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Paper:

Tool Wear and Surface Roughness in Milling of Die Steel Using Binderless CBN End Mill

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In this study, the authors describe the cutting characteristics of binderless CBN end mills in milling of die steel. A single flute radius end mill having a diameter of 0.5 mm and corner radius of 0.02 mm was in the experiment. Heat-treated steel, stainless steel, and high-speed tool steel were cut using a high-speed spindle, allowing for the analyses of tool wear and surface roughness. The results revealed that the wear volume increased with an increase in the hardness of the work material although the edge retreat amount after cutting 25 m was less than 5 μm. The average surface roughness of the finished surface was less than 15 nm in all the work materials. A mirror-finished surface was also obtained. This result contributes to the automation of the polishing process of metal molds and to the more efficient use of labor.

Keywords: binderless CBN end mill, tool wear, surface roughness, mirror finishing, die steel

1. Introduction

The demand for parts with a higher optical transparency is rapidly increasing in the automotive and medical industries, to name a few. The mold surface of these parts requires a mirror finish. In the finishing process for precision molds, polishing is performed by manual labor. Because of this, variation occurs in the accuracy of form and in the properties of the finished surface, both dependent on the skill of the laborer. Another issue is that the polishing of narrow parts, such as a minute groove, cannot be performed. In order to solve these problems, it is necessary to obtain a mirror finish only by cutting. When the work material is a nonferrous metal, such as cemented carbide or aluminum alloy, a mirror-finished surface is obtained by using a single-crystal diamond tool, yet these tools are not applicable to cutting die steel [1–4]. A polycrystalline CBN end mill is used for cutting die steel, yet mirror finishing is not performed [5–9]. Therefore, a binderless CBN end mill (hereinafter called BL-CBN end mill) is expected to be used as a tool for mirror finishing, due to its superiority in wear resistance and cutting accuracy when compared to a polycrystalline CBN end mill [10]. The BL-CBN end mill is used in applications with titanium alloys, yet its performance when applied to die steel has not been reported, and thus its cutting characteristics remain unclear [11–13]. Therefore, in order to achieve a mirror finish with a BL-CBN end mill, it is necessary to illustrate its cutting characteristics for die steel. To examine these characteristics, cutting experiments were performed on three types of die steel using a BL-CBN end mill. The cutting characteristics were analyzed by evaluating the tool wear and properties of the finished surface.

2. Experimental Procedure

2.1. Cutting Tool

Figure 1 shows the BL-CBN end mill used for the cutting experiment. It is a radius end mill having a diameter of 0.5 mm and corner radius of 0.02 mm. A single flute end mill was used instead of a two-flute end mill. This is due to the run-out that occurs to the cutting edge, directly influencing the wear and cutting force in a two-flute end mill; single flute end mills have a negligible influence on run-out [14, 15]. **Fig. 2** shows a detailed drawing of the cutting edge. The flank width and clearance angle is 0.01 mm and 7°, respectively, for both the end cutting edge and the side cutting edge. The end cutting edge concavity angle is 9°.

2.2. Work Material

The work materials used are AISI P21 heat-treated steel, AISI 420 martensitic stainless steel, and AISI M2 high-speed tool steel used for metal molds, with a hardness of 40, 52, and 64 HRC, respectively.

2.3. Machine Tool

The machine tool used in this experiment is a NC milling machine equipped with a high-speed spindle. The range of the spindle speed is 20,000–120,000 min^{-1}, and the locational accuracy is 0.1 μm.

2.4. Cutting Conditions

Figure 3 shows the direction of motion for a small end mill. The cutting depth is 5 μm, and the area of 5 mm

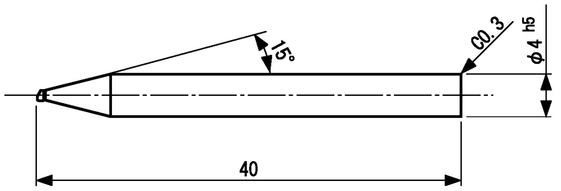


Fig. 1. Binderless CBN end mill.

