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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 characteristics and cutting conditions. An acceptable range of cutting conditions for micro cutting has been determined by extrapolating the conditions for conventional cutting and experimental verification. With cutting conditions determined, a series of experiments was conducted to investigate burr formation and tool life. Herein, tool life is defined as the number of holes created before a catastrophic increase in burr height occurs. 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.

Keywords: micro-burr formation, tool life, contour chart.

1. Introduction

Most machining operations do not often leave behind smooth or well-defined edges on the part. Instead, parts will most likely end up exhibiting ragged, protruding, sometimes hardened, material along edges, known as burrs. Kim [2000] 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 [Gillespie, 1999].
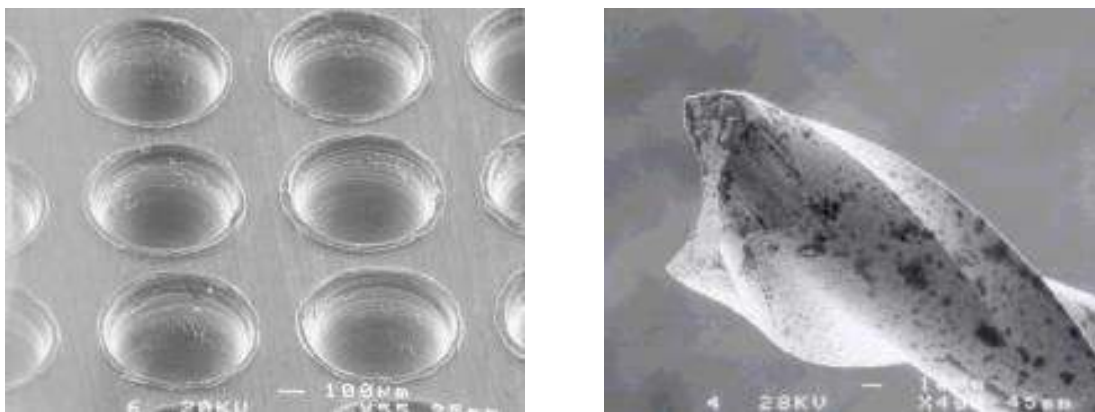

Figure 1. Micro mill (ϕ 127μm) and CMP pad mold fabricated by ball-end-milling.

In recent years, miniaturized tools down to 50 µm in diameter have been available commercially. Using these tools, micro to meso-scale parts can be fabricated, for example, CMP pad molds for polishing processes, Figure 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
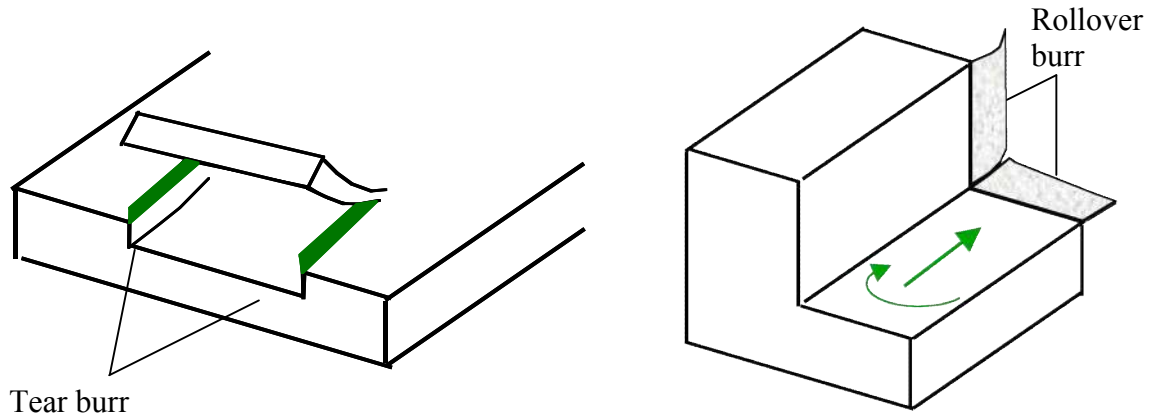

Figure 2. Schematic of tear and rollover burr formation.

introduce dimensional errors and residual stresses in the component. These problems are highly dependent on burr size and type. Hence, 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 phenomena.

