***Journal** of University of Science and Technology Beijing*
Volume 12, Number 2, April 2005, Page 187

Heat regulating strategy in numerical control end milling for hard metal machining

Ying Tang[1)] *and Yoshiaki Kakino*[2)]

1) Mechanical Engineering School, University of Science and Technology Beijing, Beijing 100083, China
2) Department of Precision Engineering, Kyoto University, Kyoto 606-8501, Japan
(Received 04-03-10)

Abstract: The trend in die/mold manufacturing at present is towards the hard machining at high speed to replace the electron discharge machining. Failure forms of the AlTiN-coated micro-grain carbide endmill when used for the machining of JIS SKD61 (HRC 53), a widely used material in die/mold manufacturing, are investigated. The endmill shows a characteristic that tool life decreases greatly due to the chipping when overload occurs or the rapid increase of wear when over-heat accumulation in cutting edges. As a consequence of the investigation, a strategy to regulate heat generation in the end milling process is proposed. This is accomplished by controlling the cutting arc length, *i.e.* the length of each flute engaging workpiece in a cutting cycle. Case studies on the slot end milling and comer rounding are conducted. The results show that the proposed strategy suggests the optimal tool path as well as the optimal pitch between successive tool paths under the cutting time criterion.

Key words: heat generation: end milling; hard metal machining; numerical control

1 Introduction

In a conventional die-making operation, the cavity manufacturing is usually accomplished by machining it to about 0.3 mm oversize dimensions firstly. The die is then hardened *via* heat treatment and then machined to final dimensions *via* EDM (electron discharge machining). After advanced cutting tools like the AlTiN-coated micro-grain carbide endmill appeared since 1990s, the trend in die/mold manufacturing is towards hard machining, both in roughing and finishing, and in replacing EDM whenever possible. The development of high speed machining tools makes the trend feasible and economical. The benefits include reducing the number of necessary machine set-ups, increasing throughput and thus reducing costs. Its profits are now being recognized not only by research institutes but also by die and mold makers.

However, to come to a profitable and straightforward machining process, high speed machining of hardened die steel requires not only specific cutting tools (ultra fine carbide with various and multiple coatings, optimized tool edge geometry, high performance cutting materials, *i.e.* PCBN (polycrystalline cubic boron nitride) and ceramics) and machine tools (rigid, high spindle speed, high feed rate, high acceleration and deceleration) but also special NC (numerical control) programming strategies [1]. Nevertheless, in order to realize high accuracy and productivity, it is important to choose the most appropriate cutting condition for the machining process on the basis of wear resistance study of endmill. In particular, this endmill has a characteristic that the tool life decreases greatly due to the chipping and the rapid increase of wear when the cutting conditions and tool paths are not determined properly.

Consequently, failure forms of the AlTiN-coated carbide endmill when used for the machining of die steel SKD61 are investigated in this study. This contributes to the construction of basic principles for the determination of appropriate NC programming strategies. Proposition in this paper is to implement heat generation regulating in the end milling process, which is accomplished by controlling the cutting arc length, *i.e.* the arc contact of a tool with a workpiece, to control the tool wear process. Through case studies on the slot end milling and corner rounding, the paper illustrates how to implement the proposed strategy to achieve optimal machining.

2 Tool failure forms

Generally, the AlTiN-coated micro-grain **carbide** endmill is capable of machining hardened steel up to **a** hardness of approximately HRC 53. The hardened die steel JIS SKD61 (C 0.32-0.42, Cr 4.5-5.5, V 0.8-1.2,

Corresponding author: Ying Tang, **E-mail:** tangydl@public3.bta.net.cn

Mo 1-1.5, Si 0.8-1.2 in wt%) with a hardness of HRC 53 is widely used for the die/mold. The hardness of cemented carbide (Hv 1600) is 2.8 times that of die steel SKD61 (Hv 580). The hardness of AlTiN coatings is Hv 2700, which is much larger than that of cemented carbide but is only 4.7 times as large as that of die steel SKD61 [2]. It is believed that the tool-to-workpiece hardness should be more than about 5 for a stable wear process. This is especially important when such hard materials are cut and the tool load is very high.

