Development of ultrasonic rotary cutting method for hardened steel

Shinichi NINOMIYA[1, a *], Satoshi NAGAKURA[1], Fumio KOGA[1], Youji YAMADA[1], Manabu IWAI[2, b] and Kiyoshi SUZUKI[1, c]

[1]Nippon Institute of Technology, Miyashiro, Saitama 345-8501, Japan

[2]Toyama Prefectural University, Imizu-shi, Toyama 939-0398, Japan

[a]ninomiya@nit.ac.jp, [b]iwai@pu-toyama.ac.jp, [c]s-kiyoshi@ipr.ne.jp

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Abstract. The authors have conducted researches on rotary cutting (spin turning) of hard-to-machine materials. In this research, an ultrasonic rotary cutting method in which a tool-driven type rotary cutting tool is ultrasonically vibrated is proposed. In order to enable a mounting on a 5-axis compound machine tool, a compact ultrasonic vibration unit was developed. As a result of applying it to the processing of the outer peripheral surface of a hardened steel workpiece, it was found that the cutting force was reduced and the surface roughness was improved after cutting. In addition, the ultrasonic rotary cutting was also effective for the linear R groove processing of hardened steel material.

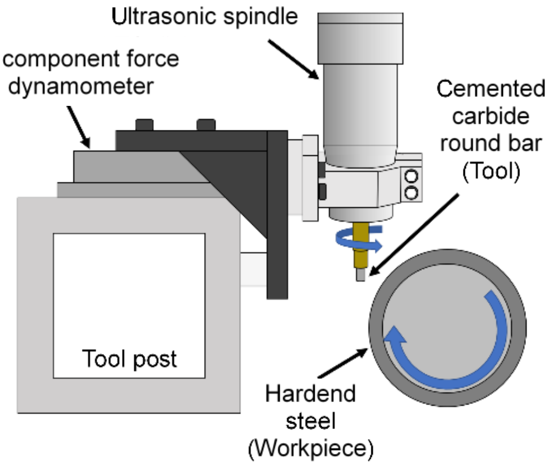
Introduction

The tool-driven rotary cutting on a lathe-type 5 axis multi-function machine has an advantage that the heat generated during processing does not accumulate on a tool tip, because the cutting edge point contacting with the workpiece changes continually as the tool is rotating. With this advantage, an uncoated round bar of solid cemented carbide can be used as a tool which can suppress tool damages to a large extent and make it possible to machine hardened steel materials. A tool with a simple geometry like a round bar can easily be shape formed on the machine, and it was found that removal of a rotational runout and shape forming of a rake face could be done on the machine[1, 2].

In this research, a new method named "Ultrasonic Rotary Cutting" was developed. In this method, ultrasonic vibrations are given to a solid cylindrical rod (round bar) tool made of cemented carbide. In order to examine fundamental machining characteristics, turning experiments were performed on the periphery of induction hardened steel workpieces. Further, machining of linear R grooves on the hardened steel was attempted.

Peripheral turning of hardened steel by ultrasonic rotary cutting method

Experimental method and conditions. The experimental setup and conditions are shown in Fig.1 and Table 1, respectively. A cemented carbide round bar of ϕ6mm was shrink fitted to the ultrasonic spindle and fixed to the tool rest of the NC turning machine through 3 component force dynamometer. The ultrasonic frequency applied was 40kHz in longitudinal vibration mode, and the amplitude was 4μm/p-p. Peripheral speed of the workpiece was set at Vw=20m/min so that the speed was below the critical cutting speed of Vc=30m/min. The tool inclination angle and the tool shift angle was set at β =10° and θ =8°, respectively. The rake angle of the tool at the actual cutting stage becomes -8°. The appearance of experimental setup is shown in Fig2.



