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Micro-burr formation and minimization through process control

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Abstract

This paper presents an investigation on micro-burr formation in machining. Micro-cutting is compared with conventional cutting in terms of cutting process characteristic and cutting conditions. In this paper, tungsten–carbide micro-mills were used to cut holes (in a drilling-like process) to investigate top burr formation. The size and type of burr created in stainless steel 304 are studied as a function of machining variables, which are feed, cutting speed and cutting edge radius, to help illuminate the micro-burr formation mechanisms. A series of experiments was conducted to study tool life as a function of cutting conditions. Tool life, here, is defined as the number of holes created before a significant increase in burr height. Based on experimental results, contour charts for predicting burr formation as well as tool life are developed to minimize burr formation and to improve tool life. The model, which includes the effect of feed, cutting speed, and the interaction between the two, predicted the burr height and tool life values with an accuracy of about ±15%.

Keywords: Micro-burr formation; Tool life; Contour chart

1. Introduction

Most machining operations do not often produce smooth or well-finished edges on parts. Instead, parts will most likely end up exhibiting ragged, protruding, sometimes hardened, material along edges, known as burrs. Kim [1] reported several problems affecting form and function of parts in the manufacturing processes due to burrs. Therefore, burrs must generally be removed in subsequent deburring processes to allow the part to meet specified tolerances. A number of burr removal processes exist for conventional machining and can be conveniently applied compared to micro-machining [2].

In recent years, miniaturized tools down to 50 μm diameter have been available commercially. Using these tools, micro- to meso-scale parts can be fabricated; one example is the chemical–mechanical polishing (CMP) pad mold for polishing process shown in Fig. 1. In the micro-machining process, however, the burr is usually very difficult to remove and, more importantly, burr removal can seriously damage the workpiece. Conventional deburring operations cannot be easily applied to micro-burrs due to the small size of parts. In addition, deburring may introduce dimensional errors and residual stresses in the component. These problems are highly dependent on burr size and type. Therefore, the best solution is to prevent burr formation in the first place. If this is not feasible, a second approach is to minimize burr formation. For the implementation of this approach it is critical to understand the basic mechanisms involved in burr formation and the relationship between the cutting parameters and burr formation.

Gillespie [3] defined four basic types of burrs: Poisson, tear and rollover burrs shown in Fig. 2, and cut-off burrs. The tear burr is the result of material tearing loose from the workpiece rather than shearing clearly. The rollover burr is essentially a chip which is bent rather than sheared resulting in a comparatively larger burr. This type of burr is also known as an exit burr because it is usually formed at the end of a cut in face-milling [4]. The Poisson burr is a result of a material's tendency to bulge to the sides when it is compressed until permanent plastic deformation occurs.

A combination of the Poisson and tear burr can end up as a so-called top burr or entrance burr [5] along the edge of top workpiece when a tool cuts a slot or along the periphery of a

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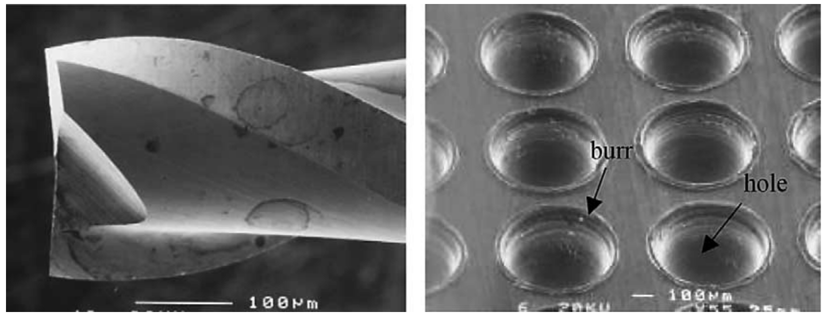

Fig. 1. Micro-mill (Ø 254 μm) and CMP pad mold fabricated by end-milling.

