Technological development for improving the cylindricity of the reaming process for CVT control valve spool holes

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Summary

It is necessary to reduce the amount of internal leakage in the control valve of continuously variable transmissions in order to improve vehicle fuel economy. That requires the use of high-accuracy machining. This article describes technical measures undertaken to improve the cylindricity of the reaming process for spool holes that require especially high accuracy.

1. Introduction

There are demands to improve the fuel economy obtained with continuously variable transmissions (CVTs). One effective measure for doing that is to reduce the amount of internal leakage in the control valve (Fig. 1). The control valve uses the hydraulic pressure generated by the oil pump to control the pressure level needed for shifting. The spool holes that were the focus of this work function as the fitting holes of the spool valves that regulate the hydraulic pressure. To reduce the amount of leakage, the clearance between the spool valves and spool holes is minimized and also high-strength material is applied to improve their durability. However, this measure worsens the reaming accuracy of the spool holes, making it especially difficult to ensure their cylindricity on the order of several μm. This article describes concrete technical measure adopted to improve cylindricity.

2. Spool hole machining method and issues involved

Spool holes are machined on a vertical machining center in two processes. In the rough casting in Fig. 2(a), pilot holes are first drilled in (b) and then reamed in (c). A single-blade reamer is used to suppress polygonal shape error of reamed holes[1] the accuracy of which is problematic. A hydraulic chuck holder with high rigidity, excellent runout accuracy and outstanding ease of attaching/releasing is used for chucking the tool. There are three main issues in spool hole reaming: cylindricity, finish surface roughness and tool life. Among them, improving cylindricity is the most difficult issue.

