An investigation on the tool cutting edge radius and 'boundary effect' on burr formation and control in micromilling

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Abstract

Burrs control and prevention in micromilling processes are essential for micromilling of miniature and micro components or products. The tool cutting edge radius plays an important role in burr formation and predominately governs the burr size in specific material micromilling. The cutting edge radius determines the effective rake angle and pressure status around the engaged cutting zone. The larger the edge radius is, the more remarkable of ploughing or extrusion effect is and thus burr formation and negative shear zone. Furthermore, burr formation mechanism is presented from the view of 'boundary effect' at entry and exit edges of workpiece, which results in deformation instability. Finally, two micromilling strategies are proposed for preventing or control of burrs generation. One is to decrease the cutting edge radius, and the other is to deposit low-melting point alloy on the component to be machine, which is verified with a case study.

1 Introduction

Micromilling is one of the key processes used to fabricate miniature and micro components, especially those with complex three dimensional configurations and features[1]. Burrs are much easier to occur in micromilling than that in conventional milling. The removal of burrs is tedious and in some cases, it is difficult to remove burrs without jeopardizing the dimensional accuracy and surface quality of the compoents[2-3]. Burr formation depends mainly on the workpiece material ductility, cuting tool geometry, cutting parameters (mainly on chip loading), tool wear, shape of the workpiece and so on[4]. Many investigations have been undertaken in micromilling on the types of burrs, the measurement of burrs, their control and removal methods, etc[5-10].

The types of burrs are classified by in reference[11] , which is shown in Figure 1 and this is widely accepted by the research community. However, there are still two questions about burrs in micromilling which attract the research interests. One is why there are more burrs occurred in micromilling than that in conventional milling. The other question is on why most of burrs occuring mostly at entry side, exit side and top side.

In this paper, these two questions are investigated from edge radius and boundary effect respectively. Based on above analysis, two methods were proposed to control and prevent burr formation. Finally, low-melting point metal was used to prevent burrs based on boundary effect as validation.

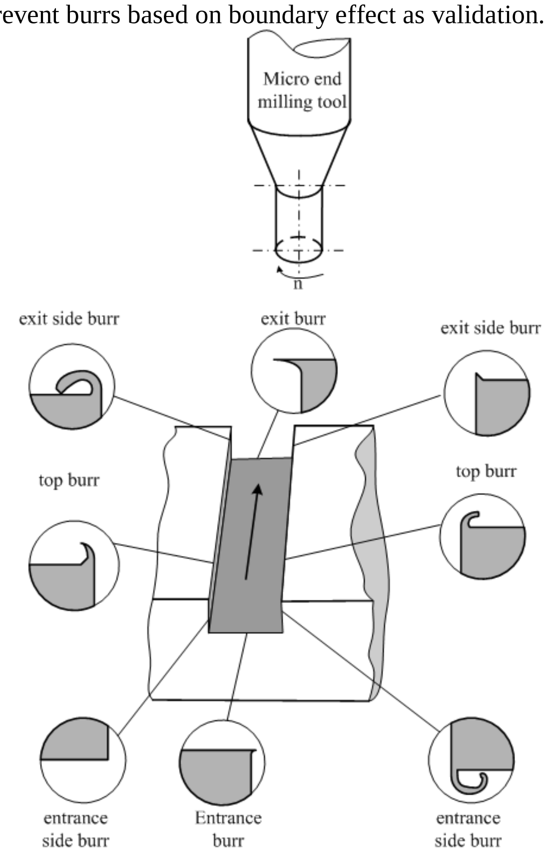
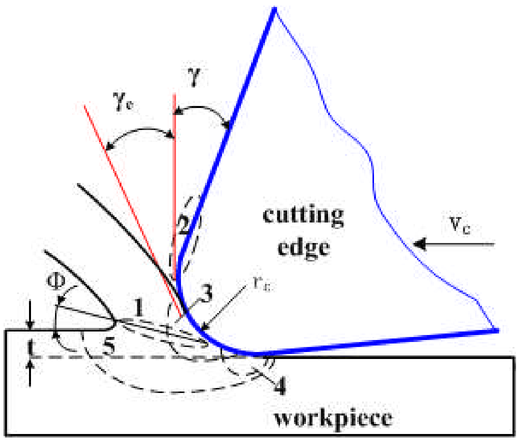


Figure 1: Types of burrs in micromilling[11]

2 Burr formation mechanism considering cutting edge radius and boundary effect

For the first question, it can be explained with size effect, especially the ratio of edge radius to depth of cut. Usually size effect has been investigated from specific cutting energy, uncut chip thickness, etc. Actually, the ratio of depth of cut to edge radius not only effects the chip formation but also burr formation. It is shown in Figure 2 that there are five zones in chip formation in micromachining, that is, primary shear plane, secondary shear plane (rake face), secondary shear plane (cutting edge), third shear plane (tool flank) and forward deformation zone. Compared with conventional machining, cutting mechanism is different in micromachining. On the one hand, secondary shear plane (rake face) is shorter or even disappear in micromachining because of the effective rake angle becomes negative. On the other hand, shear angle decreases outstandingly with the increase of the ratio of edge radius to depth. These are all concerned with the change of effective rake angle.



