Journal of
Mechanical
Science and
Technology

Journal of Mechanical Science and Technology 21 (2007) 1605~1611

Investigation of internal ultrasonically assisted grinding of small holes: effect of ultrasonic vibration in truing and dressing of small CBN grinding wheel

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(Manuscript Received May 31, 2007; Revised August 30, 2007; Accepted September 30, 2007)

Abstract

In internal grinding of small holes, it is hard to realize high accuracy truing and dressing for the grinding wheel when a conventional truing/dressing method using single diamond dresser or rotary cup wheel is employed. Because of the cantilever support condition of the spindle shaft the stiffness of shaft is reduced. Thus the truing force leads the shaft to a significant deformation during truing/dressing. In this study, for improving the truing and dressing accuracy, a new truing/dressing method was proposed, in which the grinding wheel is ultrasonically vibrated along its axis during truing/dressing with a GC rotary cup wheel. A series of experiments were carried out to investigate the effects of the wheel ultrasonication on the truing force reduction, the truing accuracy improvement and the wheel surface condition. In addition, the grinding force and work surface roughness experimentally obtained by using the wheels trued with or without ultrasonication were compared. The experimental results indicated that applying ultrasonic vibration to the wheel decreases the normal and tangential grinding forces by more than 20 % and 24 %, respectively, and the surface roughness by as much as 18 %.

Keywords: Ultrasonic vibration; Truing; Dressing; Internal grinding

1. Introduction

Modern industry requires the internal finishing of small holes measuring several millimeters in diameter, such as those found in a fuel injector for an automotive engine. For the sake of environmental protection, severe regulations are being imposed on automobile exhaust. This is raising demand for high internal finish accuracy (surface roughness and roundness) of a fuel injector, in order to maintain high oil-tightness in the fuel injection system of an automobile engine. However, as the smaller hole diameter and the higher finishing accuracy are required, the conventional techniques can not simultaneously meet qualitative and economic demands. So, new machine tools utilizing an ultra-high speed grinding spindle rotating at more than 200 thousand rpm have to be developed at an inevitably huge cost.

Meanwhile, much attention has been paid to ultrasonic grinding. In this method, machining efficiency and surface finishing quality are significantly improved by applying ultrasonic vibration to a grinding wheel or workpiece during machining operations such as coring/drilling [1-3] and super finishing [4-8]. In these processes, however, material removal is achieved by applying a constant contact force to the tool or workpiece in a direction normal to the working face. Few studies have been conducted on

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the internal ultrasonic grinding of small holes where the material removal is based on geometrical interference between the tool and the workpiece with a certain depth of cut, hence the term "internal constant-depth-of-cut UAG (Ultrasonically Assisted Grinding)".

Therefore, we focused on a fundamental investigation of the internal constant-depth-of-cut UAG and aimed to establish an alternative novel technology for internal finishing of small holes. For this purpose, an experimental apparatus primarily consisting of an ultrasonic vibration spindle was designed and manufactured in our previous work [9]. Grinding experiments were carried out on the constructed rig according to the operating principle illustrated in Fig. 1. Specifically, a small grinding wheel measuring several millimeters in diameter was screwed onto the end face of an ultrasonic vibration spindle, which is composed of a hone and a bolted langevin transducer (PZT device). The small grinding wheel is driven at a peripheral speed of V_g by a motor coupled to the ultrasonic vibration spindle. When an alternating current (AC) voltage (around 20 kHz) is applied to the PZT, the electrical energy is converted into the mechanical vibration energy, further transmitted to the grinding wheel via the hone. As a result, the grinding wheel vibrates at ultrasonic frequencies in an axial direction. Under these conditions, once a depth of cut Δ between the workpiece and the grinding wheel is obtained, and the workpiece is fed right-forward at a rate of V_f, a constant-depth-of-cut UAG is performed. Previous investigation found that ultrasonicating the grinding wheel decreases the normal and tangential grinding forces by more than 65 % and 70 %, respectively, and