Accordingly, chipping occurs soon if excessive cutting forces at the cutting edge are present. In the endmilling, chipping on one cutting edge can cause a cascade effect of successive chipping on the remaining intact cutting edges for the failing of one cutting edge leads to increased load and therefore higher cutting forces on the other edges. This makes the tool become unusable very quickly. To remedy this situation, a straightforward approach is to maintain the cutting force constant below a safety limit especially in roughing or intermediate roughing operation, where the feed rate adaptation strategy along the tool path has demonstrated its effectiveness in constant cutting force control through the experience of our research group and industrial partners [3]. The basic principle of the strategy is to adapt the feed rate to the tool path geometry. For instance, the feed rate should be damped down when cutting a concave contour or tuned up when cutting a convex contour. Even to cut the same concave contour, the feed rate needs to decrease for smaller contour radiuses to keep the cutting force constant [4].

Once chipping can be avoided *via* the above strategies, hard metal machining highly demands a so-called normal wear progress of the cutting tool which is marked by the rather long cut length achievable. Namely, the cutting edge breaks down in its late stages when extreme wear occurs, and then the end of the tool life is reached. In practice however, the endmill shows a characteristic that tool life decreases greatly due to the rapid increase of wear when cutting conditions and tool paths are not determined properly. **Figure 1** shows the results of tool life experiment of the AlTiN-coated micro-grain carbide endmills when machining the hardened die steel SKD61 of HRC 53, which were presented in our previous work [5-6]. The experiments were conducted to cut the workpiece along the trochoid tool path, a type of tool path pattern that will be described in section 4. The radius ratios of machined contour to the endmill cutter *(R/r)* were 2, 1.5, 1.35 and 1.2 respectively. The feed rate adaptation strategy was adopted to limit the cutting force below 520 N. The spindle speed was 9600 r/min while the pitch between successive trochoid tool paths was 0.5 mm. Results in figure 1 illustrate the relations of tool flank temperature with tool wear, implying the tool wear and cutting temperature are indeed interrelated and interact on each other. As shown in figure 1, the endmill cutters tested in the experiment were worn out at about 780°C, which agrees with the report in reference [7] that the maximum working temperature for titanium aluminum nitride AlTiN is 800°C, comparing with titanium carbonitride TiCN with a maximum working temperature of 400°C.

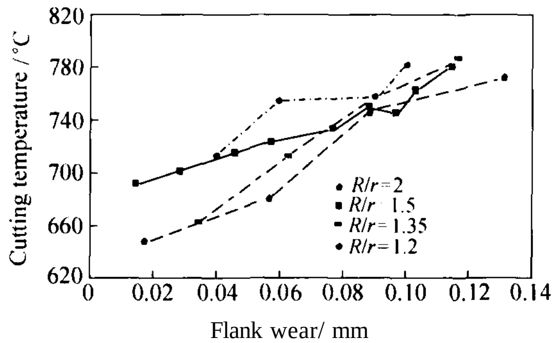

Figure 1 Relations of cutting temperature with tool wear.

3 Regulating heat generation

Tool wear and cutting temperature are interrelated and interact on each other. Excessive heat leads to the increase of tool wear rate, which reduces tool life. Thus it is strongly required to avoid over-heat accumulation in cutting edges. As an intermittent operation, thermal mechanism in end milling periodically repeats the cycle of heating under cutting and cooling under non-cutting. Figure 2 illustrates the cutting and non-cutting cycle in a revolution of endmill. Arc L denotes the length of each flute spends in a cutting cycle. By establishing how much time each flute spends in the cut and how much time it takes to cool before entering the cut again, how much heat is accumulated in the tool and the workpiece is determined.