Gillespie [1973] defined four basic types of burrs: Tear and rollover burrs (shown in Figure 2), Poisson, and cut-off burr. A tear burr is the result of material tearing loose
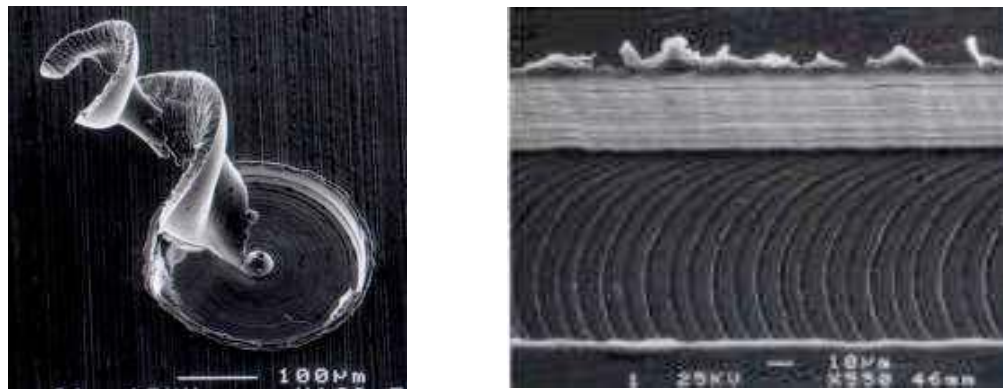

Figure 3. Top burr in a micro-slot and a micro-pocket.

from the workpiece rather than shearing. The rollover burr is essentially a chip that 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 [Hashimura, et al. 1999]. The Poisson burr is a result of a material's tendency to bulge at 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 [Lee 2001], along the top edge of a machined slot, or along the periphery of a hole when a tool enters it, as shown in Figure 3. In conventional processes, these top or
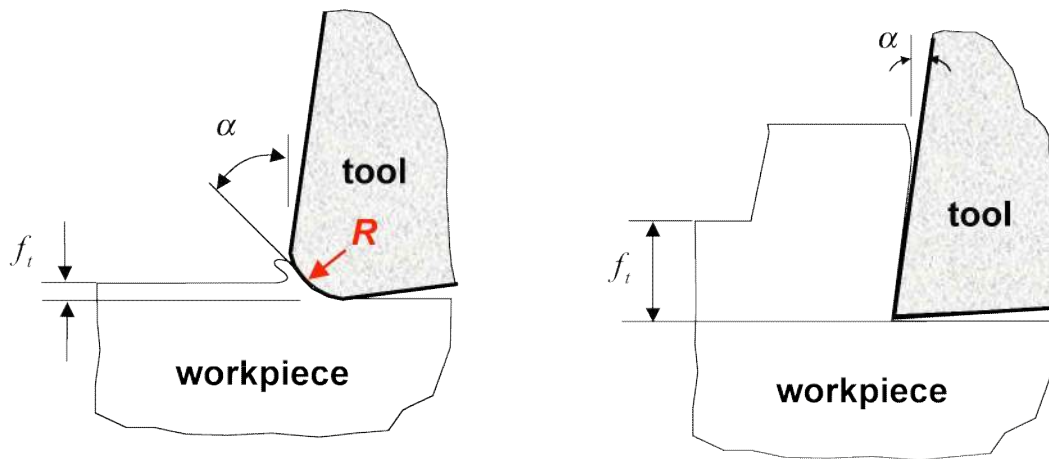

Figure 4. Schematic view illustrating difference between conventional (left) and micro cutting (right).

entrance type burrs are substantially smaller than exit type burrs, and usually no deburring process is necessary. However, micro-top or entrance type burrs are comparatively large because the radius of the cutting edge is large compared to the feed per tooth (discussed later in the paper). In this study, micro-mills were used to cut holes (in a drilling-like process) to investigate top burr formation. The cut-off burr was not included in the study.