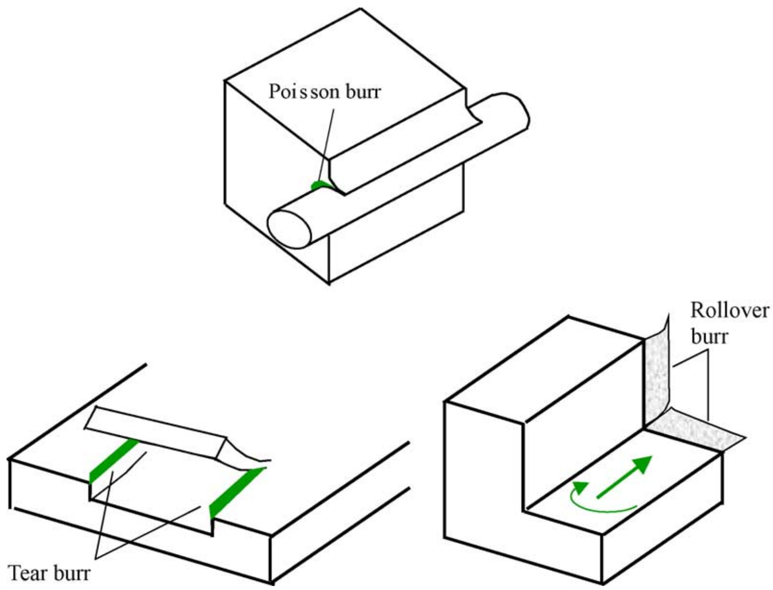

Fig. 2. Schematic of Poisson, tear and rollover burr formation.

hole when a tool enters a workpiece shown in Fig. 3. In conventional cutting processes, these top or entrance type burrs are substantially smaller than exit type burrs so that usually no deburring process is necessary. However, the micro-top or the entrance type burrs are comparatively larger because the radius of the cutting edge is larger compared to the feed per tooth (discussed later in the paper). The cut-off burr is a result of workpiece separation from the raw material before the separation cut is finished. This burr was not included in this study.

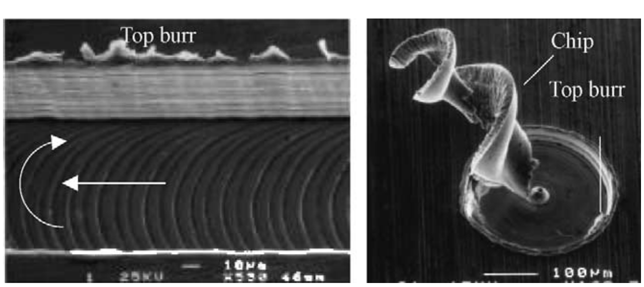

Fig. 3. Top burr in a micro-slot and a micro-pocket.

Much research has been focused on macro-scale burr formation. A few researchers [6,7] have proposed burr formation models. However, no analytical or empirical equations are available that are generally acceptable for predicting and controlling the burr formation. Other researchers have investigated the influence of machining parameters on burr formation [8–10], concentrating on the influence of the main cutting parameters in face-milling and end-milling. Similar research on macro-scale drilling has been done [11].

Little research has been carried out for micro-burr formation. Micro-burrs have been observed in micro-milling of stainless steel, brass, aluminum and cast iron [12,13]. However, the fundamental mechanisms are not well understood.

Tool wear is one of the most important aspects of machining operations because tool wear affects the quality of the machined surface and the economics of machining. Burr formation is also affected by tool wear. However, very little research has been reported regarding the relationship between burr formation and tool wear because it is very time-consuming work. In addition, tool wear is very hard to measure in micro-tools. In order to measure tool wear, the tool should be taken from a tool holder and tool wear measured at regular interval in a microscope or scanning electron microscope (SEM).

In this study, micro-mills were used to cut holes (in a drilling-like process) to investigate top burr formation (burrs formed on the entrance of the hole). The size and type of burr created in stainless steel 304 are studied as a function of machining variables to help illuminate the micro-burr formation mechanisms. The relationship between micro-burr formation and tool wear was investigated. On the basis of the relationship, tool life was defined as the number of holes produced before a significant increase in burr height was observed. A series of experiments was conducted to study tool life as a function of cutting conditions.

