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Letters

Burr reduction mechanism in vibration-assisted micro milling

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ABSTRACT

This paper investigates the effect of vibration applied in feed direction on the burr generation mechanism in vibration-assisted micro milling. Kinematic analysis and finite element simulation are conducted for micro slot milling. Due to the vibration assistance in the feed direction, up milling and down milling takes place periodically on both of the cutting-in and cutting-out sides. This results in a reduction of burr formation. The results from both simulation and experiment confirm that the size of the top burrs in the down milling side of the slot are reduced significantly due to vibration assistance compared with conventional micro milling.

1. Introduction

The demand for micro components and micro-parts with high precision machining accuracy is increasing in many applications, such as medical devices, micro moulds, and microfluidics channels, etc. [1–3]. Compared with other micro machining methods, micro milling is recognized as the most flexible micro machining process. It is capable of generating a wide variety of complex micro components and microstructures from various engineering materials in its simple set-up [4].

Dimensional accuracy and machined surface quality are two important criteria for evaluating the machining quality. In the conventional milling process, surface defects and burrs are generally removed by post-processing. However, in the micro milling process, due to the small feature size, post-process deburring is particularly difficult or impossible to perform. Moreover, the deburring process would always affect the dimensional accuracy, and may introduce additional residual stress and damage on the workpiece. Therefore, burr minimization and control become more important for micro milling. Currently developing effective burr control techniques in micro milling remains a pressing task.

In order to suppress and control burr formation, numerous studies have been conducted on the mechanism by which burrs are formed and optimization of machining parameters. Lekkala et al. [5] characterized and modeled burr formation in micro end milling. The influence of the main process parameters (speed, feed rate, depth of cut, tool diameter and number of flutes) on the formation of various burr types was studied. It was found that the burr height tends to decrease with increase of feed rate. Biermann and Steiner [6] studied micro burr formation in the milling process of austenitic stainless steel. They pointed out that in the up milling process of a slot, the top burr height is evidently reduced, but it tends to increase with cutting speed. By conducting finite element simulation, Yadav et al. [7] investigated the micro milling of Ti6Al4V and found that burrs are usually formed on the up milling side at the exit of the micro milling tool. Saptaji et al.[8] studied the effect of side edge angle and rake angle on top burrs in micro milling and found that as the taper angle increases, the top burrs were reduced significantly. Kou et al. [9] proposed a burr reducing method by depositing a layer of supporting material on the workpiece. Most burrs were formed in the sacrificial supporting material and a high quality machined surface was obtained after removing the supporting material. Kumar et al. [10] reviewed recent advances in characterization, modeling and control of burr formation in micro milling. They concluded that optimization of cutting parameters, coating, hybrid cooling/lubrication and the supporting material method could be used to minimize or prevent burr formation. However, the current methods applied to control burr formation in micro milling are either very complicated or of limited effectiveness.

In this paper, a new method for controlling burr formation in micro milling is proposed. It is based on vibration-assisted machining which not only reduces burr formation, but also eliminates the need for post-processing.

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2. Kinematics analysis

The kinematics of conventional micro milling is shown in Fig. 1(a). For slot milling, one side of the slot is generated by up milling, and the other by down milling. With the cutter penetrating into the workpiece from the up milling side, the workpiece material is squeezed and pushed. With the tool rotating and the workpiece feeding, the uncut chip thickness increases. This results in an increase in the supporting effect on the uncut material and material removal in shear action. With continuous rotation of the cutter, workpiece material is removed by the cutting edge from the down milling side, the supporting effect of the uncut material is smaller compared with the up milling side. The uncut material is pushed out of the top of the slot, which is in the direction with the lowest resistance, thereby generating a large irregular tearing burr on the down milling side. Therefore, for ductile material micro milling, the surface quality on the up milling side is better than that of the down milling side as reported in Refs. [6,7] and confirmed in this research.

Based on the top burr formation mechanism, a burr control strategy with the aid of vibration is proposed. As depicted in Fig. 1(a), in the conventional micro milling process, when the workpiece is moved along the tool rotation direction, up milling occurs. For workpiece feed in the opposite direction, down milling occurs. Therefore there is always an up milling side and a down milling side in slot milling, and the latter has a relatively poor edge quality. In this study considering the kinematics of the micro milling process, by applying the appropriate vibration in feed direction up milling and down milling can alternately occur on both sides, as shown in Fig. 1(b). Moreover, when the workpiece is locally subjected to the impact load from the vibration-driven tool, deformation and fracture of workpiece material in the cutting zone will reach a maximum in a shorter time, which changes the material removal process. Material removal in the conventional milling process is dominated by the shearing action of the tool, while in vibration-assisted milling the material removal mechanism is dependent on the hybrid interactions of the impact and shearing. Thus, the formation of burrs is effectively suppressed due to the application of vibration.