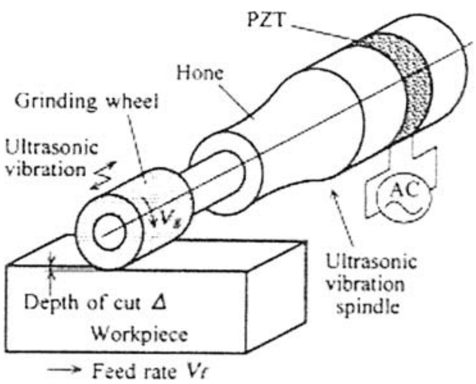


Fig. 1. Illustration of constant depth-of-cut UAG.

the surface roughness by as much as 29 % [9]. Successive theoretical and experimental investigations were conducted on the mechanism behind the decreases in the grinding force owing to the grinding wheel vibration [10]. The results indicated that the reduction of grinding force is due to the grinding chips becoming smaller, through the use of ultrasonication. Furthermore, the finishing accuracy is significantly affected by the truing accuracy of the grinding wheel. The truing accuracy is hindered when using a rotary GC wheel dresser because the open-sided structure of the grinding wheel shaft leads to a low stiffness, thus it is easy to deform by the truing force.

In our efforts to overcome such disadvantages, we have developed a procedure; a new truing and dressing method was proposed, in which the grinding wheel is ultrasonically vibrated in the axial direction during truing operation using a rotary GC cup dresser. This paper experimentally examined in details the effects of the truing parameters (frequency and amplitude of grinding wheel, reciprocation speed and in-feed rate of GC cup wheel etc.) on the truing force, the run-out of grinding wheel, grinding wheel surface properties, and the performance of the ultrasonically trued wheels in actual grinding.

2. Principle and procedure of truing/dressing experiments

The truing and dressing principle is shown in Fig. 2. During truing and dressing operations, the GC cup wheel, rotating counterclockwise at a speed of n_c, reciprocates along the grinding wheel axis (X-direction) at a particular speed V_r and particular stroke, and is fed toward the grinding wheel in its radial direction (Y-axis) at a feed rate of δ per reciprocation cycle. The grinding wheel undergoes ultrasonication along the X-axis and rotation around the X-axis.

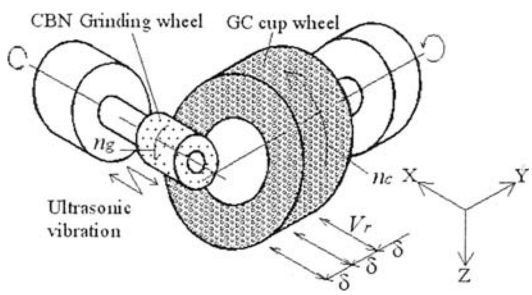


Fig. 2. Principle of truing and dressing.

Fig. 3 shows a photograph of the truing and dressing apparatus, which was constructed by installing a rotary GC wheel dresser (by Ota Co., Ltd.) on a 3-axis dynamometer (Kistler Co., Ltd., 9254) instead of the work-holding stage in the grinding experiment rig previously developed [9]. The small grinding wheel screwed onto the end face of the ultrasonic vibration spindle is rotationally driven by a motor coupled to the spindle via a coupling. The ultrasonic vibration spindle is agitated using an amplitude of scores of micrometers facilitated by the use of an AC voltage generated by an electric power supplier to the piezoelectric (PZT) transducer (see Fig. 1). The in-feed motion of the GC cup wheel toward the grinding wheel is made by a fine feed mechanism which is composed of a linear motion guide, a table, a ball screw, a stepping motor, and a controller. The rotational speed of the rotary GC cup wheel and its reciprocation speed and stroke along the grinding wheel axis are set up by the controller. The truing forces are obtained by recording the amplified output signals from the dynamometer with a charge amplifier using a digital oscilloscope.

Fig. 3. Photograph of experimental apparatus.

Table 1. Truing and dressing conditions.