Much research has been focused on macro-scale burr formation. A few researchers [Ko and Dornfeld 1991; Chern and Dornfeld 1996] have proposed burr formation models. However, no analytical or empirical equations are available that are generally acceptable for predicting and controlling burr formation. Other researchers have investigated the influence of machining parameters on burr formation [Gillespie, 1976; Olvera and Barrow, 1996; Chu, 2000], concentrating on the influence of the main cutting parameters in face-milling and in end-milling. Similar research on macro-scale drilling has been done [Kim and Dornfeld 2000].

Little research has been carried out on micro-burr formation. Micro-burrs have been observed in micro-milling of stainless steel, brass, aluminum and cast iron [Damazo, et al, 1999; Schaller, et al; Lee, et al, 2001]. The fundamental mechanisms are not well

understood. In this paper, the size and type of burr created in stainless steel 304 are studied as a function of machining variables to better understand micro-burr formation mechanisms.

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 a 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 intervals in a microscope or SEM. In this study, 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 catastrophic 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, two-flute WC-Co end mills (shown in Figure 1), provided by Robbjack Corp., were used. The mills are a stub length version with small cutting length, used only for low aspect ratios. The micro end mill was attached to a Mori Seiki TV-30 CNC drilling center. Micro-drop coolant was used. 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). Figure 3 shows a schematic illustration of the cutting edge and workpiece interaction for both types of machining.

2.1. Cutting speed

The first cutting parameter is cutting speed. One of the significant differences between micro-cutting and conventional cutting is the cutting speed. The cutting speed range for conventional machining of stainless steel is recommended as 12 to 38 m/min [Metcut 1980]. To achieve this cutting speeds using a micro end-mill with a diameter of 50 μm, for example, the rotational spindle speed required is up to 240,000 rpm. This speed is far above the limit of commercially available spindles. In addition, it was observed that micro tools used for cutting stainless steel are easily fractured at high cutting speeds. Hence, a lower range of cutting speed was used in the study.

2.2. Feed

The second parameter is feed, which plays an important role in determining chip thickness and the resulting cutting force. However, there is no available reference to

determine feed in micro-cutting. The smallest tool diameter referred to in typical machining handbooks is in the sub-millimeter range.
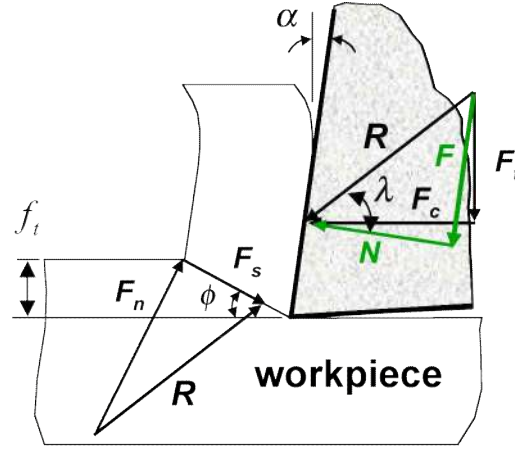

Figure 5. Cutting diagram.

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. Figure 5 shows the shear plane model applied to a section of the cutting edge of a tool. Shear force can be calculated as follows:

$$F_s = \frac{kf_t d}{2\sin\phi} \tag{1}$$

where, k is the shear strength of material and d is the tool diameter. With Merchant's equation, we can calculate F_t, the thrust force exerted on the cutting edge:

$$F_t = \frac{f_t kd \sin(\lambda - \alpha)}{2\sin\phi\cos(\phi + \lambda - \alpha)} \tag{2}$$

Since stress directly influences burr formation and tool wear, an effective stress is considered, and can be represented as follows:

$$\tilde{\sigma} = \frac{F_t}{\tilde{A}} \propto \frac{F_t}{d^2} = \frac{2 f_t k \sin(\lambda - \alpha)}{d\pi \sin\phi\cos(\phi + \lambda - \alpha)} = \frac{f_t}{d} \cdot fn(geometry, material) \tag{3}$$

Here, 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, to prevent tool breakage due to high stress, feed should also be decreased linearly. With this concept, an extrapolated feed for a micro tool can be calculated.