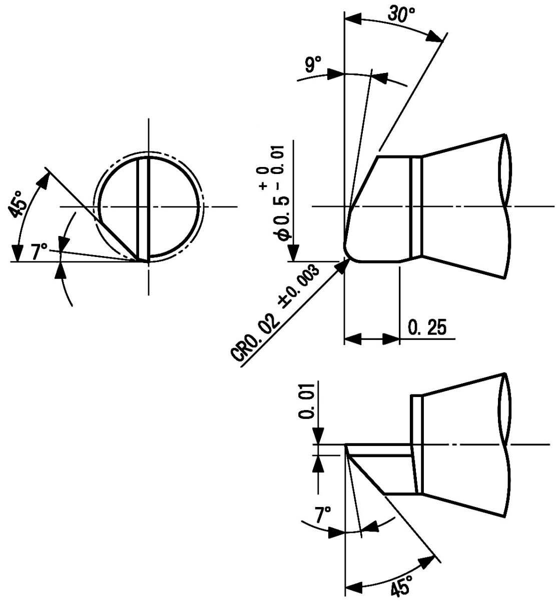


Fig. 2. Cutting edge shape of the end mill.

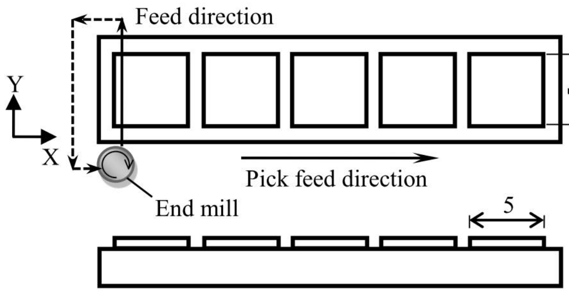


Fig. 3. Definition of tool path.

× 5 mm is cut into five faces. The tool is moved in the direction indicated by the arrow so that the cutting direction became down cut. The solid line indicates the movement of the end mill during the cutting process, while the dotted line indicates movement when cutting is not being performed. Error for the cutting depth direction is maintained at zero by moving the tool only in the X and Y directions and not in the Z direction. The spindle speed is fixed at its maximum speed of 120,000 min^{-1}. Since the cutting length per face is 5 m, the total cutting length is 25 m. The tool used to cut heat-treated steel was labeled as Tool A, the one for stainless steel was labeled as Tool B, and the one for high-speed tool steel was labeled as Tool C. **Table 1** shows the main cutting conditions for the experiment.

Table 1. Cutting conditions.

Tool number	Tool A	Tool B	Tool C
Work material	heat-treated steel	stainless steel	High speed tool steel
Spindle speed	120,000 min^{-1}		
Feed per tooth	2 μm		
Feed rate	240 m/min		
Axial depth of cut	5 μm		
Radial depth of cut	5 μm		
Cutting length	25 m		
Cooling condition	Oil mist		

3. Experimental Results and Discussions

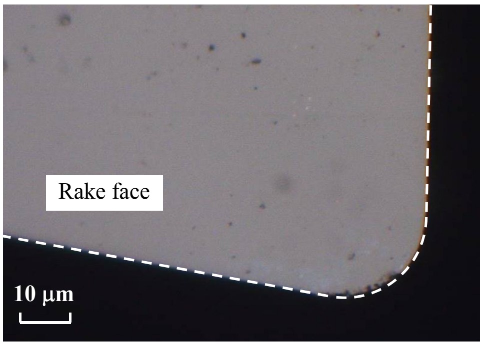
3.1. Wear Pattern

The cutting edge was observed with a microscope in order to examine the influence the work material had on the tool wear of the BL-CBN end mill. **Fig. 4** shows the end mill cutting edge after cutting a length of 25 m as observed from the rake face. The dotted line in the figure represents the cutting edge shape prior to cutting. The cutting edge shape is held in Tool A though tool wear progressed in the order of Tool B and Tool C and the cutting edge shape is not maintained.