2. Experimental setup

For machining stainless steel, 254 μm tungsten–carbide diameter end-mills (seen in Fig. 1) were used. This two-flute end-mill is made of 92% WC and 8% Co. Cobalt increases the toughness of the tool. The mills are a stub length version with a small cutting length used only for low aspect ratios (flute length is 381 μm, shank diameter 3.175 mm and overall length 38.1 mm). The micro end-mill was used in a CNC drilling center with a vegetable oil based coolant. The micro-mill was used as a drill to create flat bottom holes. Miniaturized end-mills have similar cutter geometries as conventional cutting tools. The physics of the material removal process using these tools resembles conventional macro-scale machining although differences exist due to small chip size, cutting edge effects and material property variables at the grain level (for metals). Fig. 4 shows a schematic illustration of the cutting edge and workpiece interaction for both types of machining. For conventional cutting, the effect of cutting edge radius is negligible compared to micro-cutting. To investigate this effect, the relation between feed and the radius of the cutting edge is considered in addition to feed and cutting speed in this study.

2.1. Cutting speed

The first cutting parameter considered is the cutting speed, v_c. One of the significant differences between micro-cutting and conventional cutting is the cutting speed range. The cutting speed range for conventional machining of stainless steel is recommended as 12–38 m/min [14]. Using a micro end-mill, for example, a 50-μm diameter tool, the spindle speed required is up to 240,000 rpm to achieve this cutting speed. This speed is far above the limit of most commercially available spindles. In addition, it was observed that micro-tools used for cutting stainless steel are easy fractured at high cutting speeds. Hence, a lower range of cutting speed was used in the study (Table 1).

Table 1
Cutting conditions

Parameter	Tool diameter (μm)	Cutting velocity, v_c (m/min)	Feed per tooth, f_t (μm) Designed feed	Actual range of feed
Working range	254	3.2, 4.8, 6.4	1.3	0–2.6
			2.2	0.9–3.5
			3.2	1.9–4.5

2.2. Feed

The second parameter considered is the feed, f_t, which plays an important role in determining chip thickness and the resulting cutting force. This is the feed per tooth in the drilling-like process used and corresponds to the uncut chip thickness in the orthogonal model in Fig. 5. However, there is no available reference to determine feed values in micro-cutting. The smallest tool diameter referred to in typical machining handbooks is sub-millimeter.

It is known that, in general, increased feed increases the thrust force. A correlation between feed and thrust force with varying tool diameters can be approximated by applying the Ernst-Merchant's shear plane model to the cutting process. Fig. 5 shows the shear plane model applied to a section of the cutting edge of a tool. Shear force can be calculated as follows:

$$F_s = \frac{k f_t d}{2 \sin \phi} \quad (1)$$

where k is the shear strength of material and d is the tool diameter. In contrast to pure orthogonal cutting, the rake angle

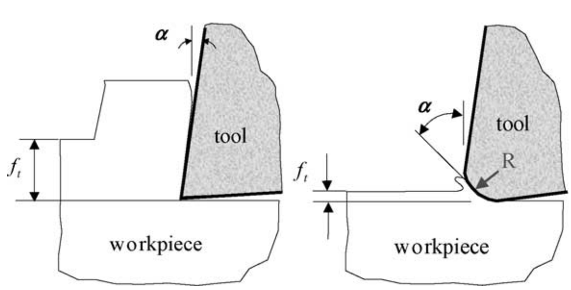

Fig. 4. Schematic view illustrating difference between conventional (left) and micro-cutting (right).

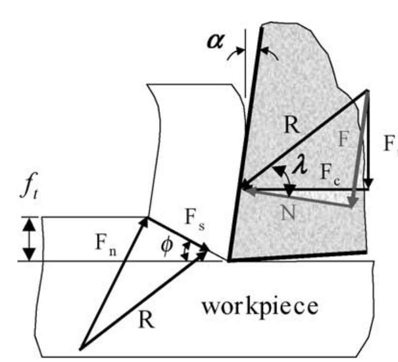

Fig. 5. Cutting diagram.