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. Feed / radius of cutting edge

The third parameter is f_t/R, or feed divided by the radius of a cutting edge, 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 tool diameter. For example, for a 19 mm tool diameter, the cutting edge radius is about 14μm. If the recommended feed of 0.13 mm is used, f_t/R is about 9, and the cutting edge radius effect is insignificant. For a micro tool, the radius of the cutting edge cannot be decreased
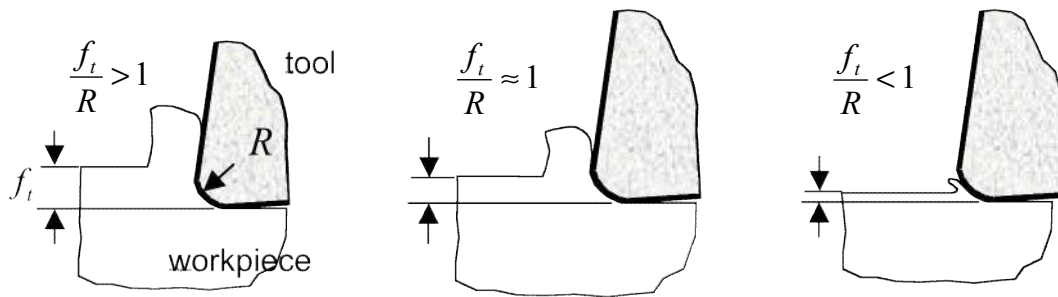

Figure 6. Schematic illustrating the influence of f_t/R in micro-cutting.

to the same extent as a decrease in diameter. This is because there is a limit to how sharp the tool can be to avoid fractures of the cutting edge. For instance, for a 254 μm tool diameter and cutting edge radius of 2.2 μm, if a 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 were used in the experiments, as shown in Figure 6. Table 1 shows the corresponding cutting conditions used in the study.

Table 1. Cutting conditions.

Parameter	Working range
Tool diameter	254 μm
Cutting velocity, V_c	3.2, 4.8, 6.4 m min^{-1}
Feed per tooth, f_t	1.3, 2.2, 3.2 μm

2.4. Measurement of burrs

One of the biggest challenges in burr research is burr measurement. There are several quantities relevant to burr measurement: burr height, burr thickness, burr volume and burr
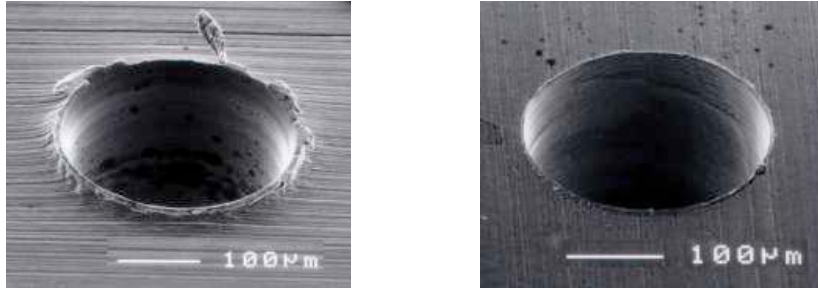

Figure 7. Top burrs in stainless steel.

hardness. Burr height and thickness are the most frequently and easily measured burr quantities. There are several methods [Kim 2000] to measure burr height and thickness such as contact method, optical microscope method, optimal CMM method and rubber casting method. Since it was observed in experiments that top burrs in stainless steel have regular shapes and high hardness (Figure 7), a surface profilometer, which is usually used for measuring macro-scale surface finish, is used in this study to measure burr height. Four points of burr height for each hole are measured, and averaged.