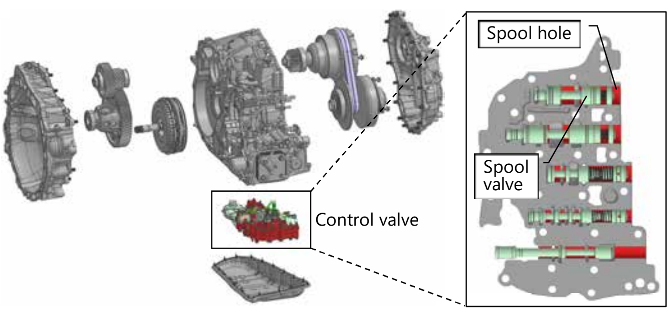

Fig. 1 Exploded view of a CVT

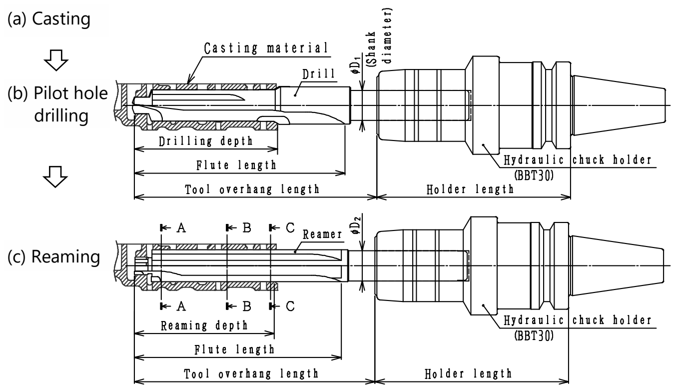

Fig. 2 Conventional tooling layout

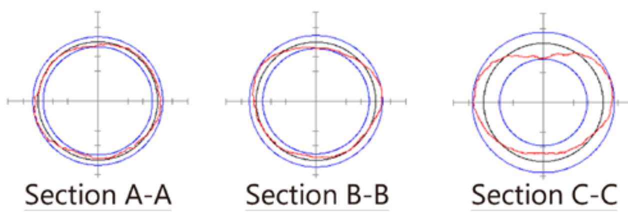

Fig. 3 Roundness profile of reamed spool hole

3. Factors influencing improvement of cylindricity

Cylindricity is defined as a combination of three

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elements: circumferential runout (hole diameter dimension), roundness and coaxiality (position deviation), which are measured with a dedicated measuring machine. As shown in Fig. 3, individual measurements are made of section C-C (mouth of hole), section B-B (middle of hole) and section A-A (bottom of hole). A comparison of the roundness of each section reveals that section C-C (mouth) has the worst roundness. Presumably, deterioration of mouth roundness is the principal cause of the deterioration of cylindricity. Therefore, based on the results of previous studies,[(1)-(5)] the factors influencing improvement of cylindricity were organized in a systematic cause and effect diagram as shown in Fig. 4. The factors influencing cylindricity include the tool/holder specifications, cutting conditions, workpiece material and the machining equipment used. This study focused on the cutting conditions (feed rate of pilot hole drilling) and tool/holder specifications (tool bending stiffness and rotational balance), and cutting tests were conducted to investigate their respective influence.

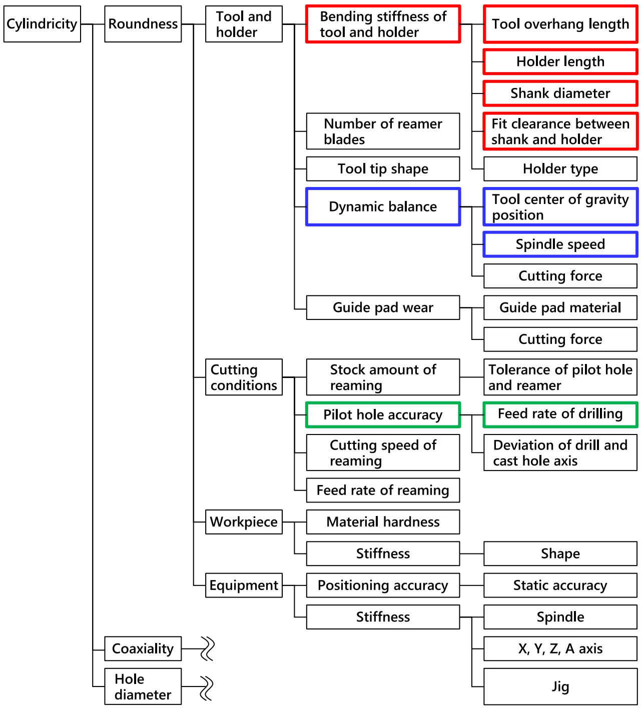


Fig. 4 Cause and effect diagram for improving cylindricity

4. Overview of cutting tests

4.1 Influence of feed rate of pilot hole drilling on cylindricity

Machining tests were conducted with the equipment shown in Fig. 5 to confirm the influence of the feed rate of

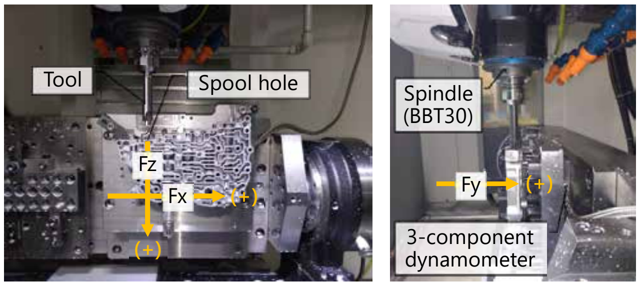


Fig. 5 Schematic diagram of cutting test

Table 1 Cutting conditions

Process	Cutting speed Vc m/min	Feed rate fz mm/tooth	Tooling
Drilling	311	0.025, 0.05, 0.1	Fig. 2(b)
Reaming	150	0.089	Fig. 2(c)

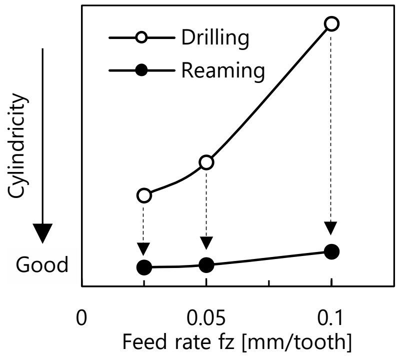
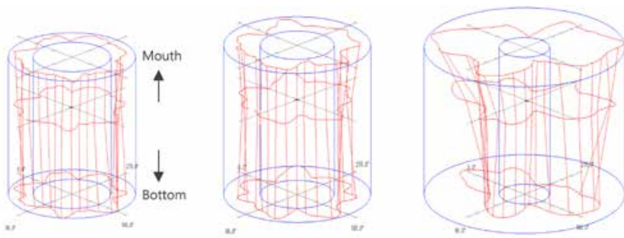