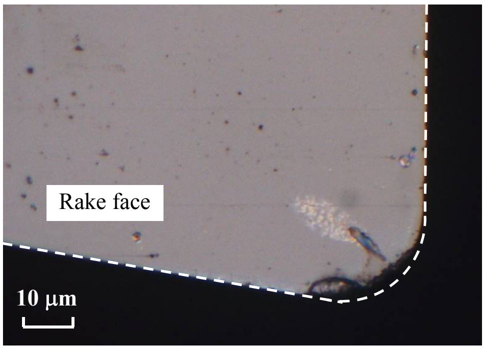
3.2. Wear Volume

Tool wear is generally evaluated based on the amount of flank wear. In Tools B and C, however, the wear progressed in all of the flank faces of 10 μm. Therefore, we evaluated tool wear by the retreat amount of the cutting edge. The retreat amount was measured based on increments of the cutting surface height. The cutting surface height was measured for five planes with a three-dimensional optical surface profiler. **Fig. 5** shows the profile curves for the pick feed direction when high-speed tool steel was cut. The left side is the starting point as shown in **Fig. 3** and the cutting surface rises towards the end point. This is due to the cutting depth decreasing as the wear progressed. **Fig. 5** shows that the curve increases slightly in proportion to increasing tool wear. The profile curves for the heat-treated and stainless steel displayed a similar result.

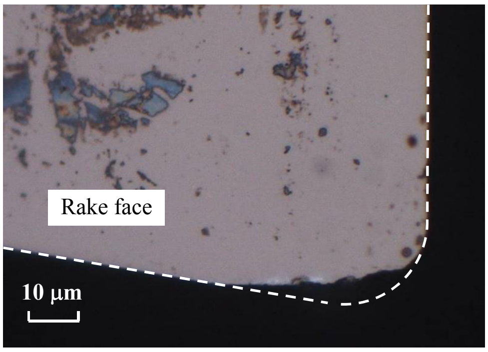
Figure 6 shows the relationship between the wear volume and the cutting length obtained from **Fig. 5**. When the maximum cutting force was applied to an end mill without rotation, the error in the depth direction was smaller than 0.1 μm. Therefore, the error due to the deflection was ignored. No sudden chipping occurred during observation in any of the tools. The tool wear gradually progressed as the cutting length was extended. Using the same cutting conditions to AISI P21 heat-treated steel, the wear of Tool A at a cutting length of 25 m is approximately 1/3 of a commercial polycrystalline CBN end mill with a different cutting edge shape. It is was found concluded that a BL-CBN end mill is more effective than a



(a) Tool A



(b) Tool B



(c) Tool C

Fig. 4. Rake face wear of the cutting edge.

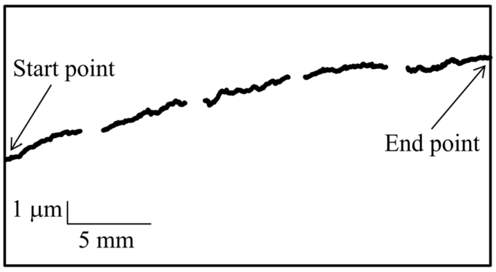


Fig. 5. Surface profile curve of the high-speed tool steel.

polycrystalline CBN end mill in small end milling of die steel. The wear of Tool A at a cutting length of 25 m is approximately 1/2 and 1/5 of that for Tools B and C, respectively, indicating that wear progression is greater with increased hardness of work material. This is because hardness has a direct influence on wear, similar to the case

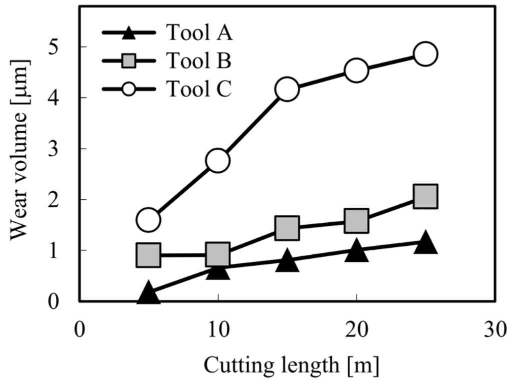


Fig. 6. Relationship between wear volume and cutting length.

of cutting die steel with an end mill made of cemented carbide [16]. The above-mentioned result has shown that wear increases more with harder work material in the case of cutting with a BL-CBN end mill.