3. Results and discussions

Figure 8(a) shows results of burr height versus feed. Feed has a strong effect on burr

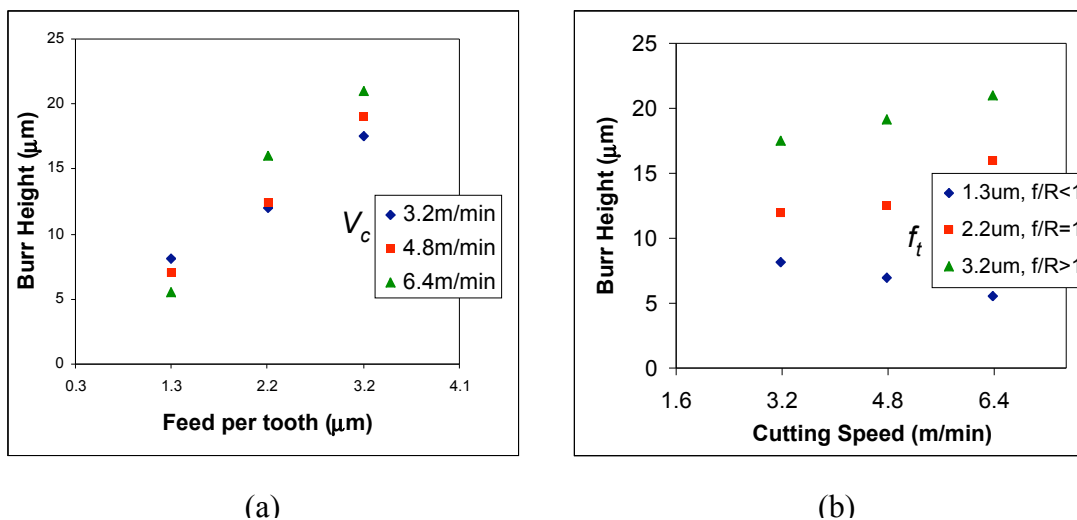(a)   (b)

Figure 8. Burr height versus feed (a) and cutting speed (b).

height and burr height is linearly proportional to feed. Figure 8(b) shows burr height as cutting speed increases. At high feeds per tooth, 2.2 and 3.2 μm, burr height increases as cutting speed increases. However, the opposite result was obtained at low feeds. This result, which can be related to tool wear, will be explained later in the report.
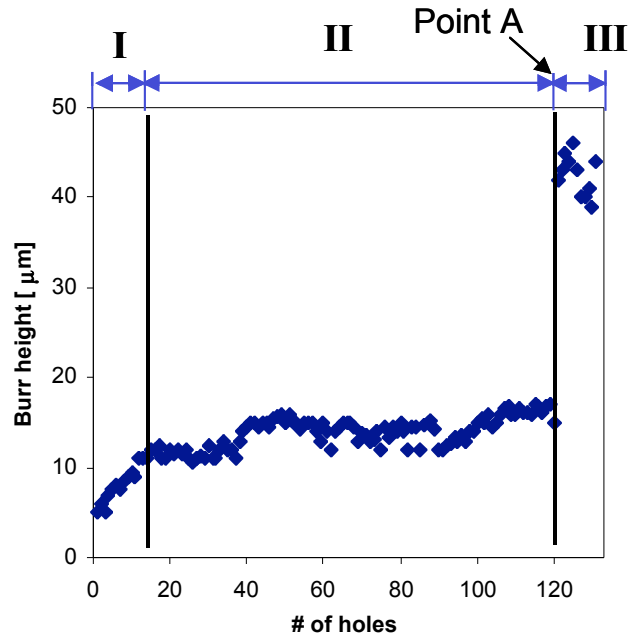

Figure 9. Burr height versus number of holes machined.