Fig. 6 Results of cutting test



(a) fz 0.025 mm/tooth (b) fz 0.05 mm/tooth (c) fz 0.1 mm/tooth

Fig. 7 Cylindricity profile of pilot hole

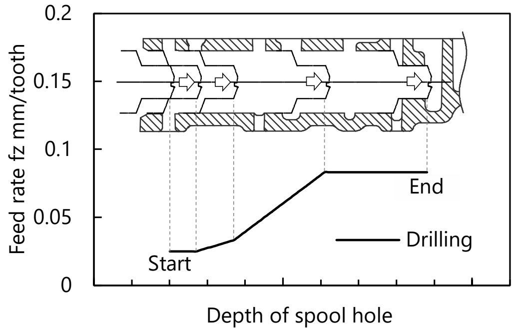


Fig. 8 Variable feed control of drilling

pilot hole drilling on the cylindricity of reamed holes. The cutting conditions are shown in Table 1. Pilot holes were drilled using three feed rate levels and the workpiece was then removed from the machine to measure cylindricity. The workpiece was then mounted on the machine again, and the holes were reamed using a single set of conditions. Since high-accuracy positioning was possible with this machine, it was assumed that position deviation between the pilot hole and the reamed hole due to removing/remounting the workpiece was negligible.

The measured cylindricity results are plotted in Fig. 6. The results confirmed that the cylindricity of the reamed holes was influenced by that of the pilot holes and also that the cylindricity of the pilot holes was influenced by the drilling feed rate.

Figure 7 shows profiles of the pilot hole cylindricity. As the feed rate was increased, the roundness of the mouth markedly deteriorated. According to a previous study,[4] that was presumably caused by unstable tool behavior at the time the tool cut into the workpiece. It was reported that using a highly rigid tool and cutting with tiny feeds in the initial phase of machining are effective in preventing such deterioration. Therefore, variable feed control was adopted in order to obtain both high accuracy and high machining efficiency. With this approach, a low feed rate is applied in the initial phase of pilot hole drilling and the feed rate is gradually raised as the drilling depth increases.

4.2 Improvement of tool bending stiffness

The bending stiffness of the tool and holder was measured with the method shown in Fig. 9 to confirm the amount of tool displacement[5] relative to the bending load of the tool when held in the holder. The measured results for the existing drill and holder specifications are shown in Fig. 10(a). Sharp displacement gradients are seen from the fulcrum where the shank is held by the holder to the tool tip, suggesting that high stiffness at the place where the shank is gripped is important. Therefore, as indicated in Table 2, an effort was made to reduce the amount of

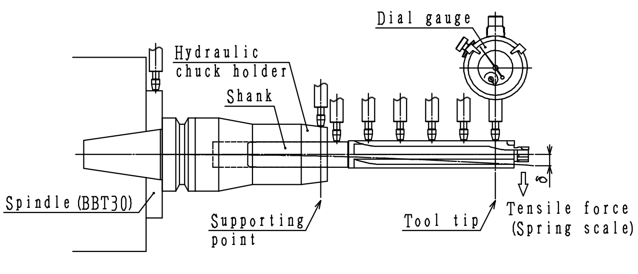


Fig. 9 Method of measuring bending stiffness of tool and holder

Table 2 Improved specifications

Contents	Drill	Reamer
Tool overhang length	↓ 30.2% shorter	↓ 35.9% shorter
Shank diameter	↑ 25.0% larger	↑ 12.5% larger
Holder length	↓ 28.6% shorter	
Fit tolerance of shank and holder	H4 (holder)/js4 (shank)	