3.3. Cutting Force

In order to examine the effect that work material and tool wear exhibit on the cutting force, a dynamometer was used to measure the cutting force acting on the cutting edge. **Fig. 7** shows the cutting force when cutting the high-speed tool steel. It is the cutting force acting at the cutting length of approximately 25 m in the X, Y, and Z directions as shown in **Fig. 3**. The cutting force, Fz, in the depth direction is highest while those in the feed and radial directions are small. This indicates a result similar to that obtained in the case of cutting stainless steel with a ball end mill made of cemented carbide [17]. It has been revealed that in a small end mill made of cemented carbide, the cutting force acting in the depth direction tends to increase more than the forces acting in other directions. Similar characteristics are observed in the BL-CBN end mill.

The cutting force was evaluated based on the maximum cutting force per pass when passing the work material. One pass was equal to 5 mm and measurements were taken for each cutting length of 5 m. **Fig. 8(a)** shows the relationship between the cutting force and cutting length acting in the depth direction. For all tools, the cutting force increases as the cutting length increases. This corresponds to the progression of wear shown in **Fig. 6**, indicating that it is caused by an increase in wear. On the other hand, hardness of work material influences the cutting force acting on the cutting edge [18], the authors presume. Therefore, the cutting force acting on Tool C is greater than those on Tools A and B because of hardness and wear on the work material.

Figure 8(b) shows that the cutting force acting in the feed direction has a similar trend, indicating that both, the wear on the end-cutting and side-cutting edge progresses in the same manner. For Tool C, the cutting force, after cutting a length of 15 m, does not increase in the depth and feed directions. This is because the decrease in cutting

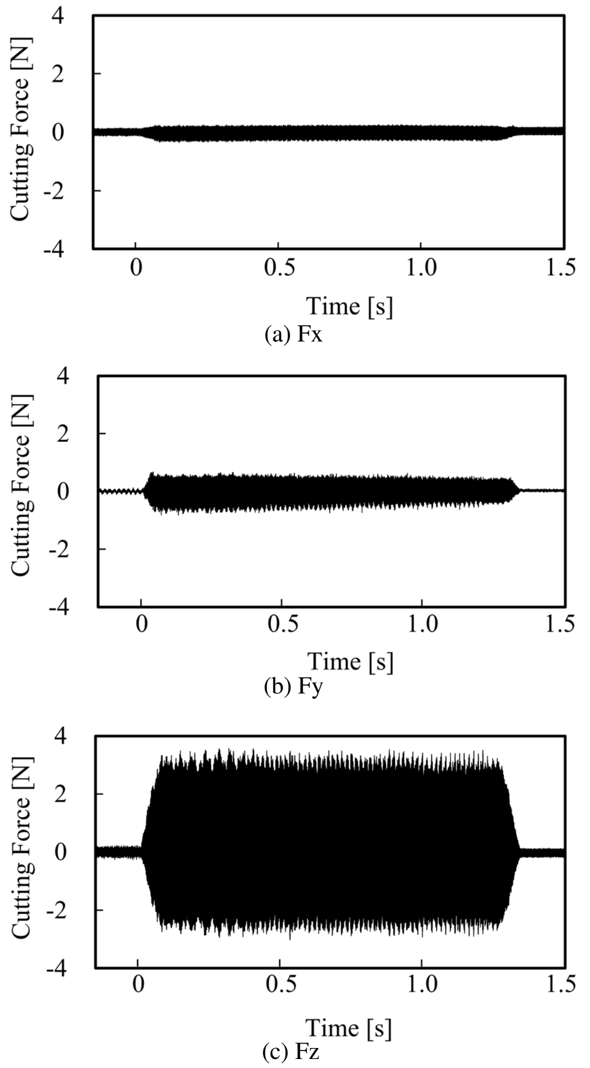


Fig. 7. Cutting force in end milling of the high-speed tool steel.