Grinding wheel	CBN#100, #400, ϕ5
Cup wheel	GC#80, #150, #600
Rotational speed of cup wheel	n_c=4700 rpm
Rotational speed of grinding wheel	n_g=1200 rpm
Ultrasonication	Amplitude: 9, 18μm Frequency: 19.2kHz
Feed rate of Cup wheel	δ=1, 2.5, 5 μm/cycle
Reciprocation speed of cup wheel	V_r=10 mm/s
Truing fluid	Solution type

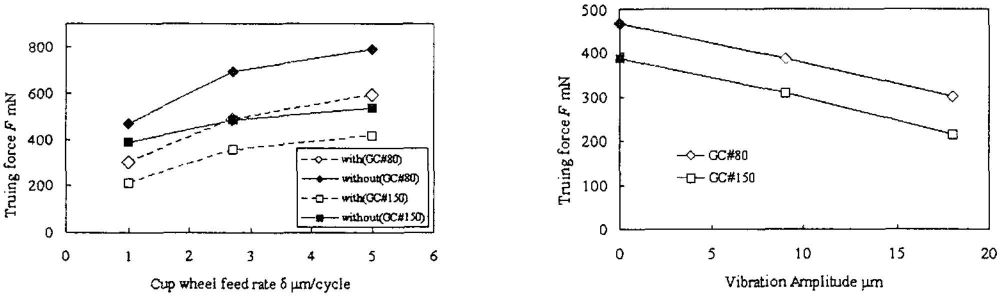
Besides the measurement of truing and dressing forces in real time, the run out of the grinding wheel before and after truing and dressing for each conditions were also investigated using an electric micrometer (Mitsutoyo Co., Ltd., M401), and the wheel surface conditions were characterized by a Digital Microscope (KEYENCE, VHX-200/100F). Details on the truing and dressing conditions are listed as in Table 1.

3. Experimental results and discussion

Plotting the truing force F obtained using different GC cup wheels against the feed rate δ and the ultrasonic vibration amplitude is shown in Figs. 4(a) and (b), respectively. In Fig. 4(b), the truing force at the vibration amplitude of 0μm was obtained under the absence of ultrasonication. It is evident that the truing force under the presence of ultrasonication is smaller than that under the absence of ultrasonication (seeing Fig. 4(a)). In addition, an increase in the vibration amplitude decreases the truing force (seeing Fig. 4(b)). An interesting result is that the GC cup wheel containing smaller abrasive grains reduces the truing force. Under the truing conditions in this work, the truing force decreases by more than 22 % due to applying the ultrasonic vibration to the grinding wheel.

From the experimental results mentioned above, it is predicted that the ultrasonication could improve the truing accuracy in terms of the run out of the grinding wheel because it can decrease the truing force, ultimately reducing the deformation of the grinding wheel shaft. In order to confirm this effect, the run out of the grinding wheel trued under the absence and presence of ultrasonication was measured using an electric micrometer. The results are shown in Figs. 5(a) and (b). The original run out of the grinding wheel was also measured as shown in Fig. 5(c) for comparison. The original run out of the grinding wheel around 150 μm, which is due to the mounting error of the grinding wheel on the spindle and the wheel form error, was decreased to around 1.1μm after truing without ultrasonication, and further was decreased to less than 0.8 μm under ultrasonication. This result indicates that the ultrasonication is essential to the truing accuracy.

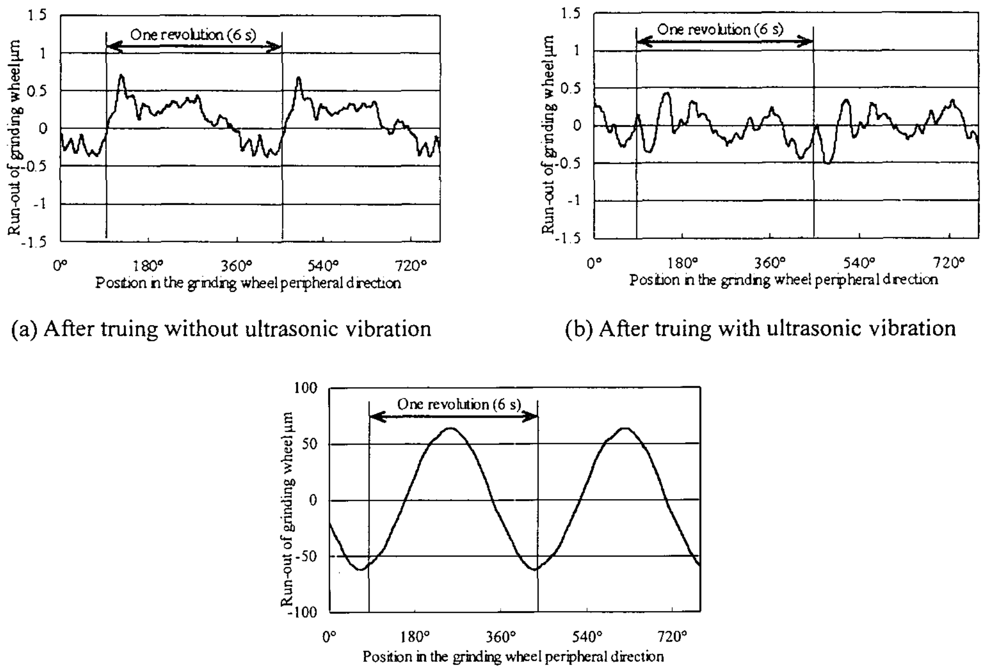
Fig. 6 shows the variation of the wheel run-out during truing. It can be seen that the wheel run out obtained with the ultrasonic vibration is smaller than



