

Novel Microsurface Machining Techniques for Improving the Traction Coefficient

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ABSTRACT

This study examined methods of machining a microsurface texture on the surface of the rolling elements of a toroidal continuously variable transmission (CVT) for improving the traction coefficient. The microsurface texture of the toroidal surfaces consists of tiny circumferential grooves (referred to here as micro grooves) and a mirror-like surface finish similar to the rolling surface of bearings. Hard turning with a cubic boron nitride (cBN) cutting tool, grinding with a cBN wheel and micro forming were applied to machine the micro grooves. The results made clear the practical potential of each method. A micro forming device was also developed for use in actual production. A mirror-like surface finish and micro crowning of the convex portions of the microsurface texture were simultaneously executed by superfinishing them with a fine-grained elastic superfinishing stone. The results showed that a microsurface texture was successfully formed on the rolling elements of a toroidal CVT variator. The specifications of the microsurface texture were then optimized in tests conducted with a four-roller tester. The test results made it clear that the traction coefficient can be improved by the microsurface texture while assuring high durability at the same time. The newly developed machining techniques were then applied to the disks of an actual toroidal CVT variator. The results of a traction performance test revealed that the traction coefficient was improved without sacrificing durability.

INTRODUCTION

The application of continuously variable transmissions (CVTs) is continuing to expand as an effective technology for meeting the stronger demands in recent years for improvement of the fuel economy and environmental performance of vehicles. In particular, a large torque capacity toroidal CVT has been implemented on production vehicles as a rear-wheel-drive system. Because a toroidal CVT incorporates a traction drive, improving the traction coefficient of its rolling elements (i.e., disks and power rollers) is vitally important for increasing the device's performance.

This study examined methods of machining a microsurface texture on the rolling elements for improving the traction coefficient. The microsurface texture consists of tiny circumferential grooves (referred to here as micro grooves) and the mirror-like finish of the toroidal surfaces. Hard turning with a cubic boron nitride (cBN) tool, grinding with a cBN wheel and micro forming were used to machine the micro grooves. A mirror-like finish and the desired radius of curvature of the convex portions (referred to here as micro crowning) were simultaneously applied to the toroidal surfaces by superfinishing them with a fine-grained superfinishing stone. As a result, a microsurface texture was successfully formed on the rolling elements of a toroidal CVT variator. Additionally, the newly developed machining methods were applied to test pieces and toroidal CVT parts to evaluate the resultant effect on traction performance.

MICROSURFACE TEXTURE MACHINING METHODS

A microsurface texture is applied to the rolling surfaces of the disks of a toroidal CVT variator, as shown in Fig. 1. A typical example of a microsurface texture pattern is shown in the figure. It basically consists of convex portions having nanometer-order surface roughness and micro grooves of micrometer

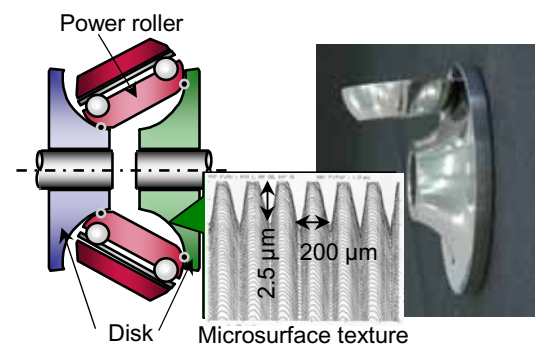


Fig. 1 Rolling elements of CVT variator and microsurface texture

dimensions. The rolling elements are made of carburized and quenched steel having a surface hardness of 60-64 HRC. Figure 2 outlines various microsurface machining methods. In selecting machining methods for use in this study, emphasis was put on assuring the shape accuracy of the microsurface texture and achieving high machining efficiency. Hard turning, grinding and micro forming were selected as the processes for machining the micro grooves, and superfinishing was chosen as the surface finishing technique. The following discussion describes the characteristics of each machining technique and the results of a study concerning their applicability to the machining of the desired microsurface texture.

The characteristics of the techniques selected for machining the micro grooves can be summarized as follows:

1. Hard turning: The excellent shape accuracy of the tools used in this process makes it easy to assure the shape accuracy of the micro grooves. However, tool wear is an issue.
2. Grinding: While there is little wheel wear, a method for accurately truing the grinding wheel and the stability of the micro grooves are issues of concern.
3. Micro forming: Machining efficiency is high, but the ability to transfer the surface pattern to a hard material is unknown and the assurance of shape accuracy is also an issue.

The most critical issues of each machining method were examined and the results are presented below.