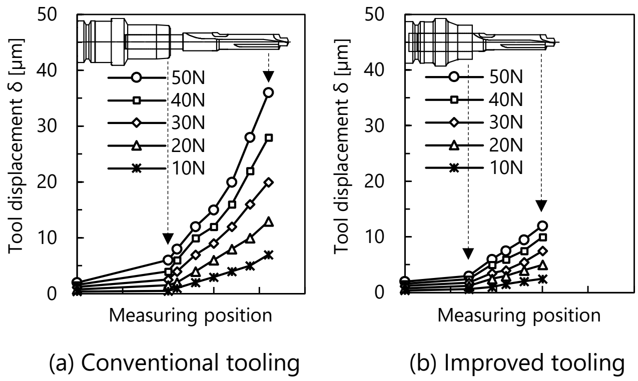


Fig. 10 Measured bending stiffness of drill and holder

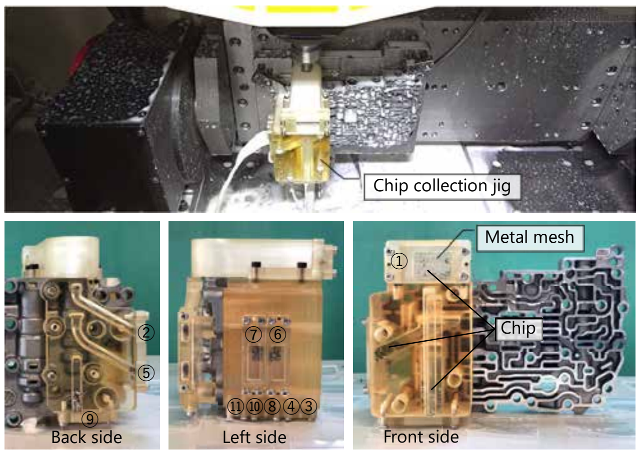


Fig. 11 Chip collection jig

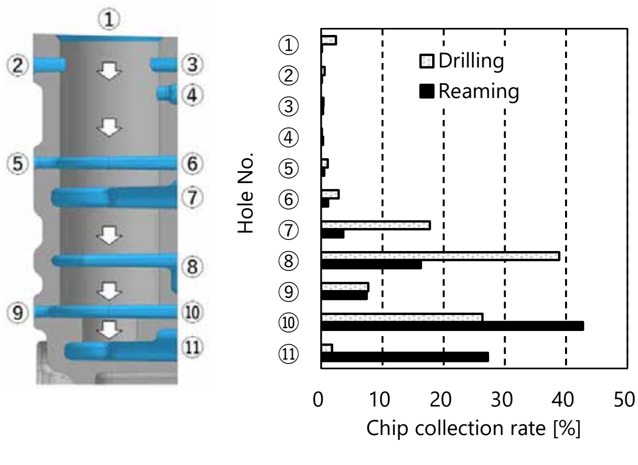


Fig. 12 Chip collection results

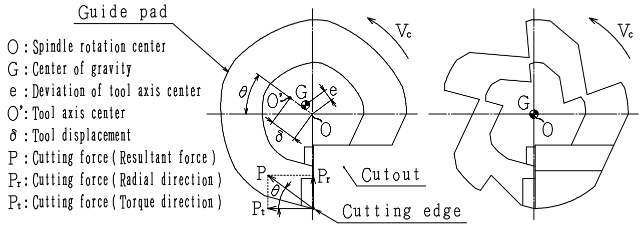
displacement through a combination of measures, including reducing the tool overhang length, increasing the shank diameter, shortening the holder length and minimizing the fit clearance between the shank and the holder. The results obtained are shown in Fig. 10(b).

Conceivable ways of reducing the tool overhang length include shortening the flute length of the drill and reamer as shown in Fig. 2(b) and (c). However, that could worsen the evacuation of chips toward the mouth of the spool hole, giving rise to concern that chip clogging might gouge the machined surface. To prevent that, a fluid simulation was used to optimize the positions and angles of the coolant discharge ports of the tool with the aim of evacuating chips from the spool hole mouth toward the bottom of the hole. Figure 11 shows a chip collecting jig made of resin by 3D printing, which was used to confirm the effects of this improvement. This jig fits tightly without any gaps to the spool hole mouth (1) and each of the side openings ((2)-(11)) shown in Fig. 12. A metal mesh incorporated at the exit ports makes it possible to separately collect only the chips that are evacuated together with the coolant. The results obtained with the jig are also shown in the figure. The results confirmed that chips were concentrated at side openings (7) to (11) toward the bottom of the hole as was intended.