(a) Schematic of experimental set up

(b) Ultrasonic spindle (industria)

Fig.1 Outline of turning experiment by ultrasonic rotary cutting

Table 1 Experimental conditions for rotary cutting of hardened steel with a round bar tool

Machine used	NC lathe (Dainichi, DL530)
Rotary tool	Round bar tool made of cemented carbide (WC) A1, ϕ6mm (Overall length including a shrink fit holder: 55mm)
Workpiece	Hardened steel : ϕ63mm (HRC63)
US rotary cutting conditions	Peripheral turning, Vw=20m/min, Tool speed: Vt= 6.7(Vw /3) m/min, f=0.1mm/rev, a=0.2mm/pass, Number of cuts: N=3pass, cutting length l=20mm, Dry cutting, Tool inclination angle: β=10°, Tool sift angle: θ=8°
US conditions	Vertical vibration, 40kHz, 4μm/p-p

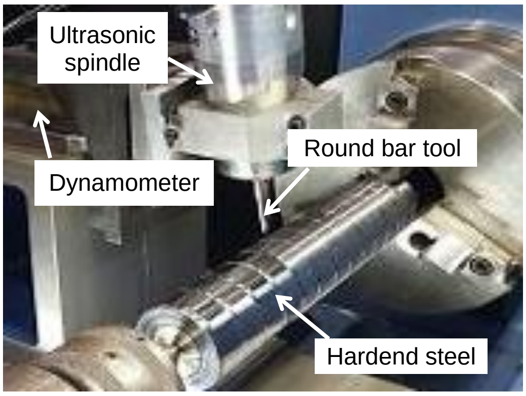
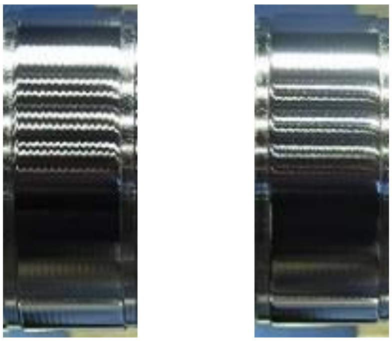


Fig.2 Photo of experimental set up

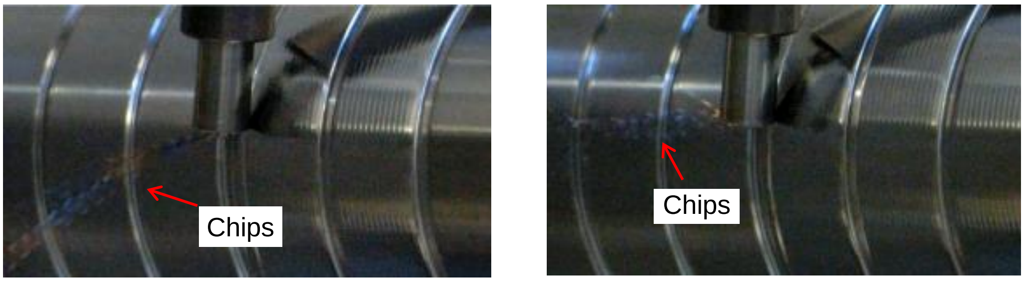


(a)Without US (b)With US

Fig.3 Appearances of the workpiece surface after rotary cutting

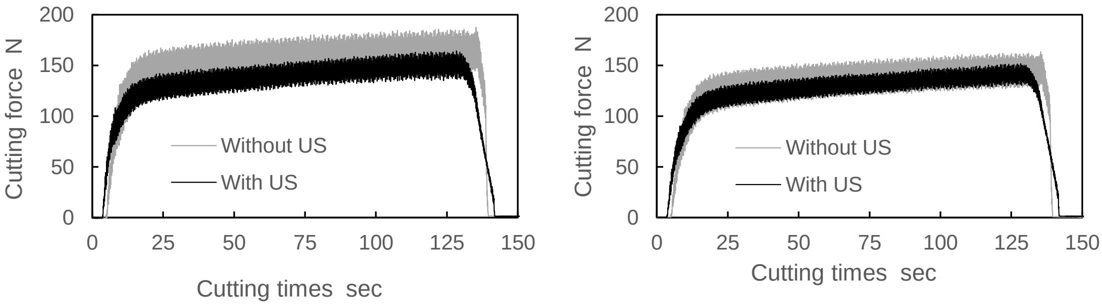
Experimental results of peripheral turning. Appearances of the workpiece surface after rotary cutting are shown in Fig.3. Regardless of with or without ultrasonic vibrations, it seems good machining was done. Observing the actual condition during the machining, it can be seen that both exhibit a shiny surface such that the tool in use is reflected on the processed surface.