for the end-mill varies with the radial location, r/R. With Merchant's equation, we can calculate ΔF_t, the thrust force that is exerted on a portion of cutting edge, ΔW:

$$\Delta F_t = \frac{k f_t \sin(\lambda_i - \alpha_i)}{2 \sin\varphi_i \cos(\varphi_i + \lambda_i - \alpha_i)} \Delta W \quad \Delta W = (\rho_{i+1} - \rho_i)R, \quad i = 1, 2, \ldots, n \tag{2}$$

where ρ is the relative radius, r/R. Therefore, the total thrust force, F_t, is

$$F_t = \sum_{i=1}^{n} (\Delta F_t) = \sum_{i=1}^{n} (k f_t d f_n \ \text{(geometry, material)}) \tag{3}$$

The stress directly influences burr formation and tool wear and an effective stress is considered here and can be represented as follows [15]:

$$\tilde{\sigma} = \frac{F_t}{\tilde{A}} \propto \frac{F_t}{d^2} = \frac{f_t}{d} f_n \ \text{(geometry, material)} \tag{4}$$

In this study, the same tool geometry and material are being considered, so it can be assumed that the effective stress is determined only by f_t/d. As the tool diameter decreases to the micro-scale, in order that the tool not to be broken due to high stress, feed should also be decreased linearly. With this concept, an extrapolated feed for a micro-tool can be calculated from recommended feed used in conventional machining handbooks. However, this can only be a starting range for the experiments. Therefore an optimal feed for burr formation and tool life should be determined.

2.3. The relation between feed and the radius of the cutting edge

The third parameter of interest is the feed divided by the radius of a cutting edge, f_t/R, which affects rake angle, chip thickness and consequently specific energy. This parameter shows how much the cutting edge radius plays a role in the cutting process with respect to the tool diameter. For example, for a 19-mm tool diameter, the cutting edge radius is about 14 μm. If the recommended feed, 0.13 mm, is used, f_t/R is about nine so that the effect of the cutting edge radius is insignificant. For a micro-tool, the radius of cutting edge cannot be decreased as much as the decrease in diameter. This is because there is a limit to how sharp the tool can be to minimize fractures on the cutting edge. For instance, for a 254-μm tool diameter of which the radius of the cutting edge is 2.2 μm (determined from 10 tools measured by SEM images, ±0.3 μm), if 2.2-μm feed is used, the ratio is about 1. For this case, the rake angle becomes negative and consequently the chip thickness increases. To investigate this effect, three different values of f_t/R are used for experiments as shown in Fig. 6. Table 1 shows the corresponding cutting conditions used for the study.

It has previously been shown that tool run-out creates a greater problem for the dimensional accuracy of parts created by a micro end-milling process as compared to parts created by a traditional end-milling process [16]. In this blind hole drilling process using a micro end-mill, the axial run-out is important because this value affects the uncut chip thickness. The axial run-out is the difference of the position, in the axial direction, of the two end cutting edges of the end mill (Fig. 1(a)). The average value of the axial run-out measured from the tool manufacture is 1.3 μm. This amount of the axial run-out could affect the uncut chip thickness substantially at low feeds (Table 1). However, this effect decreases toward the center of a tool eventually to zero. In addition, the influence of f_t could be comparatively evaluated for different feeds.

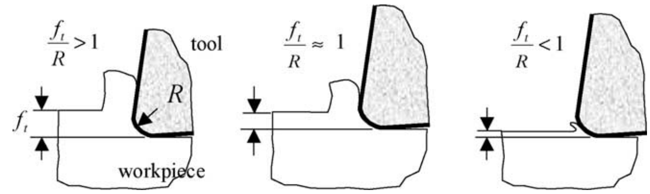

Fig. 6. Schematic view illustrating the influence of f_t/R in micro-cutting.

2.4. Measurement of burrs

One of the biggest challenges for burr research is the measurement of the burr. There are several quantities for burr measurement: burr height, burr thickness, burr volume and hardness. Burr height and thickness are the most frequently and easily measured burr quantities. There are several methods [1] to measure burr height and thickness, such as contact method, optical microscope method and optical coordinate measurement machine (CMM) method. Since it was observed in experiments that top burrs in stainless steel have regular shapes and high hardness (Fig. 7), a surface profilometer, which is usually used for measuring macro-scale surface finish, is used in this study to measure burr height. Burr height at four quadrants for each hole is measured and averaged.