HARD TURNING

A study was made of tool wear, which is the most critical issue in hard turning with cBN tools. The tools used were made of three types of materials that are typically employed for hard turning tools. In addition, the depth of cut was set considerably smaller than the generally used values in order to investigate the characteristics of micro groove machining.

Figure 3 shows the flank wear width (V_b) of the different tools used as a function of the cutting length. Tool flank wear tended to be virtually the same regardless of the tool material. All of the tools showed an initial wear region after a cutting length of 30 μm and a steady-state wear region. However, the cutting length until fracture occurred differed among the tool materials, with tool material C displaying the longest tool life. In micro groove machining, it is very important to have a good understanding of the wear characteristics of the tool because minute wear of the tool tip has an especially large influence on tool life. The results of these hard turning tests made it possible to select a suitable tool and machining conditions for micro groove machining.[1] Hard turning was found to be applicable to toroidal CVT disks because of its good machining accuracy over short cutting lengths.

GRINDING WITH A CBN WHEEL

Grinding with a cBN wheel offers the possibility of resolving the tool life problem that occurs in hard turning.

However, forming the radius of curvature (R) of the wheel tip is particularly difficult, and it is not known how long the shape of the wheel tip can be maintained. Therefore, on-machine electrodischarge truing was used for forming the shape of the wheel tip. Figure 4 shows a schematic diagram of the principle of on-machine electrodischarge truing and a photo of the truing process.[2] Electrodischarge truing was performed with a rotating copper plate electrode positioned at a right angle to the cBN wheel. The wheel was fed under servo control to true the side surfaces of the wheel tip alternately at a 45° angle. A metal bonded cBN wheel

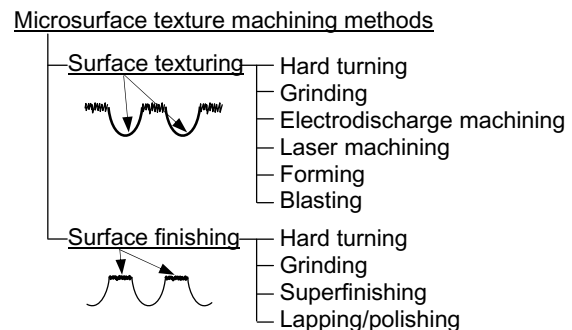


Fig. 2 Various methods of microsurface texture machining

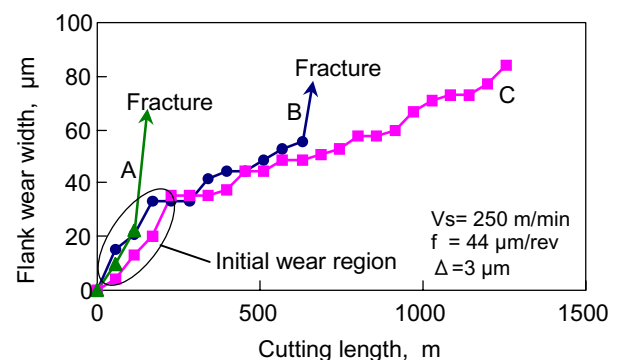


Fig. 3 Change in flank wear of various cutting tools used in hard turning

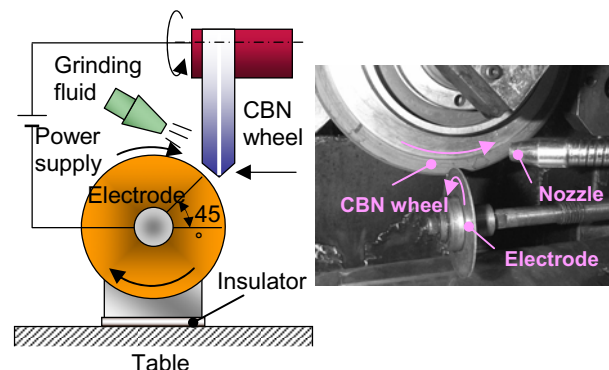


Fig. 4 Electrodischarge truing on the machine

(Noritake Super Abrasives Co., Ltd.) was used in the grinding tests.

After first optimizing the electrodischarge truing conditions, the wheel specifications and grinding conditions were investigated. Figure 5 shows a typical example of the grinding test results. The figure shows the change in the wheel tip radius and wheel radius wear when the largest amount of grinding stock was removed. After electrodischarge truing the wheel tip radius R by approximately $50\text{ }\mu\text{m}$, micro grooves were ground into the workpiece. The change in the amount of wheel radius wear and in the size of the wheel tip radius after removing a certain specified amount of grinding stock was monitored. Upon grinding approximately 300 m , it was observed that the wheel tip wore and the wheel tip radius R increased by around $10\text{ }\mu\text{m}$. At that point, electrodischarge truing was performed on the machine to correct the wheel tip radius R . Grinding was then resumed, and the micro grooves were successfully machined to the desired shape accuracy.[1] However, using this method to machine toroidal CVT disks would require the on-machine electrodischarge truing equipment mentioned above and an arc-rotating motion mechanism for rotating the peripheral wheel surface along the outer disk shape.