(a) Truing force vs. Cup wheel feed rate (b) Truing force vs. Vibration amplitude

Grinding wheel: CBN#400, GC cup wheel feed rate: δ=5μm/cycle, Vibration amplitude: 18μm

Fig. 4. Truing forces under various truing conditions.



(a) After truing without ultrasonic vibration (b) After truing with ultrasonic vibration

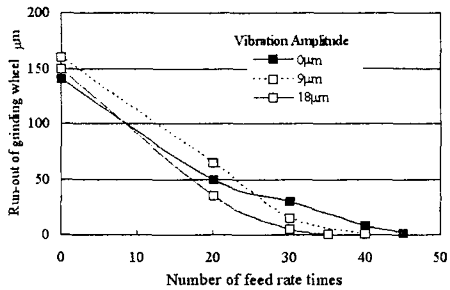
(c) Before truing

Grinding wheel: CBN #400, Cup wheel: GC#150; Feed rate: δ=1μm/cycle; Vibration amplitude: 18μm

Fig. 5. Grinding wheel form error before and after truing.

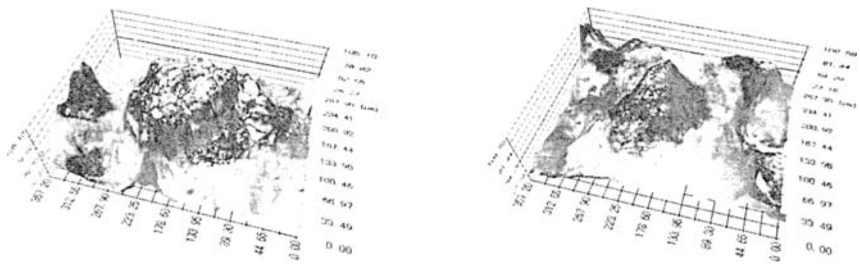
that without the ultrasonic vibration, and higher truing accuracy can be achieved with the larger ultrasonic vibration amplitude.

The microscopic morphologies of the surface trued under the absence and presence of ultrasonication were observed with a 3D digital Microscpoe (VHX-200/100F, KEYENCE Co., Ltd.) A number of dulled abrasive grains showing abrasion wear were observed on the grinding wheel trued without ultrasonication in Fig. 7(a). On the contrary, few dulled abrasive grains and more clearly extruded grains appeared on the grinding wheel dressed with ultrasonication as Fig. 7(b) demonstrates. Fig. 8 shows the result of the entire grinding wheel in the direction of the wheel axis under the absence and presence of ultrasonication, respectively. It is clear that the



Grinding wheel: CBN #400, GC cup wheel: #150, GC cup wheel feed rate: δ=1 μm/cycle

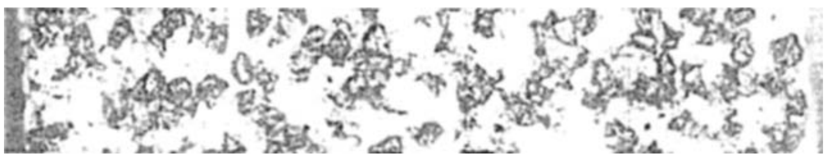
Fig. 6. Result of run-out of grinding wheel.