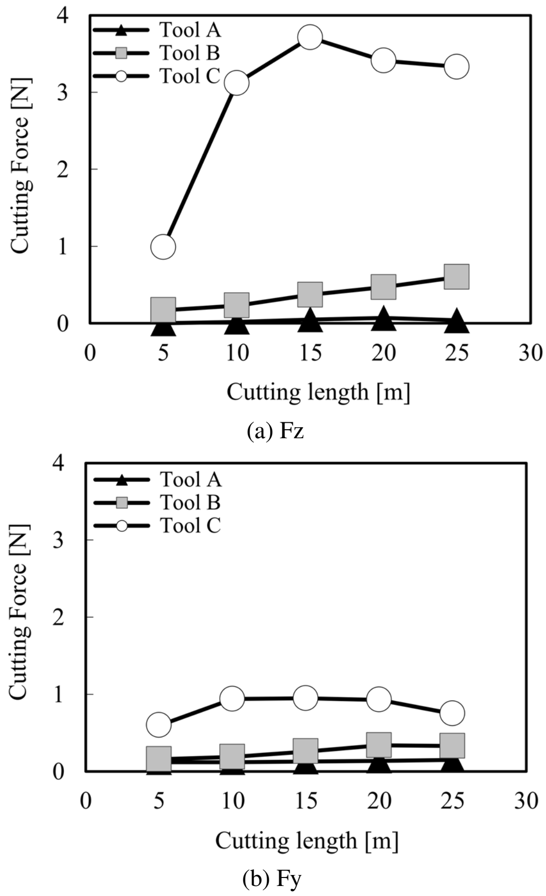


Fig. 8. Relationship between cutting force and cutting length.

depth caused by wear progress lead to fall of the cutting force rather than the cutting force increased by the change in cutting edge shape by wear.

3.4. Comparison of Cutting Surface

Figure 9 shows an image of how the letters are reflected on the cutting surface. The letters are clearly reflected in all die steel, indicating that a satisfactory cutting surface was obtained. It has been shown that BL-CBN end mills enable the mirror finishing of steel, similar to the cutting of aluminum alloy with a single-crystal diamond end mil.

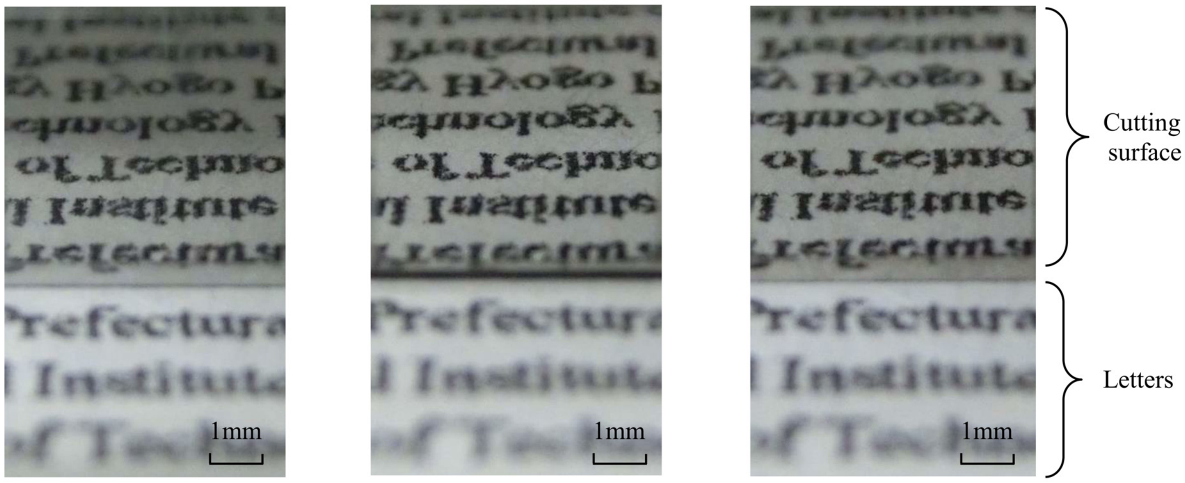
3.5. Comparison of the Cutting Surface Properties