Though long continuous chips were discharged in both cases, it was confirmed that the discharge direction of the chips varied depending on with or without ultrasonic vibrations (Fig.4). It is conceivable that some variation arose in the friction caused by the contact of the chips with the tool rake face by the ultrasonic vibrations.



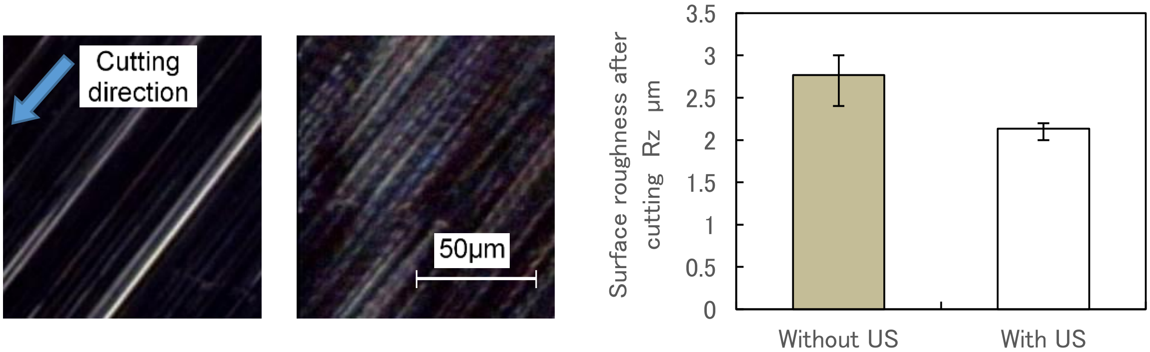
(a)Without US (b)With US

Fig.4 Difference of chip discharge direction during rotary cutting



(a) Principal forces (b) Thrust force

Fig.5 Cutting force during rotary cutting (2nd pass)



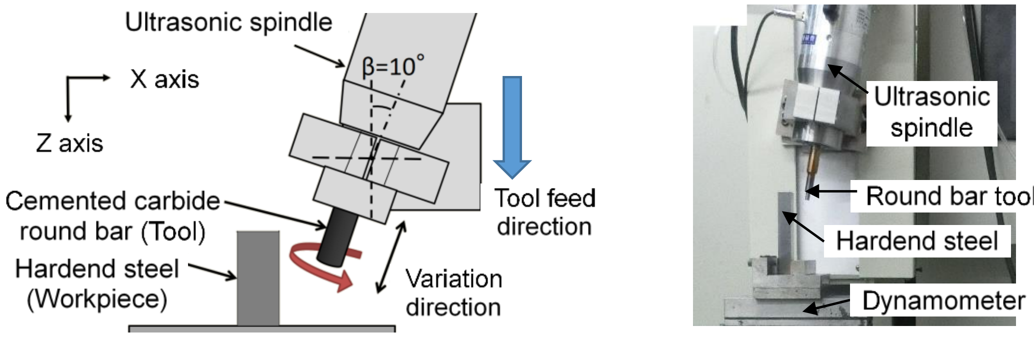
(a)Without US (b)With US (c) Surface roughness Rz of feed direction

Fig.6 Surface conditions and surface roughness of hardened steel after rotary cutting

Fig.5 shows the cutting forces during the 2nd pass measured with the 3 component dynamometer. Comparing the results by with or without ultrasonic vibrations, it was found that both principal and thrust forces continued to be slightly lower in the case of with ultrasonic vibrations than without ultrasonic vibrations.

Fig.6 shows appearance observed on the CCD microscope and surface roughness of the hardened steel workpiece after turning. Comparing the cutting marks on the worked surface, while straight line scratches resulted and large flaws were partially found in the case of without ultrasonic vibrations, intermittent cutting marks caused by the ultrasonic vibrations were observed along the cutting direction and no notable scratch was seen in the case of with ultrasonic vibrations. As to the surface roughness (Maximum height Rz), roughness values with ultrasonic vibrations were smaller and the variation of there values were much smaller in comparison with those without ultrasonic vibrations. Accordingly, it was found that stable surface quality could be obtained by giving ultrasonic vibrations to cemented carbide tools.

