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Characteristics and mechanism of top burr formation in slotting microchannels using arrayed thin slotting cutters

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ABSTRACT

This paper investigates the characteristics and mechanism of top burr formation, and the influence of cutting conditions on top burr formation in slotting microchannels on stainless steel (SS304L) using arrayed thin slotting cutters. Saw-like top burr that is a combination of Poisson part and tear part was observed in the experiments. A 3D finite element model was developed for analysis of the top burr formation processes. The mechanism of top burr formation was proposed based on a series of stress contours and the progressive deformation of microchannel edge obtained from simulation. The process of top burr formation can be divided into four stages: Poisson part initiation, Poisson part development, tear part formation and tear part toppling. The top burr height was found to be largely determined by feed and cutting speed, while the top burr width was found to be strongly influenced by cutting depth, feed and cutting speed.

1. Introduction

The observation by Tuckerman and Pease [1] that decreasing the dimensions of liquid channels to micron scale increases solid–fluid heat transfer rates, has led to increasing use of microchannels in such diverse applications as micropower generation, biomedical applications, computer chips, microchannel heat exchanger and chemical separations processes. Microchannels on stainless steel can be used for microchannel reactors [2] and microfuel cells [3] since stainless steel has high mechanical strength, thermal stability, and erosion resistance. Several methods such as UV–LIGA [3,4], dry etching, micromolding, wet chemical etching, micro electro-discharge machining and laser ablation [5] have been reported in the last decade for the fabrication of microchannels on stainless steel. However, these methods are time-consuming and costly. There is, therefore, a need to develop efficient and low-cost microchannel fabrication methods.

Slotting by arrayed thin slotting cutters is a cost-effective method to fabricate parallel microchannels on stainless steel. However, this method leaves burrs on the two surfaces of machined microchannels. In many cases, time consuming and expensive deburring processes must be applied to ensuring the desired functionality [6].

Different descriptions of burr exist, depending on application, manufacturing process, shape, formation mechanism and material properties. Gillespie and Blotter [7] classified machining burrs into four types: Poisson burr, rollover burr, tear burr and cut-off burr based on the mechanism of formation. Nakayama and Arai [8] described machining burrs formed in various cutting operations, by the cutting edge and by the mode and direction of burr formation. Hashimura et al. [9] classified burrs in face milling according to burr location, shape and mechanism of formation. Lin [10] investigated burr formation during the face milling of stainless steel and found that five types of burr can be produced at the exit edge, viz. knife-type, saw-type, burr breakage, curl type and wave-type. Chern [11] investigated the mechanism of burr formation in face milling of aluminum alloys and observed five types of burrs in the experiments: knife-type, wave-type burr, curl-type, edge breakout and secondary burr. Lekkala et al. [12] presented the results of the influence of main process parameters on the formation of the various types of burrs such as exit burrs and top burrs produced during micro-end milling operation.

A great effort in the past decade has been devoted to chip formation simulation and burr formation with finite element method. Guo and Dornfeld [13] developed a 3D finite element model for simulation of drilling burr formation processes of 304L stainless steel. The results show that the burr thickness is largely determined by the distance between the pre-defined machined surface and the pivoting point, while the burr height is determined by the positions of the pivoting point and the cap formation. Park and Dornfeld [14,15] established an FE model to simulate orthogonal

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cutting and predict burr formation using the FE code Abaqus and an assumed ductile failure criterion. Aurich et al. [16] developed a 3D thermo-mechanically coupled finite element model of grinding process and used it to help in understanding the burr formation mechanism at the exit edge. The research gives detailed information on the developed finite element model and describes a new method of material removal to be used in grinding simulations. Min et al. [17] conducted finite element analysis of burr formation using the commercial software Abaqus. Based on the chip geometry, the stress and strain contours, the burr formation process was divided into four stages: initiation, development, pivoting, and final development. Sartkulvanich et al. [18] investigated the effects of tool geometry (i.e., rake angle and cutting edge radius) and flank wear upon burr formation in face milling of a cast aluminum alloy using FEM. The recommendations of tool geometries that reduce burr formation in face milling is provided. Deng et al. [19] developed a coupled thermo-mechanical model of plane-strain orthogonal metal cutting including burr formation using the commercial finite element code. The normalized Cockroft–Latham damage criterion was proposed for the purpose of better understanding the burr formation mechanism and obtaining a quantitative analysis of burrs near the exit of orthogonal cutting. Yu and Guo [20] developed a finite element model for orthogonal cutting and applied it to simulating burr formation of three typical workpiece materials. The simulation results reveal that either positive or negative burrs depend on the material properties. Up to now, little research on burr formation in slotting microchannel is reported in the literature. The experimental work and practical theoretical models including finite element analysis are also scarce. Most available finite element models adopted 2D FEM simulation programs to provide some insights to the fundamental understanding of burr formation. And they are not suitable for predicting burr formed in the slotting microchannel for its geometrical complexities.