3. Results and discussions

Fig. 8(a) shows the burr height versus feed. The feed has a strong effect on burr height and burr height is linearly proportional to feed. Fig. 8(b) shows burr height versus cutting speed, v_c. At higher feeds per tooth, 2.2 and 3.2 μm, burr

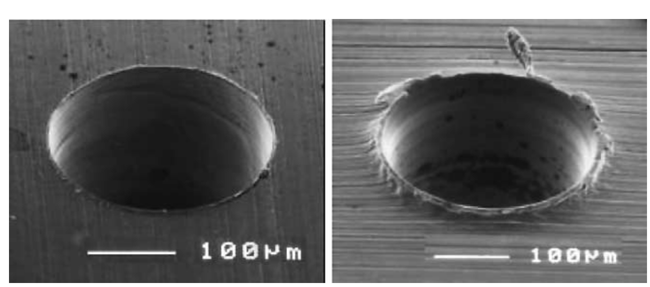

Fig. 7. Top burrs in stainless steel.

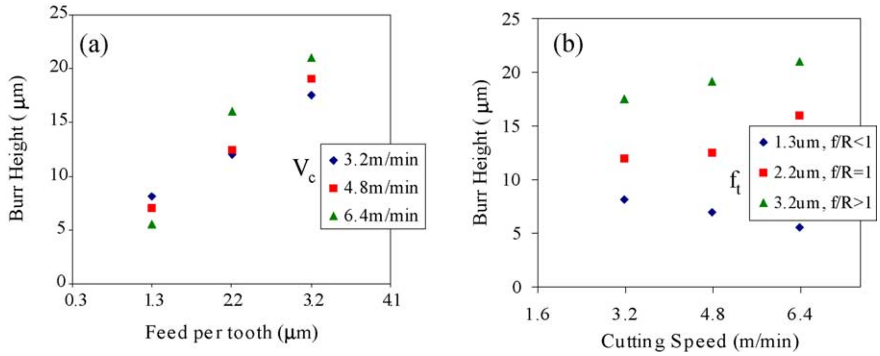

Fig. 8. Burr height vs. feed (a) and cutting speed (b).

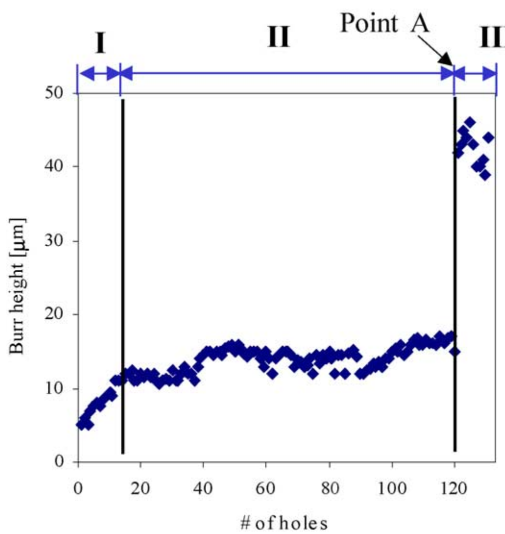

Fig. 9. Burr height vs. number of holes machined.

height increases as cutting speed increases. However, the opposite result was obtained at lower feed. This result will be explained with tool wear later.

It is hard to measure tool wear in general and it is more difficult in micro-cutting due to the small size of tools. It was observed that burr size is related to the amount of tool wear. Fig. 9 shows the burr height versus the number of holes machined for a typical test. A big jump in burr height at point A can be seen due to fatal tool wear (Fig. 10). As a tool wears, f_t/R decreases because of an increase of cutting edge radius. As f_t/R decreases, the rake angle becomes more negative and chip thickness increases. Consequently, burr size increases. Therefore, the tool should be changed before the limiting amount of cut, point A, in order to avoid large burr formation and also to prevent severe tool deformation. Here, tool life is defined as the number of holes created until a rapid increase of burr height is exhibited. To investigate the effect of cutting parameters on tool life, three iterations for each of the nine conditions have been tested. This resulted in 3000 holes created and their burrs measured because about 100 holes were created for each condition.