(1 primary shear plane 2 secondary shear plane (rake face) 3 secondary shear plane (cutting edge)4 third shear plane (tool flank) 5 forward deformation zone.)
Figure 2: Chip formation mechanics in microcutting

The effective rake angle is actually negative. The average value of the effective rake angle can be derived by

$$\gamma_{ave} = -\frac{\pi}{2} + \cos^{-1}(1 - \frac{t}{r_\varepsilon}) \tag{1}$$

Where t is the undeformed chip thickness and rε is the tool edge radius[12]. It can be deduced that with a decrease in undeformed chip thickness, the effective rake angle would be more negative. So ploughing plays an important role in micromachining. When cutting edge moves approach to the exit side, the negative shear zone comes into being, shown in Figure 3. High biaxial compressive stress pushes material toward the free surface and generates large top burrs[13]. In micromillilng, feed rate per flute can be approximately regarded as the maximum depth of cut in one cycle. Therefore, the ratio of edge radius to depth of cut is propotional to the ratio of edge radius to feed rate per flute. In talbe 1, different burr topography in milling titanium alloy with different ratio of edge radius to feed rate per flute.Although it does not belong to micromilling, a conclusion can be drawn combined with the analysis of above analysis that when the size of edge radius is close to uncut chip thickness, more burrs are generated. Furthermore, burrs gennerated in up milling are much larger in size and more in amounts than that in down milling, the reason was also given in the paper[14]. So in order to control the burr formation, a tool with more sharper edge radius should be selected or fabricated. For example, in the micromilling of non ferrous materials, edge radius of diamond tool are much smaller than that of cemented carbide tools.

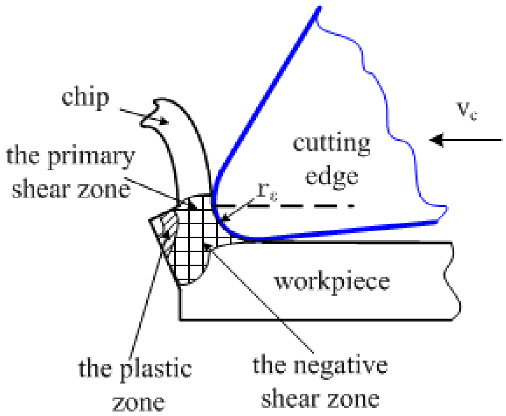


Figure 3: Effect of negative shear zone

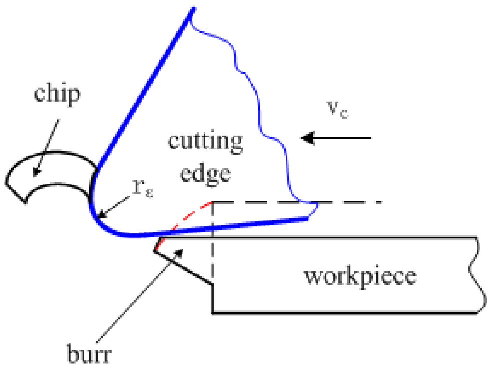
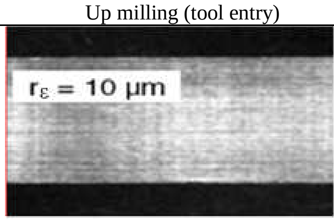
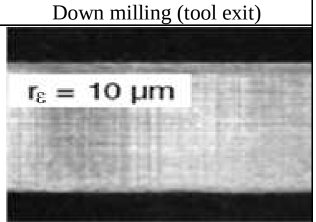
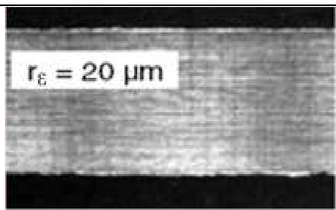
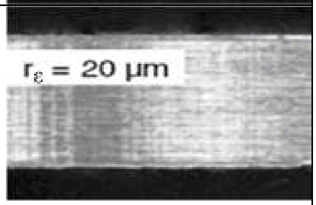
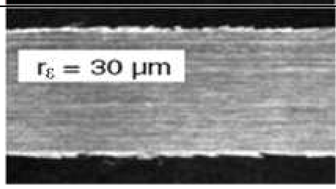
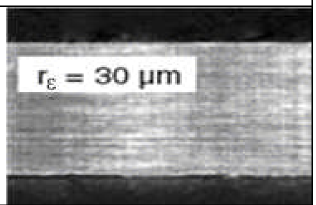
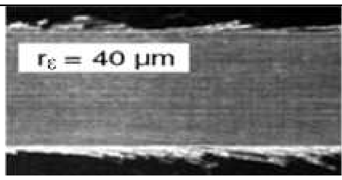
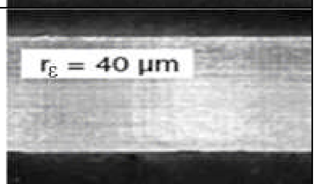
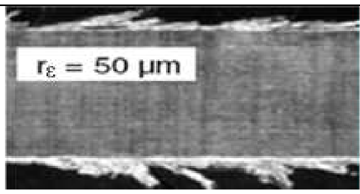
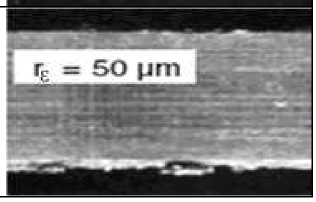