Therefore, one way of minimizing heat generation and retention is controlling the cutting arc length [8, 9]. When the cutting arc length is too great, the flute builds up heat because there is insufficient time to cool the flute before it re-enters the workpiece. With a smaller cutting arc length, there is an appreciable cooling action, which controls heat generation. By regulating the heat generation with cooling action, higher rpms can be used without reaching the fatal temperature of the coating. In other words, when the proper process is implemented there should be no build-up of heat in the workpiece. On the contrary, once the fatal temperature of the coating is reached, there is a rapid deterioration of the cutting edge, which shortens the tool life significantly.

As shown in figure 2, the cutting arc length L is determined by an angle named by the engagement angle α_{en}. To cut a given contour radius R with the endmill in radius r, the engagement angle α_{en} and thus cutting arc length L are governed by the radial depth of cut R_d.

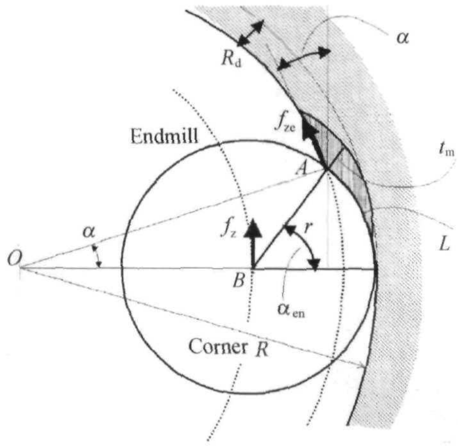

Figure 2 Engagement between the cutting tool and workpiece in a concave contour end-milling process. L—the cutting arc length; t_m—the maximum uncut chip thickness; α_{en}—the cutting-related angle; α—the angle formed by f_z and f_{ze}; f_z—the feed per tooth at the tool center; f_{ze}—the feed per tooth at the tool tip; R_d—the radial depth of cut; r—the endmill radius; R—the contour radius.

$$L = r\alpha_{en} \quad (1)$$

$$(R-R_d)^2=(R-r)^2+r^2-2(R-r)r\cos(n-\alpha_{en}) \quad (2)$$

Other parameters associated in figure 2 can be calculated with the following formulas.

$$t_m = f_z \sin \alpha_{en} \quad (3)$$

$$f_{ze}=f_z(R-R_d)/(R-r) \quad (4)$$

$$\sin\alpha = r\sin\alpha_{en}/(R-R_d) \quad (5)$$

$$t_m=f_{ze}\sin(\alpha_{en}-\alpha) \quad (6)$$

Seen from these equations, to reduce the arc contact between the tool and the workpiece, maintaining a limited radial depth of cut R_d is desired. While if a certain radial depth of cut R_d needs to be removed, a big ratio of the contour radius to tool R/r is recommended. And then in conjunction with proper feeds and speeds, the endmill can remove a large amount of material without generating excessive heat that increases tool wear and shortens tool life.

From the point of view of heat generation, we therefore conclude that tool path and cutting parameter are critical elements to the success of a high-speed end milling of hard metal. They determine the way that the tool engages the material and thus the heat induced into the tool. This conclusion agrees with some well-used programming strategies in the practice of high-speed machining of hard metal, such as "circle strategy" in pocket machining or "helix strategy" when vertical entering a cavity. Both act on limiting the tool contact with workpiece and hence on regulating the heat generation in the machining process **[8]**.