4.3 Improvement of tool rotational balance

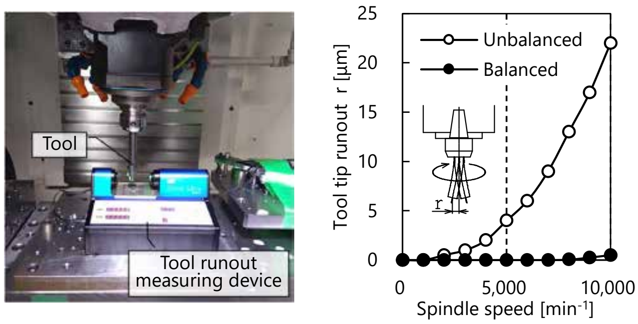
In addition to improving tool bending stiffness as explained in 4.2, an investigation was made of the influence of the rotational balance on tool tip runout. Although a single-blade reamer is advantageous for avoiding polygonally shaped reamed holes, there was concern that the tool rotational balance might worsen for the following reasons. (1) The center of gravity (G) on the guide pad side might deviate due to gouging of the cutting edge as shown in Fig. 13(a). (2) Reamer behavior at the onset of cutting might become unstable due to the application of cutting force (P) on the guide pad side which is in reverse phase of the cutting edge, thereby worsening the roundness of the hole mouth. To prevent that, the reamer outer circumference was designed with a shape so that the spindle rotation center (O) would be positioned at the center of gravity (G) as shown in Fig. 13(b).

Figure 14(a) shows the appearance of the tool measuring device based on an optical line sensor along with the method of measuring tool tip runout. The measured results are shown in Fig. 14(b). It is seen that the execution of a balanced design effectively reduced tool tip runout at high rotational speeds.



(a) Unbalanced (b) Balanced

Fig. 13 Cross section of reamer



(a) Schematic diagram (b) Dynamic balance

Fig. 14 Results of dynamic balance test

5. Optimized specifications and application results

Based on the results presented in section 4, the stiffness of the tool and holder was increased by the measures listed in Table 2 and combined with the balanced reamer rotational design shown in Fig. 13(b). Figure 15 presents the results of a cutting test conducted with the cutting conditions shown in Table 3. Compared with the existing

Table 3 Improved cutting conditions

Process	Cutting speed Vc m/min	Feed rate fz mm/tooth	Tooling
Drilling	311	0.025-0.083 (Variable feed control)	Table 2 and balanced
Reaming	225 (50% faster)	0.1 (12% faster)	

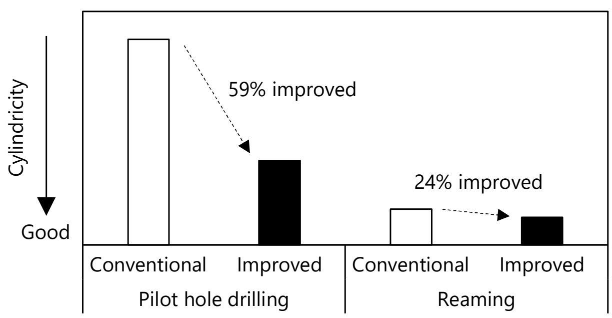


Fig. 15 Results of cutting test

cylindricity, it is seen that the cylindricity of both the pilot hole and the reamed hole was improved, thereby confirming the effectiveness of these specifications.

6. Conclusions

Optimizing the tool and holder specifications used in machining the control valve spool holes improved hole cylindricity by 24% over the existing dimension. The following insights were gained in this study.

(1) The cylindricity of reamed holes is greatly influenced by that of pilot holes. Reducing the feed rate for drilling pilot holes is effective in improving their cylindricity.

(2) Shortening the tool overhang length, increasing the shank diameter and minimizing the fit clearance between the shank and holder are effective measures for suppressing tool displacement.

(3) The tool flute length can be shortened by optimizing the positions and angles of the coolant discharge holes in the tool so as to promote chip evacuation from the spool hole mouth toward the bottom of the hole.

(4) Tool tip runout at high rotational speeds can be reduced by designing a single-blade reamer with high stiffness and excellent rotational balance.

7. References

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