(a) Without ultrasonic vibration (b) With ultrasonic vibration

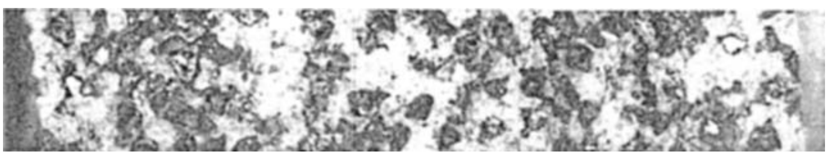
Grinding wheel: CBN #100, Cup wheel: GC #600; Feed rate: δ=1 μm/cycle; Vibration amplitude: 18μm

Fig. 7. Abrasive grain condition after dressing.



Distribution density of abrasive grain: 10 pieces/mm^2

(a) Without ultrasonic vibration.



Distribution density of abrasive grain: 14 pieces/mm^2

(b) With ultrasonic vibration

Grinding wheel: CBN #100, Cup wheel: GC #600; Feed rate: δ=1 μm/cycle; Vibration amplitude: 18 μm

Fig. 8. Grinding wheel surface condition after dressing.

distribution density of abrasive grain was improved by ultrasonic vibration. The probable reason is that the truing force reduces because of the ultrasonic vibration, and the dropout of abrasive grain decreased as a result.

To confirm the positive performance of the grinding wheel trued with ultrasonication in actual grinding operations, grinding experiments were carried out with an apparatus capable of constant-depth-of-cut UAG of a surface previously fabricated

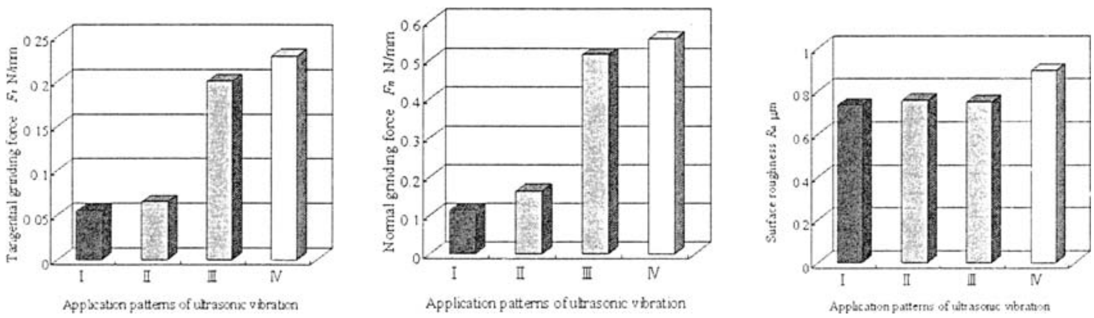
Table 2. Grinding experiment conditions.

Vibration amplitude (frequency)	18μm (19.2kHz)
Grinding wheel	CBN#400,ϕ5
Rotational speed of grinding quill n_g	1200 rpm
Work-table feed rate V_f	1.0 mm/s
Depth of cut Δ	1.0 μm
Cup wheel	GC#600
Rotational speed of cup wheel n_c	4700 rpm
Feed rate of cup wheel δ	1.0 μm/cycle
Reciprocation speed of cup wheel V_r	10 mm/s
Workpiece	SUS440C
Coolant	Solution type

Table 3. Application patterns of ultrasonic vibration.

Pattern	I	II	III	IV
During truing	○	×	○	×
During grinding	○	○	×	×

○ denotes with ultrasonic vibration, × denotes without ultrasonic vibration



(a) Tangential grinding force (b) Normal grinding force (c) Surface roughness

Fig. 9. Results of experiments.

[9]. Table 2 and 3 show the grinding experiment conditions and the application patterns of ultrasonic vibration during both experiments. The normal and tangential grinding forces were measured with a 3-axis dynamometer (Kistler Co., Ltd., 9254). The surface roughness of the ground workpiece was examined using a surface roughness tester (Tokyo Seimitsu Co., Ltd., Surfcom 2345).