3. Finite element simulation

To determine the influence of vibration on burr formation in the slot milling process, a finite element (FE) model is established using ABAQUS/Explicit commercial finite element software as shown in Fig. 2. Titanium alloy (Ti6Al4V) is selected as the workpiece material. The dimensions of the workpiece in the FE model are $2 \times 1 \times 0.2\ \mathrm{mm}^3$ and the minimum element size is set as 10 μm. A 1 mm diameter tungsten carbide end mill with a 3 μm cutting edge radius is used in the simulation. The machining parameters used are: tool rotational speed n = 40,000 rpm, feed per tooth f_z = 15 μm, axial depth of cut a_p = 50 μm. Vibration (frequency 5000 Hz, amplitude 10 μm) is applied to the workpiece in the feed direction. The Johnson-Cook (JC) material constitutive and damage models are used to model material plasticity and damage respectively. Details of the JC model parameters of the material can be found in Ref. [7]. The coefficient of friction between tool and workpiece is set at 0.6.

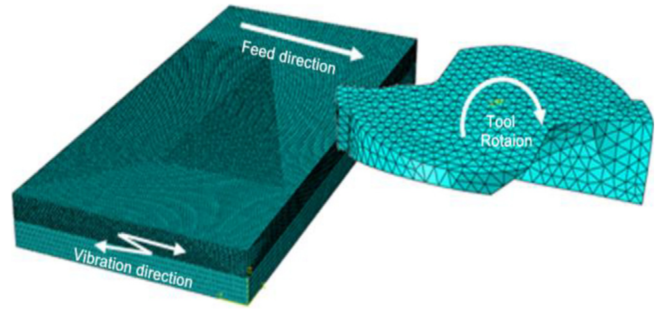

Fig. 2. Finite element model of slot milling with vibration assistance in feed direction.

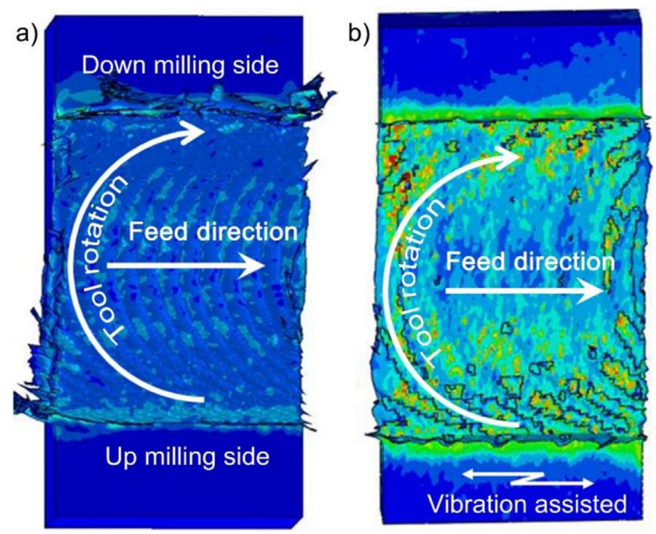

Fig. 3. Slot micro milling simulation results: (a) conventional, (b) vibration-assisted.

Fig. 3 shows the simulation results for conventional micro milling and vibration-assisted micro milling, respectively. It can

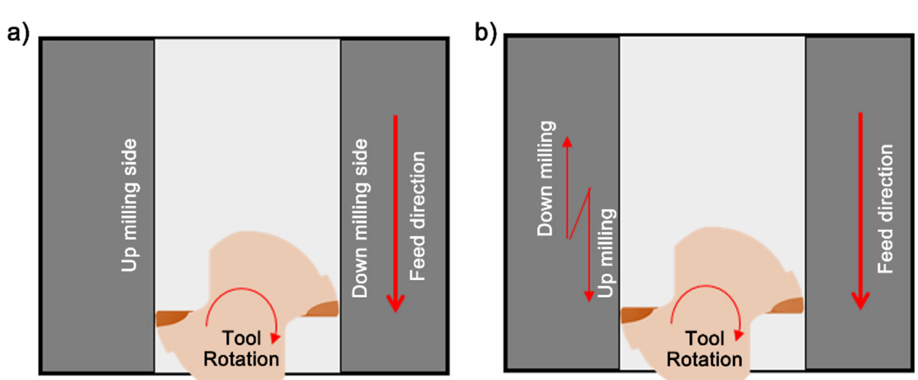

Fig. 1. Schematic diagrams of slot milling: (a) conventional micro milling, (b) vibration-assisted micro milling.