. Li and Liu (2008) experimentally found that reasonably selecting the overhang, flute length and teeth number of the cutters can also improve the chatter stability of milling process. Ma et al. (2008) used the dynamics of both thin-walled workpiece and tool-spindle system to elaborate SLD, which was then adopted as a basis for changing spindle speeds to achieve the goal of controlling vibrations. Kalinski and Galewski (2011) developed a spindle speed optimal-linear control to surveille and reduce vibrations by using instantaneous spindle speed as command.

There are also some researches aiming at suppressing vibrations by using hardware. Zhang and Sims (2005) used piezoelectric active damping to avoid chatters in milling of flexible parts. Duncan et al. (2005) investigated the effect of dynamic absorber effect on the stiffness of milling system. Bolsunovsky et al. (2013) proposed a tuned mass damper to reduce the vibrations in machining of thin-wall workpiece. Yang et al. (2015) devised a vibration suppression device to generate a force to resist vibrations, and then realized increasing the stable cutting domain. Kolluru et al. (2013) and Wan et al. (2018) mitigated vibrations occurring in thin-wall milling by attaching additional masses to the workpieces. Zhang et al. (2016) experimentally found that tension force can effectively enhance the stiffness and natural frequency of blade-fixture system; however, they did not theoretically study the relationship between the applied tension force and the system's stiffness and natural frequency. Besides, Luo et al. (2018) used thin-film sensors embedded in inserts to realize capturing the cutting forces, which can be adopted as reference for chatter determination. Shamoto et al. (2010) used simultaneous double-sided milling to suppress the chatters for thin-wall workpieces.

This paper presents a prestressing method together with a prototype device to improve the stability in thin-wall milling of long strip-like workpiece, which usually needs to have two ends being clamped. Contribution lies in that the influence of workpiece natural frequency on the critical axial depth of cut and the relationship between the prestress and the workpiece natural frequency are theoretically derived and explained for the first time. It is found that increasing the workpiece natural frequency can locally improve milling stability, and based on this fact, mathematical expressions on how much natural frequency as well as how much prestress should be increased to raise the critical axial depth of cut to the expected level are formulated in detail. Based on the theoretical formulation, a new device is originally invented to carry out the proposed method. Experimental validation of the proposed stability improvement method with and without prestress is presented by conducting a series of thin-wall milling tests.

2. Description of the methodology

2.1. Calculation of a_{lim} and monotonicity of $H_{R,w}(\omega_c)$ vs. $\omega_{w,n}$

The most typical characteristic of thin-wall milling process lies in that the workpiece is very easy to vibrate in its surface's normal direction due to the fact that the dynamic stiffness of workpiece in normal direction is far less than that in feed direction. This means that the dynamic receptance of milling system in normal direction will decisively contribute to the formation of chatter vibrations. That is, for the convenience of derivations, only the dynamic receptance in normal (Y) direction is taken into account in the following contents.

For the milling system shown in Fig. 1, the dynamic chip thickness, i.e. $\Delta h(\theta_i)$, contributed by the vibration Δy in Y-direction is evaluated as follows (Altintas and Budak, 1995).

$$\begin{aligned}\Delta h(\theta_i) &= \Delta y \cos\theta_i\ k(\theta_i)\\ \Delta y &= y - y_0\end{aligned} \tag{1}$$

where θ_i is the instantaneous immersion angle of the ith tooth measured clockwise from the positive direction of Y-axis, as shown in Fig. 1. y and y_0 represent the Y-dynamic displacements of the milling system at the present and previous tooth periods, respectively. i is tooth index, and $k(\theta_i)$ is the windows function that depends on whether the cutter is in or out of cut.

$$k(\theta_i) = \begin{cases}1, & \theta_{st} \le \theta_i \le \theta_{ex}\\ 0, & \text{otherwise}\end{cases} \tag{2}$$

where θ_{st} and θ_{ex} are the start and exit angles of cut, respectively. The cutting forces **F** in X- and Y-directions can be calculated as follows.