In general, it is difficult to measure tool wear, and even more so in micro cutting, due to the small size of the tools. It was observed that burr size is related to the amount of tool wear. Figure 9 shows 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. A SEM of a worn tool after point A can be seen in Figure 10. As a tool becomes worn, f_t /R decreases because of an increase in cutting edge radius. As f_t /R decreases, the rake angle becomes more negative and chip thickness increases. Consequently, burr size increases. Therefore,
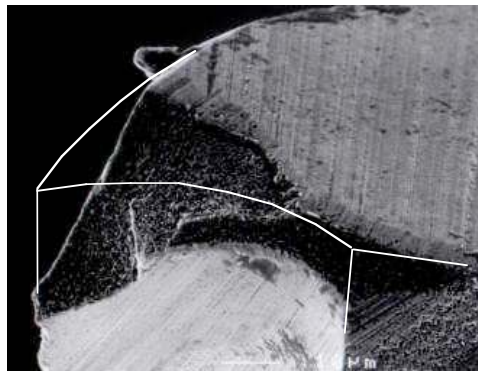

Figure 10. SEM of a fractured tool.

the tool should be changed before the limit amount of cut, point *A*, in order to avoid large burr formation, and also to prevent severe tool deformation. Herein, tool life is defined as the number of holes created until rapid increase of burr height occurs. To investigate the effect of cutting parameters on tool life, 3 iterations for each of the 9 conditions have been tested. This resulted in 3000 holes created, and the burr size of each was measured.

Figure 11(a) shows tool life versus feed. As feed increases tool life decreases due to an increase of cutting force. But tool life also decreases at feed = 1.3 µm, which is smaller

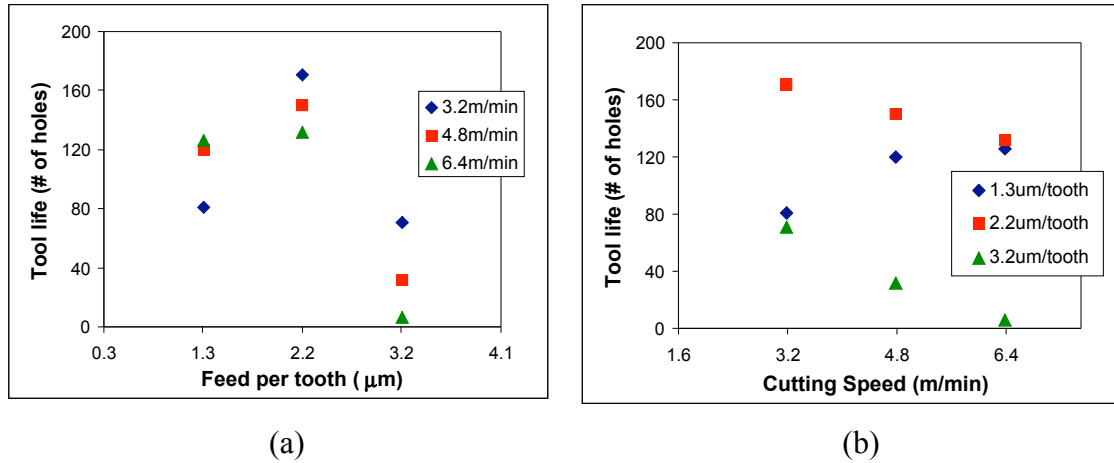(a)   (b)

Figure 11. Tool life versus feed (a) and cutting speed (b).

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 below the cutting edge radius [Backer 1952]. 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. Figure 11(b) shows tool life versus cutting speed. Except for the lowest feed per tooth, tool life decreases as cutting speed increases. At the lowest 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 metal flow around the tool edge tends to become more uniform and laminar as cutting speed is increased, the built-up edge persists when using WC-Co tools and the rate of wear decreases as cutting speed increases [Trent and Wright, 2000]. This uniform metal flow can explain why burr height decreased as cutting speed increased at this particular feed.