MICRO FORMING

Because the depth of cut is fixed in hard turning and grinding processes, machining accuracy tends to be influenced by the accuracy of the workpiece and changes in the ambient environment. As a solution to that problem, a micro forming method was devised for performing micro plastic machining under a constant pressure. A schematic diagram of a prototype device (referred to here as the prototype) for confirming the principle of the micro forming process is shown in Fig. 6. A rotating tool with the desired tip radius R is pressed against a rotating workpiece under a constant pressure to machine the micro grooves. Because the constant-pressure loading mechanism is built in, it is thought that machining accuracy is less apt to be influenced by circumferential deflection of the workpiece or ambient temperature changes, thereby facilitating a stable machining process.[1] Fundamental micro forming experiments were conducted using this prototype.

Table 1 shows the experimental conditions. The relationship between the applied load and the micro groove depth was examined using tools having a different tip radius R . The results obtained are shown in

Table 1 Fundamental conditions of micro forming experiments

Forming tool	Tungsten carbide ($\Phi 63.5\text{ mm}$) Tip radius R : 0.5, 0.1, 0.05 mm
Workpiece	SCM420 ($\Phi 40\text{ mm} \times 20\text{ mm}$, 62 - 63.5 HRC)
Load	10 - 450 N
Rotational speed	300 min^{-1}
Coolant	Straight oil (mist)

Fig. 7. The tools were made of a fine-grained tungsten carbide and three tool tip radii ($R = 0.05, 0.1$ and 0.5 mm) were used. The results indicated that the micro groove depth increased with increasing load and that this tendency differed depending on the size of the tool tip

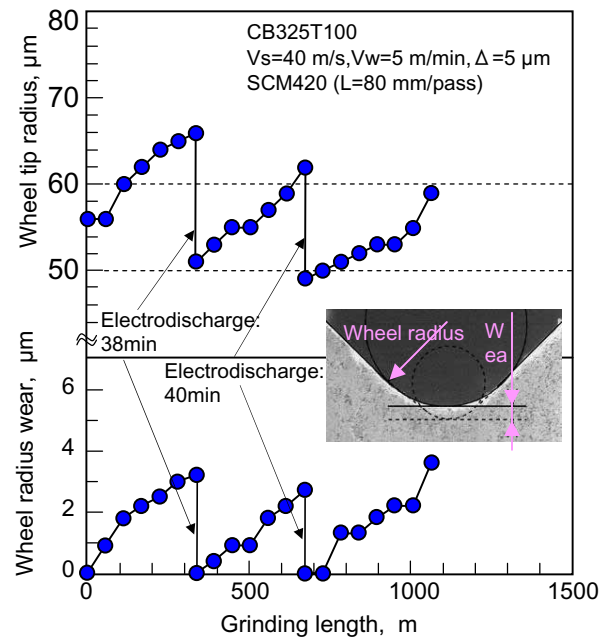


Fig. 5 Change of wheel tip radius and wheel radius wear in groove grinding

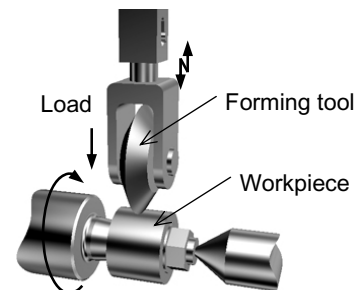


Fig. 6 Schematic diagram of prototype micro forming device

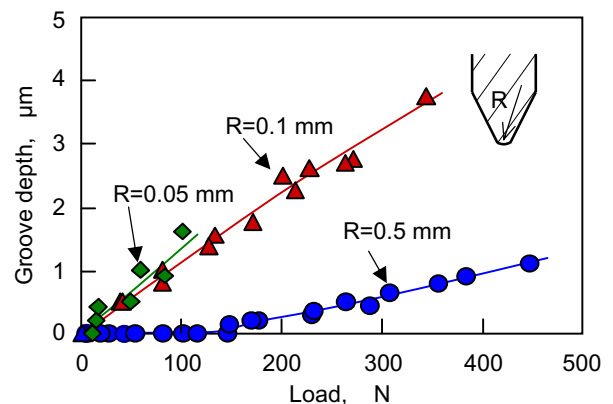


Fig. 7 Relationship between load and groove depth in micro forming