4 Case studies

To be continued, cases to endmill slot or to round corner in hardened die/mold steel are studied in the section to show how to implement NC programming with the proposed heat-generation regulating strategy to maximize the metal removal rate of end mill while providing increased tool life. In the study, the AlTiN-coated micro-grain carbide radius endmill with a diameter of 10 mm, a 45° helix angle, 6 flutes **(figure 3)** and a wide core with a negative rake angle (-14°) is supposed to use. The bottom corner of each cutting edge is rounded with a radius of 1 mm. The hardened steel JIS SKD61 with a hardness of HRC 53 is chosen as the workpiece material. In this stage, only rough and intermediate rough cutting processes are considered. Parameters common to two-case studies are overhang the length L_0=(10-14)r, the spindle speed S=9600 r/min and the axial depth of cut A_d=10 mm. The feed rate in the machining process is solved along the tool path to maintain the cutting force approximately constant at the specified safety limit, which is set on account of the workpiece hardness, tool diameter and slot/corner dimensions.

Figure 3 AlTiN-coated micro-grain carbide radius endmill.

As in die/mold machining industry, demands for making die/mold in far less time is very crucial in market competition. The total time I, that a tool is engaged in cutting is measured in the study as the criterion. And this is accomplished by calculating the exact cutting time by adding the times spent on the cutting arc length of each chip,

$$T_t = \sum_i \frac{L_i}{f_{zei}} + T_{ac} \quad (7)$$

where L_i is the cutting arc length of the ***i*-th** chip, f_{zei} the feed per tooth to cut the chip, T_{ac} the total time of air cutting in the tool path, where the air cutting speed is set at 30 m/min.

The simulation is conducted first to endmill a slot of 100 mm long *(W),* 50 mm wide *(B),* and 10 mm deep *(H)* in a cutting layer. Practically, a slot can be machined with trochoid tool-path pattern **(figure 4)** where successive trochoid cycles have the same pitch. We are interested in seeking an optimal pitch value with constraint that the maximum engagement angle α_{en} is not beyond a specific value. Here the cutting force target is set at 300 N. The simulation result of the slot end milling processes **(figure** 5) shows an optimal bound of the maximum engagement angle at about 30°, which corresponds to the pitch of 0.54 mm. In other words, the total cutting time to endmill the slot reaches its minimum 1.85 min with the pitch 0.54 mm and the engagement angle in the machining process below 30°. The result coincides with the practice of high-speed end-milling hardened die/mold when determining the redial depth of cut, which is generally 5% of the cutter diameter in a roughing operation.

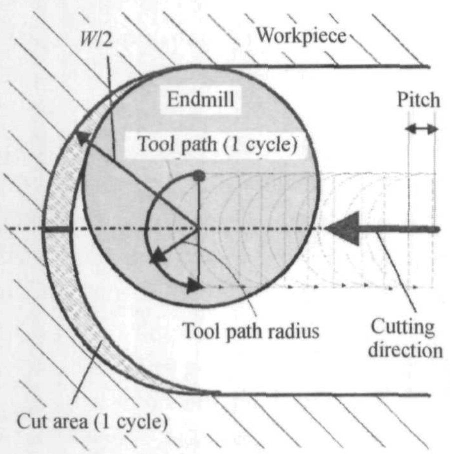

Figure 4 Trochoid tool path pattern for slot end milling.

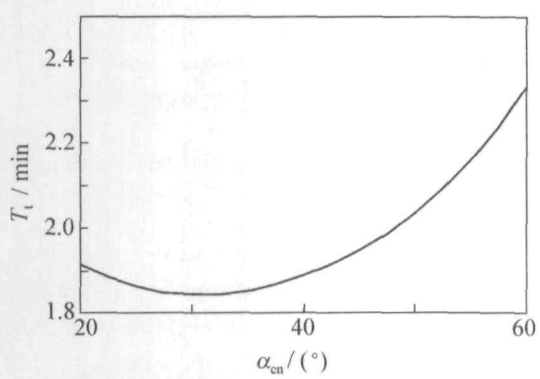

Figure 5 Total cutting time engaged in the slot end milling below the limited engagement angles.