In addition, no significant tool wear was observed in both tools after the experiment.



(a) Schematic of experimental set up (b) Photo of experimental set up

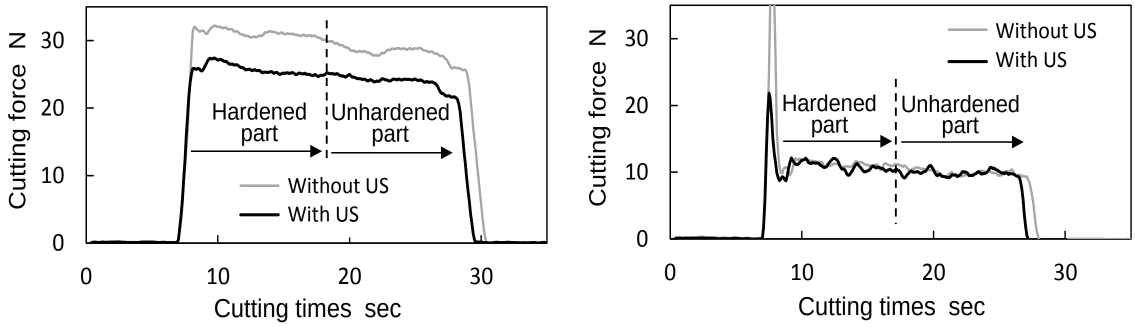
Fig.7 Outline of linear R groove machining experiment by ultrasonic rotary cutting

Table 2 Experimental conditions for linear R groove machining of hardened steel

Machine used	Simplified 5 axis machine (Mitsubishi)
Rotary tool	Round bar tool made of cemented carbide (WC) A1, ϕ6mm
Workpiece	Hardened steel : t12mm×L63mm (HRC63)
US rotary cutting conditions	*V*w=0.4mm/min, Tool speed: *V*t= 6.7 m/min, *f*=0.1mm/rev, *a*=0.2mm/pass, Number of cuts: *N*=1pass, cutting length *l*=10mm (5mm of the hardened part and 5mm of the unhardened part), Dry cutting, Tool inclination angle: *β*=10°, Tool sift angle: *θ*=0°
US conditions	Vertical vibration, 40kHz, 2μm/p-p

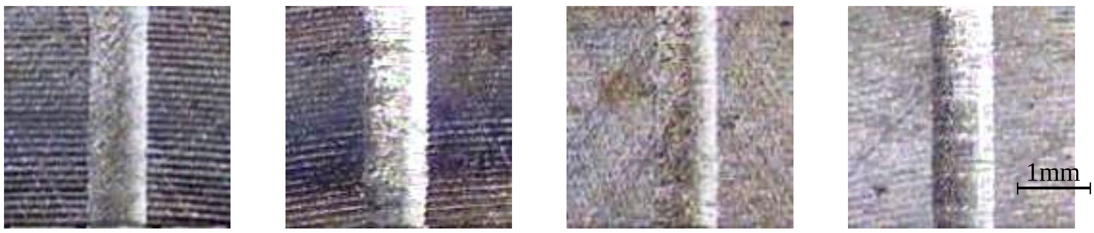
Linear R groove machining on hardened steel by ultrasonic assisted rotary cutting

Experimental method and conditions of linear R groove machining. Mounting an ultrasonic spindle to the Z axis of the simplified 5 axis machine, linear R groove machining was attempted (Fig.7). The cemented carbide tool of ϕ6mm fixed to the ultrasonic spindle was set so that the clearance angle becomes 10°. The rake angle in this case is negative 10°. The workpiece material is induction hardened steel with a hardened thickness of 5mm radially from the periphery. Setting a depth of cut to the X axis at 0.2mm/pass, a groove of 10mm in length (5mm of the hardened part and 5mm of the unhardened part) was machined to the Z axis direction. A feed rate was restricted to 0.4mm/sec in this experiment (Table 2).