Figure 4: Burr formation in exit side

In Figure 1 and Talbe 1, most burrs are generated at the entrance side and exit side of one cutting cycle. Except the effect of edge radius, a more important reason is called “boudanry effect”. Boundary effect in machining is defined the effect that cause an obvious change in boundary of two different system interactions. For example, the two systems can be workpiece and air, a kind of metal material and another one, etc. In entrance boundary, some materials are extruded due to the existence of edge radius and come into burrs. While a cutting tool moves close to exit boundary, forward deformation zone in Fig.2 become to negative shear zone in Figure 3.Then, as shown in Figure 4, some plastic deformation material can not be cut down with cutting edge and change to burrs. In a brief summary, if the workpiece is deposited with a kind of material that is easy to be removed, burrs will generate on the extra materials. For instance, low melting point alloy can be easily deposit and removed, which can be used as the burr prevention material.

Table1: Burr topography in milling Ti–6Al–4V with different edge radius (vc=70 m/min, fz=0.08 mm, ae=25 mm) [14]

No.	r_ε/f_z	Up milling (tool entry)	Down milling (tool exit)
1	12.5%		
2	25%		
3	37.5%		
4	50%		
5	62.5%		

3 Case study on burr prevention and control

Based on the analysis of boundary effect in burr formation, a method is proposed to prevent burr formation in micromilling with low melting point alloy (LMPA). The low melting point alloy refers to the melting point of alloy that below 232°C, usually comprises low melting point metal elements such as Bi, Sn, Pb, etc. Basically, the melting points include 47°C, 70°C, 92°C, 120°C and so on, according to different elements.

LMPA is firstly deposited on workpiece to be machined and form a very thin layer enclosing the workpiece. When workpiece is machined, burr generates in LMPA material in place of workpiece. LMPA can be melted easily using water bath or oil bath and lead to a burrs-free component.

The experiment was conducted on KERN five-axis micro machining center, shown in figure 5.And a cemented carbide micromilling cutter was used with 0.3mm diameter, shown in figure 6. The workpiece material was aluminum alloy 7050-T7451 deposited with 130µm 70°C LMPA in thickness. A microgroove was machined with the parameters of spindle rotational speed n=30,000rpm, feed rate f_z=0.5µm/flute, depth of cut a_p=200µm, without coolant.

Figure 5: Five-axis micro machining center

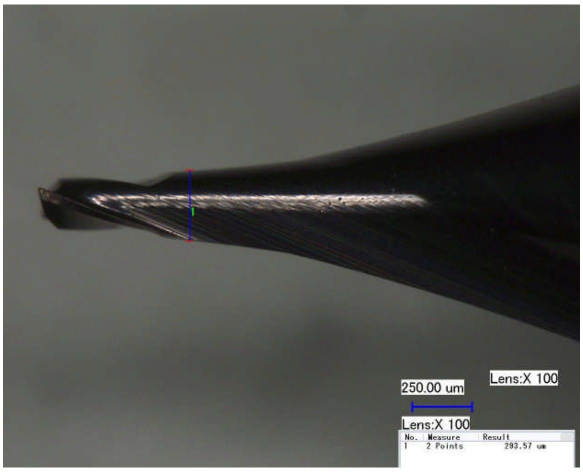


Figure 6: Mircomilling tools (diameter is 0.3mm)

After micromilling, burr topography was observed with digital microscope and shown in Figure 7. There are lots of burr on top surface which actually changed from LMPA. When LMPA was removed by hot water bath, the workpiece was dipped into acetone and cleaned with ultrasonic washer for 5 minutes and then air dried. Figure 8 depicts the topography of aluminum alloy workpiece, in which almost all burrs have been removed. In order to examine whether the workpiece was contaminated by LMPA material, EDS analysis on the surface of workpiece was carried out and the results shown in Figure 9. The results illuminate that the main elements belong to 7050 aluminum alloy. The elements such as Bi, Pb, Sn,Cd, are not attached on the workpiece. The key point of this method is the control of deposit layer thickness, which will affect the real depth of cut.