Fig. 11(a) shows the tool life versus feed. As feed increases tool life decreases due to an increase of cutting force. But tool life also decreases at 1.3 µm feed, which is smaller than the radius of the cutting edge. This result can be explained by the increase of specific energy required to form a chip as the feed is decreased down to smaller than the cutting edge radius [17]. At the lower feed, defined as $f_t/R < 1$, the rake angle becomes negative so that the sliding and the plowing processes dominate instead of the cutting process. Fig. 11(b) shows the tool life versus the cutting speed. Except for the lower feed per tooth, tool life decreases as cutting speed increases. At the lower feed, tool life increases as cutting speed increases. This can be explained by the built-up edge observed in several SEM images of tools at this particular condition. If the part of the built-up edge remains on the tool, the tool can continue to cut for a long time without wear. Since the metal flow around the tool edge tends to become more uniform and laminar as cutting speed is increased, the built-up edge persists on the tools and the rate of wear decreases as cutting speed increases [18]. This uniform metal flow can explain why burr height decreased as cutting speed increased at this particular feed.

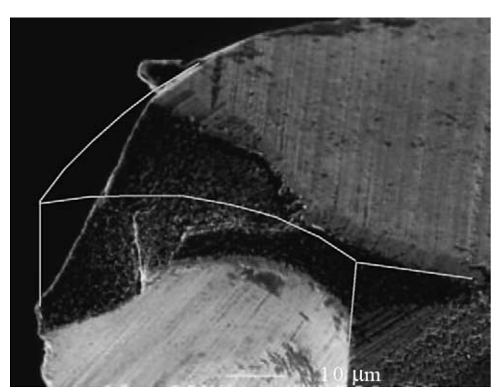

Fig. 10. SEM of a fractured tool.

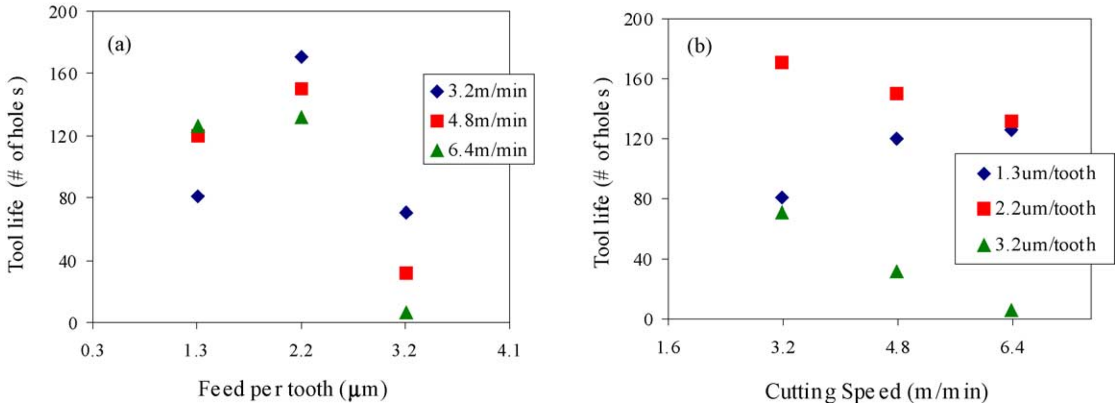

Fig. 11. Tool life vs. feed (a) and cutting speed (b).

4. Control and optimization

With the appropriate parameters developed and cutting conditions, a series of experiments has been conducted. Based on experimental results, empirical models developed by least squares method and contour charts describing the results are proposed for use to minimize burr formation and improve tool life. An empirical model of burr formation obtained by least squares method is shown below. Here, y is the burr height (μm).

$$y = 7.5 - 3.5v_c + 5.3f_t + 0.2v_c^2 - 0.8f_t^2 + 1.0v_c f_t \quad (5)$$

where v_c is cutting speed and f_t is the feed per tooth. Fig. 12 shows a contour chart based on Eq. (5).Eq. (6) is an empirical model for tool life.

$$w = -387 + 44v_c + 443f_t - v_c^2 - 89f_t^2 - 18v_c f_t \quad (6)$$

where w is the number of holes created before tool failure. Fig. 13 shows a contour chart based on Eq. (6). These models predict the burr height and tool life within about plus or minus 15% of the measured value. With these two charts, burr formation and tool life can be predicted and controlled. For example, Fig. 14 shows the combined contour chart of Eqs. (5) and (6). Using this chart, a confirmation test was conducted to compare burr formation and tool life at two cutting conditions, A and B, Table 2.