A three-dimensional optical surface profiler was used to validate the cutting surface. The observational range was 0.2 × 0.2 mm, and the evaluation was performed based on the average surface roughness within this range. **Fig. 10** shows the relationship between the average surface roughness and the cutting length. In all the work material, the average surface roughness was less than 15 nm and a mirror-finished surface was obtained. For a cutting length of 5 m, although the difference in the average surface roughness of each work material is small, the average surface roughness decreases in stainless steel and high speed tool steel as cutting length extends. This is because the cutting edge, which generates a cutting surface morphed by the progression of wear, indicates a trend similar to that seen in the case of plane cutting of stainless steel with a ball end mill [19].

On the other hand, fluctuation of the average surface roughness in heat-treated steel is greater than those in stainless and high-speed tool steels. As shown in **Fig. 11**, a local scratch on the cutting surface affects the average surface roughness. Since this scratch corresponds to the movement trace of the cutting edge, it is likely caused by the heat-treated steel adhered to the end-cutting edge [20, 21]. It has been shown that the average surface roughness increases and decreases depending on the progression of wear, while the average surface roughness of the cutting surface is maintained below 15 nm in all the work materials.

4. Conclusion

As a result of cutting three types of die steel with a BL-CBN radius end mill, 0.5 mm in diameter and 0.02 mm in corner radius, the following conclusions have been ob-



(a) Heat-treated steel (b) Stainless steel (c) High speed tool steel

Fig. 9. Cutting surface.

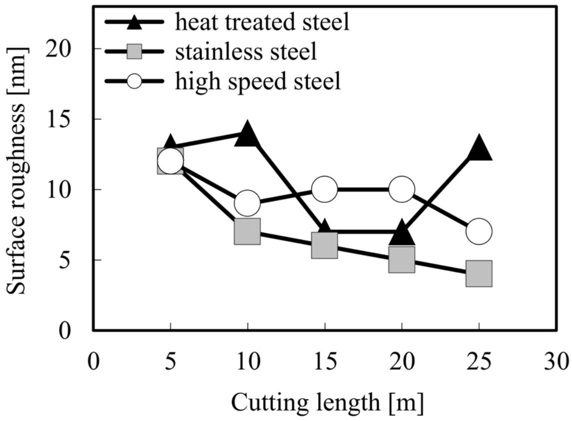


Fig. 10. Relationship between surface roughness and cutting length.

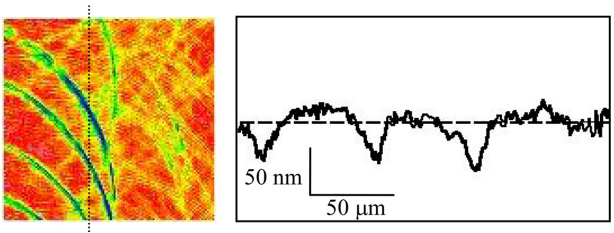


Fig. 11. Cutting surface on heat-treated steel.

tained:

1. Tool wear increases more as hardness of the die steel becomes higher.

2. The edge retreat amount, when cutting heat-treated steel, is suppressed below approximately 1/2 and 1/5 of stainless steel and high-speed tool steel, respectively.

3. A mirror-finished surface, with an average surface roughness of less than 15nm, is obtained for all work materials.

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