Figs. 9 (a), (b) and (c) show the tangential and normal grinding forces and the work surface roughness achieved under different application patterns of ultrasonic vibration. The grinding force when using a grinding wheel trued under ultrasonication is smaller than that without ultrasonication, the normal and tangential grinding forces with an ultrasonically trued wheel were decreased by more than 20 % and 24 %, respectively, compared to that without ultrasonic truing. The work surface roughness R_a achieved with an ultrasonically trued wheel is smaller than that without ultrasonic truing; the value of R_a with ultrasonic truing was smaller than that without ultrasonic truing by around 18 %. Consequently, ultrasonication decreases the grinding force and improves the surface roughness by improving the abrasive grain sharpness, grain extrusion, and the distribution density of abrasive grain.

4. Conclusions

For the internal ultrasonic grinding of small holes, a new method for truing and dressing the small grinding wheel was proposed in which the grinding wheel is vibrated ultrasonically in its axial direction during truing/dressing with a rotary cup wheel dresser. Experiments were carried out to investigate the effects of the wheel ultrasonication on the truing/dressing force truing accuracy, and wheel surface properties. The performance of the wheel trued under ultrasonication was also confirmed experimentally. The obtained results can be summarized as following.

(1) The truing force under ultrasonication is less than that under non-ultrasonication; its value increases with the decrease in the wheel vibration amplitude. In the current experimental conditions, the truing force decreased by more than 22 % owing to ultrasonication.

(2) Better truing accuracy can be attained under ultrasonication; the run out of the grinding wheel is improved from around 150 μm before truing to less than 0.8 μm after truing. Also, better grinding wheel surface properties in terms of the abrasive grain sharpness and the grain extrusion are achieved by ultrasonicating the grinding wheel.

(3) The grinding force when using a grinding wheel trued under ultrasonication is smaller than that without ultrasonication; in the current grinding conditions, the normal and tangential grinding forces with an ultrasonically trued wheel were decreased by more than 20 % and 24 %, respectively, compared to that without ultrasonic truing.

(4) The work surface roughness R_a achieved with an ultrasonically trued wheel is smaller than that without ultrasonic truing; in the current grinding conditions, the value of R_a with ultrasonic truing was smaller than that without ultrasonic truing by around 18 %.

References

[1] P. Logge, Ultrasonic, Jul., (1966).

[2] A.I. Markov, Industrial diamond review, (1972).

[3] U. Kuniaki, N. Kazuhito, M. Akira, T. Hiroshi, The trial construction of ultrasonic grinding equipment and the machining characteristics–Study on high efficient grinding for brittle materials (1st Report), *Journal of JSPE*, (in Japanese). 52(1) (1986) 107-113.

[4] J. Kumabe, Ultrasonic vibration grinding, *Journal of JSPE*, (in Japanese). 27(6) (1961) 369-374.

[5] K. Suzuki and T. Uematsu, Fundaments of ultrasonic grinding process, *Kikai to Kougu (Machines and Tools)*, (in Japanese). 44(4) (2000) 96-102.

[6] Y.Tanaka, Study on the fine finishing by an ultrasonically vibrated abrasive stone (1st Report), *Journal of JSPE*, (in Japanese). 29(3) (1963) 232-237.

[7] Y.Tanaka, Study on the fine finishing by an ultrasonically vibrated abrasive stone (2nd Report), –On the fine finishing resistance– *Journal of JSPE*, (in Japanese). 30(3) (1964) 253-258.

[8] Y.Tanaka, Study on the fine finishing by an ultrasonically vibrated abrasive stone (3rd Report), -On the loading of grinding stone- *Journal of JSPE*, (in Japanese). 31(4) (1965) 306-311.

[9] Y. Wu and M. Nomura, Study of internal ultrasonic vibration assisted grinding of small holes –construction of ultrasonic vibration spindle and its fundamental performances– *Journal of JSAT*. (in Japanese). 47(10) (2003) 550-555.

[10] Y. Wu and M. Nomura, Modeling of grinding force in constant-depth-of-cut ultarasonically assisted grinding, *Materials Science Forum*. 471-472 (2004) 101-106.