(a) Thrust force (b) Principal forces

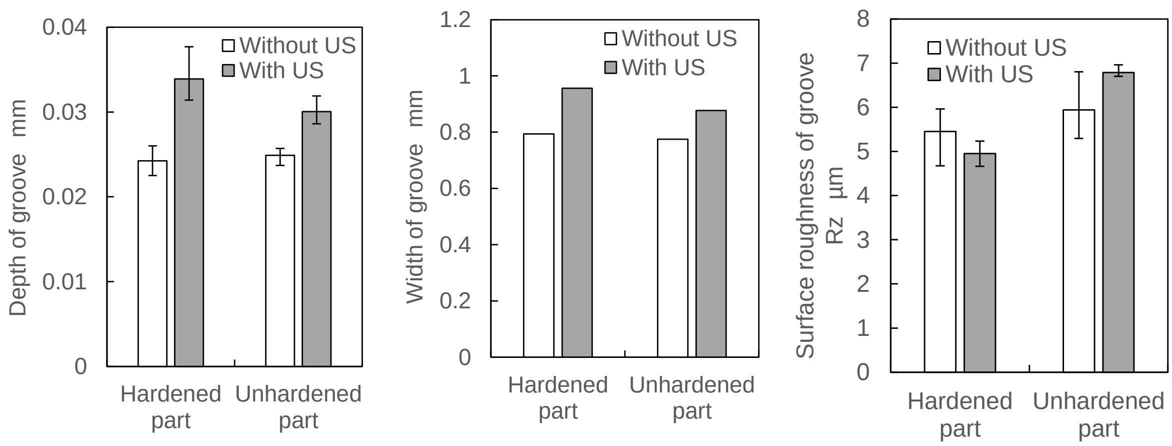
Fig.8 Cutting force during machining of linear R groove



Without US With US Without US With US

(a) Hardened part (b) Unhardened part

Fig.9 Groove condition of hardened steel after machining



(a) Maximum groove depth (b) Groove width (c) Surface roughness of groove (Feed direction)

Fig.10 Maximum groove depth, groove width and surface roughness of the workpiece

Result of linear R groove machining experiment. Cutting force during machining of linear R groove is shown in Fig.8. Looking at the cutting forces, the thrust force against the tool continued to be lower in the machining with ultrasonic vibrations than the case of without ultrasonic vibrations. As to the principal force indicating a component of the feed direction, it was found that the value at the moment when the tool started cutting largely decreases in the case of with ultrasonic vibrations. Looking into the conditions of the machined grooves (Fig.9), there is no big difference observed in the aspect of the grooves, but a width of the groove machined was wider both on hardened and unhardened parts in the case of with ultrasonic vibrations. Fig.10 shows maximum groove depth, groove width and surface roughness of the workpiece. There could be seen a tendency in the case of with ultrasonic vibrations that a depth and a width of the groove were slightly more than the case of without ultrasonic vibrations. Though there was not significant difference in the surface roughness value (Maximum height = Rz), it could be seen that the roughness variation with ultrasonic vibrations was smaller.

Conclusion

"Ultrasonic Rotary Cutting" method in which ultrasonic vibrations are given to the cemented carbide round bar tool was proposed. In order to investigate fundamental machining characteristics of this method, experiments of circumferential turning and linear R groove machining were performed on the induction hardened steel with the hardness of more than HRC63 and the following conclusions were drawn.

1) In the circumferential turning of the induction hardened steel, by using the ultrasonic rotary cutting method where ultrasonic vibrations are given to the cemented carbide tool, values of cutting forces and surface roughness became lower in comparison with the conventional rotary cutting. On the machined surface, machining marks unique to the ultrasonic cutting were obtained.
2) In the linear R groove machining of the induction hardened steel, the principal cutting force at the moment when the tool just start cutting drastically decreased and the thrust force was kept lower as well by giving ultrasonic vibrations to the cemented carbide tool. Considering the fact that depth and width of the machined groove become larger, it was found that the Ultrasonic Rotary Cutting should have an effect on improving the tool biting to the workpiece.

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