An Ultra-precision Cutting of Carbon Steel by Diamond Tool in CO$_2$ Atmosphere

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Abstract. The precise and economical production of high-strength die is demanded. Mirror surface processing is essential for such a precision product. An ultra-precision diamond cutting technique is widely applied to mirror surface finishing of soft-metal materials such as copper and aluminum, while the diamond cutting is not completely available to ferrous materials like carbon steel. This study was performed to examine the effect of the CO$_2$ gas blow atmosphere and the cutting conditions on the reduction of tool wear and the improvement of surface finish in the ultra-precision diamond cutting of the carbon steel. The experiments of the precision cutting of S25C and S55C were carried out under cutting speed of 47, 94 and 188 m/min and the effect of the machining atmosphere on the tool wear and the surface roughness were discussed. As a result, especially under cutting speed of 188 m/min the tool wear was reduced and the surface roughness was improved by cutting of both S25C and S55C in CO$_2$ gas blow atmosphere.

Introduction

An ultra-precision cutting technology is widely applied to mirror surface finishing of soft-metal materials such as copper, aluminum and those alloys at the present day. Diamond cutting technique has been recently applied to the mirror finishing of the tungsten carbide mold. However, it remains a challenge that the diamond cutting is not completely available to ferrous materials like carbon steel due to a severe tool wear of the diamond tool. If the ultra-precision diamond cutting is practically able to apply to the steel materials, that might have a spillover effect on the highly-functional products and the production cost. However, the diamond has chemical activity to the steel material. Then, the diamond tool is difficult to be applied to the mirror surface cutting because the diamond tool is rapidly worn away [1]. For that reason, the diamond cutting technology is limited to the particular materials like soft metals and non-metal materials at present [2].

The wear mechanisms of diamond tools in cutting of the steel materials are explained as follows. 1) Oxidation-reduction reaction caused by the work material, 2) Graphitization and diffusion of carbon on tool rake face, 3) Constitution of the carbide with the work material content [3]. Therefore, if the vicinity of cutting point is covered with inert gas, it is expected that tool wear is
Reduced by restraining the oxidation heat of new surface finished by the cutting process. In our previous work, the ultra-precision diamond cutting of S45C was conducted with CO₂ blow and it was found that the tool wear was restrained and the finished surface roughness was improved [3]. However, the experimental data had a problem of repeatability with dispersion because CO₂ gas was blown around the tip of cutting tool from the jetting nozzle located above the cutting tool. Then, in this study, a cutting tool with the gas flow pass in the tool shank was newly designed and CO₂ gas was blown to the rake face and the flank face of the insert from two small holes drilled in the tool shank.

Main factor for the wear of diamond tools in cutting iron-based materials is graphitization and diffusion of diamond tools. By using the newly designed cutting tool for the CO₂ gas blow, it is expected that the reliability of the experimental data is elevated. This study was performed to examine the effect of the CO₂ gas blow atmosphere and the cutting conditions on the reduction of tool wear and the improvement of surface finish in the ultra-precision diamond cutting of the carbon steel. The experiments of the precision cutting of S25C and S55C were carried out under cutting speed of 47, 94 and 188 m/min and the effect of the machining atmosphere on the tool wear and the surface roughness were discussed.

**Experimental methods**

The ultra-precision cutting machine (ULC-100A made by Toshiba Machine Co., Ltd.) was employed for the turning experiments. This is the face turning type of the machine equipped with a main spindle supported by ultra-precision cylindrical air bearing. Then, specially designed workpiece was attached on the vacuum chuck for the outer periphery turning shown in Fig. 1 and cutting speed is kept constant during cutting.

The single crystal diamond tool (A.L.M.T. Corp, NWD-CL308) with tool geometry of rake angle 0°, relief angle 7°, and nose radius 0.8mm was used. Figure 2 shows a specially designed diamond cutting tool with flow pass of CO₂ gas. As shown in the cross-sectional illustration (Fig.2(b)), the CO₂ gas flow pass was made in the tool shank. CO₂ gas is supplied from the hole at the tool shank end and is locally blown to the rake face and the flank face of the insert from two small holes drilled in the tool shank. Blow pressure is 0.3 Mpa and flow rate is 25 L/min.

The cutting conditions are shown in Table 1. As the work material, two kind of carbon steel were used. Amounts of carbon content in the work materials are 0.22-0.28%C in S25C and 0.52-0.58%C in S55C. The workpiece diameter and length cut in the turning experiments are 50 mm and 68 mm, respectively.
Experimental results and discussions

**Effects of CO₂ gas blow on the tool wear**

In this section, the tool wear was compared when S25C and S55C were cut in the air and CO₂ gas blow.

**1) Turning of low carbon steel (S25C)**

Figure 3 shows the microscope photographs of the rake face and flank face of single crystal diamond (SCD) tools after cutting S25C in the air and CO₂ gas blow. Under the condition of the
cutting speed 47 m/min and 94 m/min, the wear of the flank face and the attrition of the cutting edge look like in the same level from the photographs, although the tool wear increases with an increase in the cutting speed.