Next, the simulation is conducted on corner rounding, which is a more complicated and more critical end milling process. It is assumed that the corner is machined from a radius of 10 mm to 5.15 mm with the endmill cutter of $\phi 10$ mm. The cutting force target is decreased to 250 N concerning the frequent chipping accidents in the practice of corner machining. As the final dimension of the machined corner is close to the endmill radius, any inappropriate tool path may cause nearly 1/4 circle of the endmill to be immersed in cutting, thus inducing overheat readily. In the traditional offset tool-path generation algorithm, the radial depth of a cut R_d has to be controlled very small to limit the cut arc contact, resulting in a huge number of trochoid cycles and hence an inefficient machining process consequently. In the study, a tool path pattern with two cycles shown as an example is designed **(figure** 6). In each cycle, a 1/4 circle plus its entering and exiting straight lines are used for cutting, and then an air cutting to connect two points, beginning where the endmill enters the cut to where the endmill exits the cut. Pitch, the distance between the centerlines of successive parallel cuts, is determined according to the limit of the maximum engagement angle, hence has a character of getting smaller cycle by cycle. We are interested to know that what engagement angle limit and thus how many tool-path cycles to round the corner are optimal.

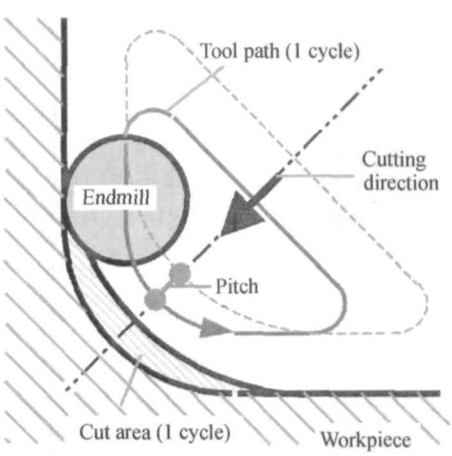

Figure 6 Tool path pattern for corner rounding.

Figure 7 shows the curve of total cutting time under different limits of maximum engagement angle in the corner rounding processes. The optimal value of engagement angle limit 45° is obtained from the curve. Pitches between the successive cycles are calculated respectively and shown in **figure 8,** implying a 4-cycle end milling process to cut the corner in 0.38 s. As seen in the figure, pitch is controlled smaller and smaller. The corner contours formed from each cycle of cutting (gray solid-lines) are shown in **figure 9,** while the gray dashed-line shows the contour of the corner uncut. Comparing with it, the total cutting time will get to 0.54 s in total 35 cycles with a constant pitch of 0.06 mm to control the engagement angle below 45°. With the proposed strategy to generate tool path, about 30% time cut is achieved in the corner rounding process.

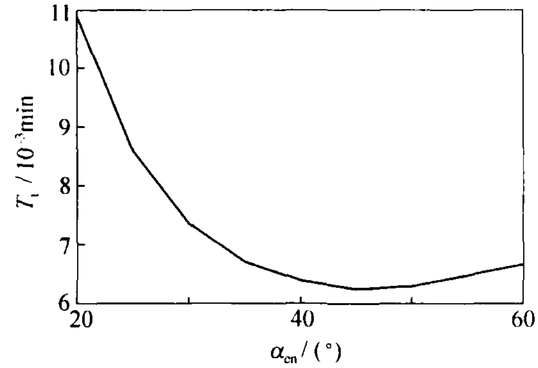

Figure 7 Total cutting time engaged in the corner rounding under limited engagement angles.

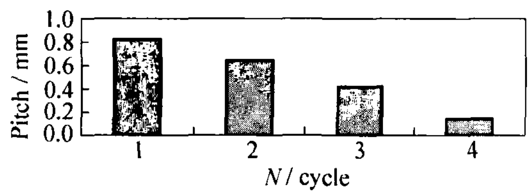

Figure 8 Pitches between successive cycles to round the corner.