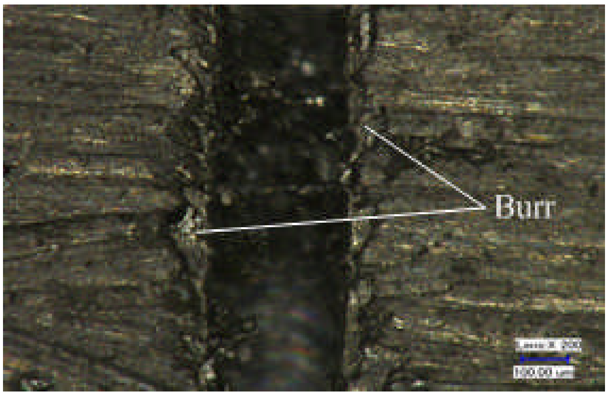


Figure 7: Burr topography with LMPA

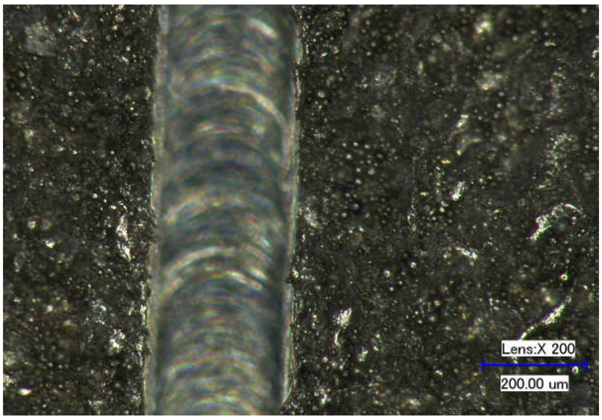
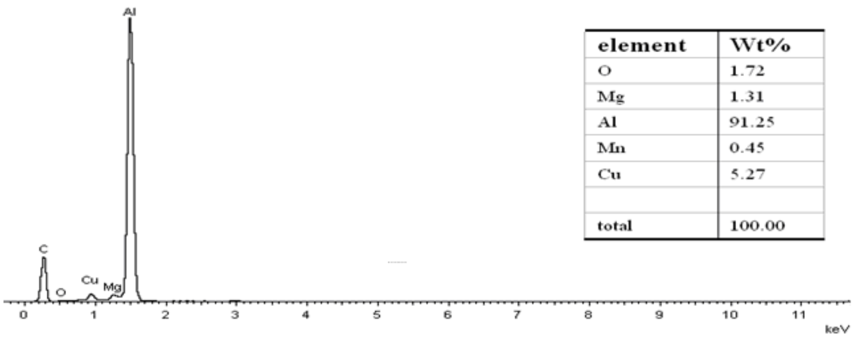


Figure 8: Burr topography after removal of LMPA



element	Wt%
O	1.72
Mg	1.31
Al	91.25
Mn	0.45
Cu	5.27
total	100.00

Figure 9: Element analysis by EDS

4 Conclusions

This paper presents a mechanism analysis on burr formation in micromilling machining from the viewpoints of edge radius and boundary effect. Two approaches to prevent burr formation have been proposed and experimental investigation has been carried out as case study. Following major conclusions can be drawn.

(1) The ratio of of edge radius to depth of cut predominately determine the effective rake angle and pressure status around engaged zone in micromachining. With the increase of ratio, more burrs generate because ploughing force leads to larger plastic deformation zone in cutting and negative shear zone at the boundary of workpiece.

(2) Based on above mechanism analysis, two methods have been proposed to prevent the burr generation in micromilling. One is minimization of edge radius by sharpness or application of diamond cutting tools in non ferrous material cutting. The other one is to deposit low melting point alloy on workpiece to extend the support region and remove it after micromilling.

(3) Experimental study has been conducted as case application. The application of LMPA is very efficient in preventing the generation of burrs. Furthermore, contamination has not be introduced into the machined surface by investigation of EDS. The key point of industrial implementation of LMPA is to control the layer thickness precisely and automatically.

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