4. Control and optimization

With the appropriate parameters developed and cutting conditions, a series of experiments has been conducted. Based on experimental results, an empirical model described by least squares and a contour chart describing the results are proposed for use

to minimize burr formation and improve tool life. An empirical model of burr formation obtained by lease squares method is shown below. Here, y is burr height [μm].

$$y = 7.5 - 3.5V_c + 5.3f_t + 0.2V_c^2 - 0.8f_t^2 + 1.0V_cf_t \qquad (4)$$

where, V_c is cutting speed and f_t is feed per tooth. Figure 12 shows the contour chart based on Equation (4).
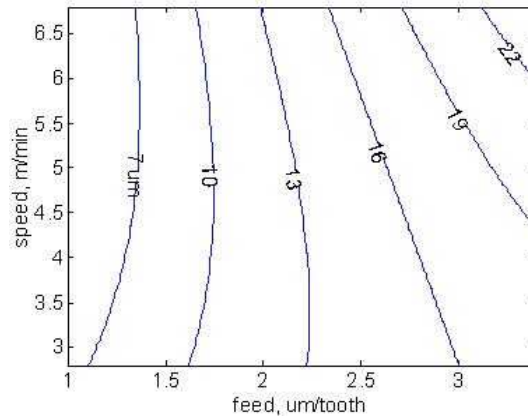

Figure 12. Contour chart of burr formation.

The following equation is an empirical model for tool life:

$$y = -387 + 44V_c + 443f_t - V_c^2 - 89f_t^2 - 18V_cf_t \qquad (5)$$

where, y is the number of holes created before the failure. Figure 13 shows a contour chart based on Eq. 5. With these two charts, burr formation and tool life can be controlled and optimized. For example, Figure 14 shows the combined contour chart of equations 4 and 5. Using this chart, a confirmation test was conducted to compare burr formation and tool life at two cutting conditions, A and B.
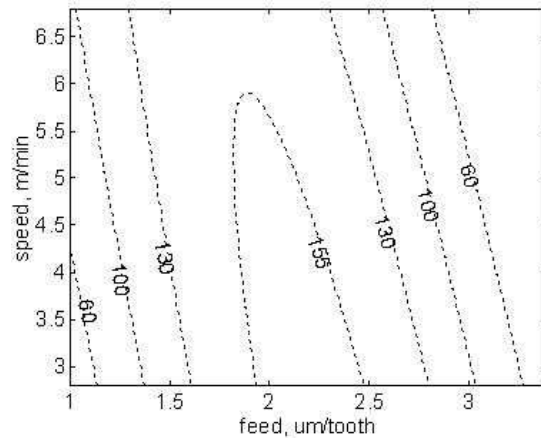

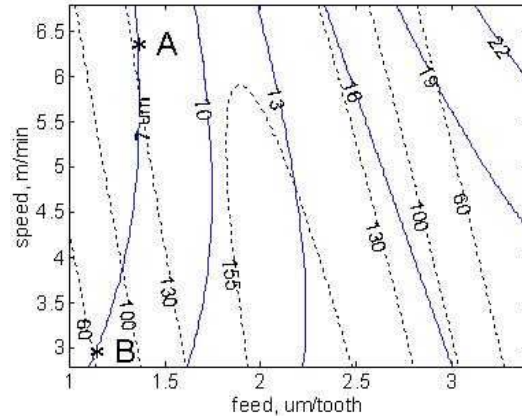Figure 13. Contour chart of tool life in terms of the number of holes created.

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

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

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

	A	***B***
Burr Height [μm]	7.2	6.7
Tool Life, # of holes	120	78
MRR [mm³/min]	1.1	0.4

5. Conclusions

Micro-burr formation in stainless steel cutting was investigated under various feed per tooth and cutting speed values. In this study, tool life was defined as the number of holes created until rapid increase of burr height occurred. Parameters, V_c, f_t and f_t/R were evaluated for micro-machining. Several important experimental results were observed:

- The burrs in hole fabrication by micro-milling are 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 approach can be applied for other materials and processes

Acknowledgments

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