Slotting of microchannels by arrayed thin slotting cutters is a unique machining operation where two distinct kinds of burr are generally observed namely, top burr and exit burr. Top burrs formed in the microchannel slotting degrade the assembly performance and sealability of products. Besides, the morphology and formation mechanism of the top burrs are quite different from the burrs formed in other machining operations. A clear understanding of the top burr formation mechanism is important to develop techniques to minimize burr and hence, improve the manufacturing precision of microchannel.

The objective of this research is to describe the characteristics of top burr formed in microchannel slotting and develop a finite element model to investigate the top burr formation process. The effects of cutting parameters on top burr size are also studied experimentally.

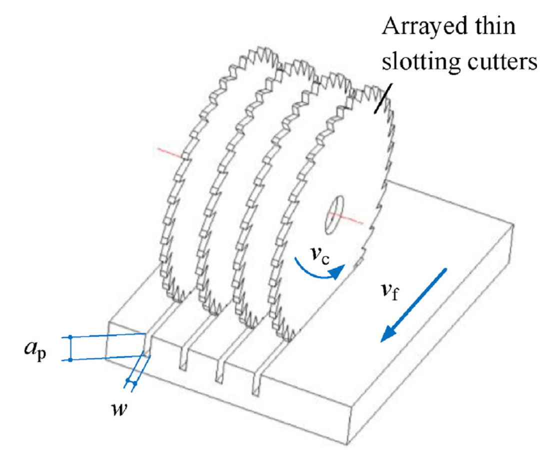


Fig. 1. Schematic drawing of microchannel slotting using arrayed thin slotting cutters.

2. Experimental procedure

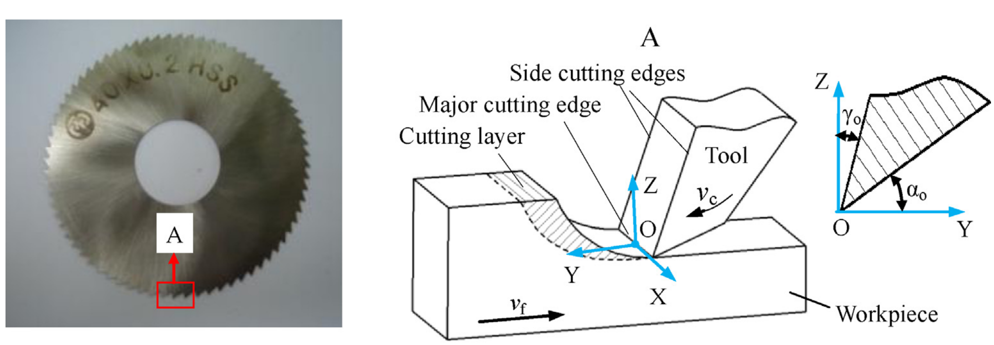
2.1. Experimental setup

The stainless steel (SS304L) workpieces were machined in a vertical milling machine X5032 under dry conditions. The schematic drawing of microchannel slotting by arrayed thin slotting cutters is shown in Fig. 1 where v_c is the cutting speed, v_f is the feed speed, a_p and w are cutting depth and width respectively. The up-milling method was chosen in the experiments because chips stick to the mircochannels easily during the down-milling process.

High speed steel slotting cutters with diameter of 40 mm and 72 teeth were used to machine the workpiece. Fig. 2 shows the geometry and tool angles of the thin slotting cutter. The nominal rake angle γ_o and the clearance angle α_o of each tooth are 4° and 15° respectively. The side rake angle and side clearance angle are all 0°.

2.2. Burr measurement

The burr height (b_h) and burr width (b_w) were measured along the cross-section of the microchannel and were used as characteristics of burr size in this work. Since the burr size varies randomly at the same cutting condition, repetitive burr size measurements were taken in ten different wave crests on both sides of the microchannel. The burr dimensions were measured using Keyence microscopy VHX-1000E.



(a) Slotting cutter (b) Schematic drawing of slotting process

Fig. 2. Geometry and parameters of thin slotting cutter.