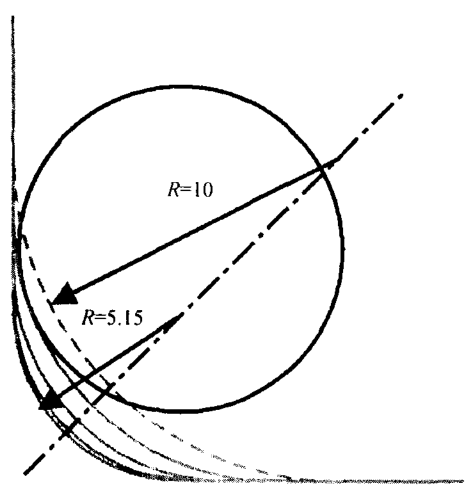

Figure 9 Corner contours formed from each cycle.

5 Conclusions

Excessive heat leads to the increase of tool wear rate in the end milling process, which reduces tool life. It is strongly required to avoid over-heat accumulation on cutting edge. As an intermittent operation, thermal mechanism in end milling periodically repeats the cycle of heating under cutting and cooling under non-cutting. Therefore, one way of minimizing heat generation and retention is controlling the cutting arc length, which indicates the length of each flute spends in a cutting cycle. That is the heat generation strategy proposed in the paper for high-speed machining of hard metal. Cases to cut a slot or to round a corner in the hardened die/mold JIS SKD61 (HRC 53) with the AlTiN-coated micro-grain carbide endmill are studied to implement NC programming with the proposed strategy to minimize the total time that the tool is engaged in cutting. The proposed strategy suggests the optimal pitch for the slot end milling process under the cutting time criterion. While for the more critical corner rounding process, the proposed strategy suggests a tool path pattern with changeable pitch, which saves time up to 30% compared with the machining by using tool path with constant pitch.

Acknowledgements

The authors would like to thank the Kakino Lab and its INC research group at the Department of Precision Engineering of Kyoto University for providing technical and experimental supports.

References

[1] Taylan Altan, Blaine Lilly, and Y.C. Yen, Manufacturing of dies and molds, *Ann. CIRP,* 50/2(2001), p.405.

[2] Yoshiaki Kakino, Andre Schram, Masashi Sasaki, Hirotoshi Ohtsuka, Heisaburo Nakagawa, and Toshiki Hirogaki, Analysis of tool wear and chip formation process during endmilling of hardened steel by (Al, Ti)N-coated micro-grain carbide cutter, [in] *Proceedings of the 4th International Conference on Progress of Cutting and Grinding,* 1998, Beijing, China, p.106.

[3] Y. Kakino, A. Schramm, H. Otsuka, T. Hirogaki, and H. Nakagawa, Intelligent CAM system for the manufacturing of hardened steel made dies and molds, [in] *Proceedings of International Conference on Advanced Manufacturing Technology,* 2000, Johor Bahru, Malaysia, p.49.

[4] Y. Kakino, H. Otsuka, H. Nakagawa, and T. Hirogaki, NC programming for constant cutting force in die machining, [in] *Proceedings of 2000 International Conference on Advanced Manufacturing Automation,* 2000, Guangzhou, China, p.471.

[5] I. Yamaji, *Study on Intelligent Die/Mold Machining System* [Dissertation], Kyoto University, Japan, 2003.

[6] Atahi, *Study on the Influence of Cutting Temperature on Tool Life in Die/Mold Manufacturing* [Dissertation], Kyoto University, Japan, 2003.

[7] Mike Macarthur, Cutting tool selection impacts the outcome of hard metal machining, *Moldmaking Technol. Mag.,* 2003,No.11,p.1.

[8] Ed Kwasnick and Rob Keenan, High-speed machining of hardened die and mold steels—a total concept, *Moldmaking Technol. Mag.,* 2002, No.11, p.1.

[9] T. Tang, Theoretical modelling of cutting temperature in high-speed endmilling process for die/mold maching, *J. Univ. Sci. Technol. Beijing,* 12(2005), No.1, p.90.