However, under the condition of the cutting speed 188 m/min and CO\(_2\) gas blow cutting, the attrition of the cutting edge and the flank wear width were reduced to about one third comparing with the normal cutting. In this experimental condition, the effects of CO\(_2\) gas blow cutting on the tool wear was obtained in the range of the high cutting speed 188 m/min. It is expected that the graphitization and diffusion of carbon on the cutting tool are accelerated in higher cutting speed. Therefore, the tool wear was improved under the high cutting speed condition by CO\(_2\) gas blow cutting.

(2) Turning of high carbon steel (S55C)

Figure 3 shows the microscope photographs of the rake face and flank face of SCD tools after cutting S55C in the air and CO\(_2\) gas blow. When S55C steel with high carbon content was cut, the wear of diamond tool was reduced comparing with the cutting of S25C. Furthermore, the wear of the flank face and the attrition of the cutting edge were greatly improved by CO\(_2\) gas blow cutting under every cutting speed conditions. CO\(_2\) gas blow cutting has a better effect on the tool wear under the condition of higher cutting speed. Especially, in the cutting speed 188 m/min, the tool wear was greatly suppressed for CO\(_2\) gas blow cutting. The flank wear width and the attrition of the cutting edge was slightly 2 µm.

In a diffusion phenomenon between the solute and the solid substance, it is known as Fick’s first law that the amount of diffusion depends on the gradient of solute consistency at the interface. The diffusion of the carbon dominantly influences the tool wear in cutting of carbon steel by the diamond tool. It is estimated that the progress of the diffusion wear depends on amount of carbon contain in work material. Then, the tool wear becomes large when the S25C with small content of carbon is cut. Because the gradient of carbon consistency at the interface of the chip and the tool face becomes larger than S55C.

The tool wear during CO\(_2\) gas blow cutting of S55C is improved under the condition of cutting speed 47 m/min and 94 m/min while there are no effects in cutting of S25C under that cutting speed. It is estimated that the cutting temperature in cutting of S55C exceeds that in cutting of S25C. The effect of CO\(_2\) gas blow cutting is expected to become available in a certain cutting temperature or more.
Effects of CO$_2$ gas blow cutting on the finished surface

(1) Turning of low carbon steel (S25C)

Figure 5 shows the microscope photographs of the finished surfaces of S25C in each cutting speed and in each cutting atmosphere. In the cutting speed 47 m/min, there was little difference from surface conditions between the cutting in the air and CO$_2$ gas blow cutting. However, when the cutting speed elevated to 94 m/min and 188 m/min, the feed marks with larger interval than the feed of 5$\mu$m were remained on the finished surfaces obtained by cutting in the air. Consequently, the finished surface was deteriorated comparing with that obtained by CO$_2$ gas blow cutting.

Figure 6 shows the relationship between the cutting speed and the surface roughness of arithmetic average roughness (Ra) and maximum height (Rz). The surface roughness obtained by cutting in the air and CO$_2$ gas blow cutting at the cutting speed of 47 m/min and 94 m/min are almost same level. However, at the cutting speed of 188 m/min, the finished surface by CO$_2$ gas blow cutting is reduced and has better quality roughness. This is well corresponding to the results of the tool wear as shown in Fig. 3. The progress of the tool wear makes the surface quality worse.

On the other hand, in the cutting speed 94 m/min, the surface integrity obtained by CO$_2$ gas blow cutting looks better than that by cutting in the air, although the both surface roughness and the tool wear are almost same. This indicates there is a possibility that the CO$_2$ atmosphere itself affects directly the good finished surfaces.
(2) Turning of high carbon steel (S55C)

Figure 7 shows the microscope photographs of the finished surfaces of S55C in each cutting speed and in each cutting atmosphere. The relationship between the cutting speed and the surface roughness of arithmetic average roughness (Ra) and maximum height (Rz) is shown in Fig. 8 as the plots corresponding to the finished surface in Fig. 7, though some of photograph is not shown in Fig. 7. Many ploughed marks are observed on the finished surface obtained by cutting in the air. In contrast, smooth surface without the ploughed marks is observed by CO$_2$ gas blow cutting in cutting speed 94 m/min and 188 m/min. The surface roughness is obviously improved as shown in Fig. 8. Comparing with CO$_2$ gas blow cutting of S25C, the surface roughness is greatly reduced as the cutting speed is increased.

Figure 9 shows the finished surface profiles obtained by cutting in the air and CO$_2$ gas blow cutting in cutting speed 94 m/min and 188 m/min. Several deep crack patterns are observed in the finished surface profiles by cutting in the air. The depth of crack pattern increases with an increase in the cutting speed. On the other hands, noticeable crack patterns are not observed on the finished surface by CO$_2$ gas blow cutting.
Conclusions

In this study, the effect of the CO\(_2\) gas blow cutting and the cutting conditions on the reduction of tool wear and the improvement of surface finish in the ultra-precision diamond cutting of the carbon steel were examined. The findings which were obtained from cutting tests are presented below.

The tool wear and the surface roughness were improved by CO\(_2\) gas blow cutting. When the carbon steel S25C with low content of carbon was cut, the flank wear and the attrition of the cutting edge becomes larger than that of S55C with high content of carbon. By CO\(_2\) gas blow cutting, the tool wear and the finished surface quality obtained by cutting of S25C and S55C were improved.
under the conditions of the cutting speed 188 m/min or more and the all conditions of these experiments, respectively.

References