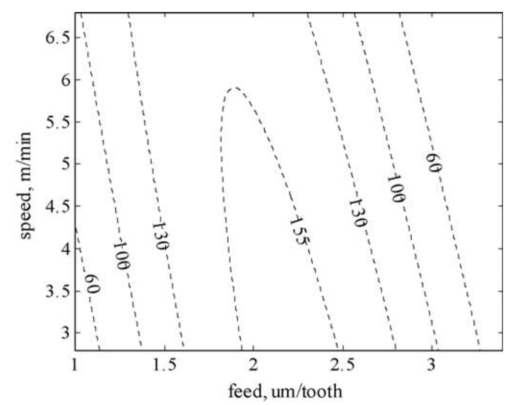

Fig. 13. Contour chart of tool life in terms of the number of holes created.

Table 2 shows burr height, tool life and material removal rate, MRR $= \frac{\pi d^2}{4} 2 f_t n$, where n is the spindle speed of cutting conditions A and B obtained by the confirmation test. While burr height remains similar, tool life and MRR are improved.

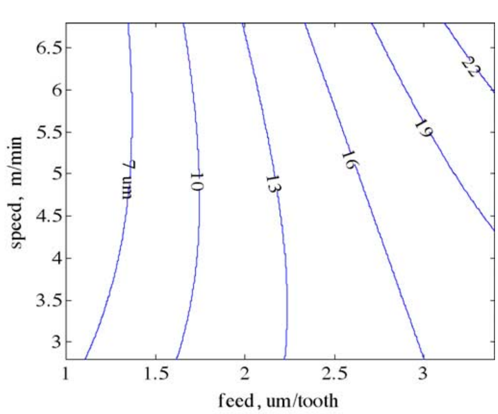

Fig. 12. Contour chart of burr formation.

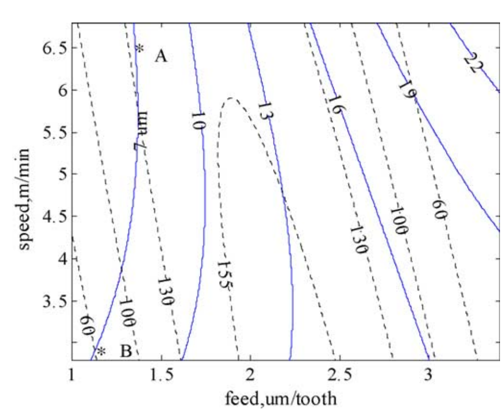

Fig. 14. Contour chart of burr formation and tool life.

Table 2
Comparison of burr height, tool life and MRR between A and B

	A	B
Feed, f_t	1.3 μm/tooth	1.2 μm/tooth
Speed, v_c	6.5 m/min	3 m/min
Burr height (μm)	7.2 (7.19)[a]	6.7 (7.6)[a]
Tool life, # of holes	120 (130)[a]	78 (75)[a]
MRR (mm^3/min)	1.1	0.4

[a] Calculated from Eqs. (5) and (6).

5. Conclusions

Micro-burr formation in cutting stainless steel was investigated according to various feed per tooth values and cutting speeds for a blind hole drilling process using a micro end-mill. For this experiment, tool life was defined as the number of holes created until a rapid increase of burr height was observed. Parameters, v_c, f_t and f_t/R were evaluated for micro-machining. Several important experimental results were observed:

- The burr in hole formation by micro-milling is relatively larger than in conventional milling.
- Burr height is linearly proportional to f_t.
- Burr height is related to tool wear.
- For $f_t/R < 1$, tool life increases as v_c is increased.
- Burr size and tool life can be predicted and controlled through the control charts developed.
- The same analysis approach is suitable for application with other materials and processes.

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