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INFLUENCES OF VARIOUS CUTTING PARAMETERS ON THE SURFACE ROUGHNESS DURING TURNING STAINLESS STEEL

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Abstract – This paper presents an investigation of the process factors affecting the surface roughness in ultra-precision diamond turning with ultrasonic vibration. Stainless steel was turned by diamond tools with ultrasonic vibration applied in the feed direction with an auto-resonant control system. Surface roughness was measured and compared along with the change of the cutting parameters. The relation curves between the cutting parameters and surface roughness were achieved by comparing the experimental results with different cutting speeds, feed rates, cutting depths. Experimental results indicate that cutting parameters have an obvious effect on the surface roughness. The conclusions are draw in given conditions, the smaller amplitude of the vibration, the worse the surface quality and the higher vibrating frequency, the better surface quality, and the deeper the cutting depth and the more the feed rate, the worse the surface quality. Among these parameters, the feed rate was the most important factor on surface quality.

Keywords: Turning; Diamond Tool; Stainless Steel; Ultrasonic Vibration; Surface Roughness.

1. INTRODUCTION

Stainless steel is one of the metal materials because of a favorable combination of mechanical properties, corrosion resistance and cost effectiveness. It has been widely used in industry, especially in aerospace and military fields in which there are more and more strict demands on machining surface quality of the stainless steel workpiece [1]. However, stainless steel is very difficult to machine with conventional tools. Even the cubic boron nitride and precise ceramic tools can not meet the higher manufacturing requirements because of their mechanical and physical characteristics [2]. But natural single crystal diamond can be made into sharp knife-edge as to cut down such thin sheer scraps, and it can be used to manufacture a mirror with high accuracy and perfect surface quality. Whereas the tools are worn out very fast when being used to machine stainless steel workpiece in conventional methods, by which the operations can't carried on smoothly, and the surface quality of the workpiece can not be ensured [3]. In this paper, ultrasonic vibration was applied in turning stainless steel experiments by natural single crystal diamond tool. Therefore, the ultrasonic vibration turning of these materials is feasible in modern manufacturing environment [4]. The results of ultrasonic vibration machining are significantly affected by the inherent vibration and accuracy of the machine tool. Special ultra-precision machines and arrangements were used for the ultrasonic applications [5]. However, when the ordinary machine tools were used, in most cases an improvement of surface finish would be reported. Achieving improvements on surface finished is relevant to the industrial applications, which can simplify or even eliminate some additional manufacturing operations.

In machining parts, surface quality is one of the most specified requirements by customers. The surface roughness is the main indication of the surface quality of machined parts. Surface roughness is an important parameter representing the surface quality of the ultra-precision machining workpiece [6]. Numerous theoretical and experimental studies on surface roughness of machined products have been reported. There are many factors influencing the surface roughness of stainless steel workpiece in ultrasonic turning, such as machining specification, machining data, tool material, tool geometry parameters and its abrasion, the material structure and characteristic and the turning space between the workpiece and tools, lubricating

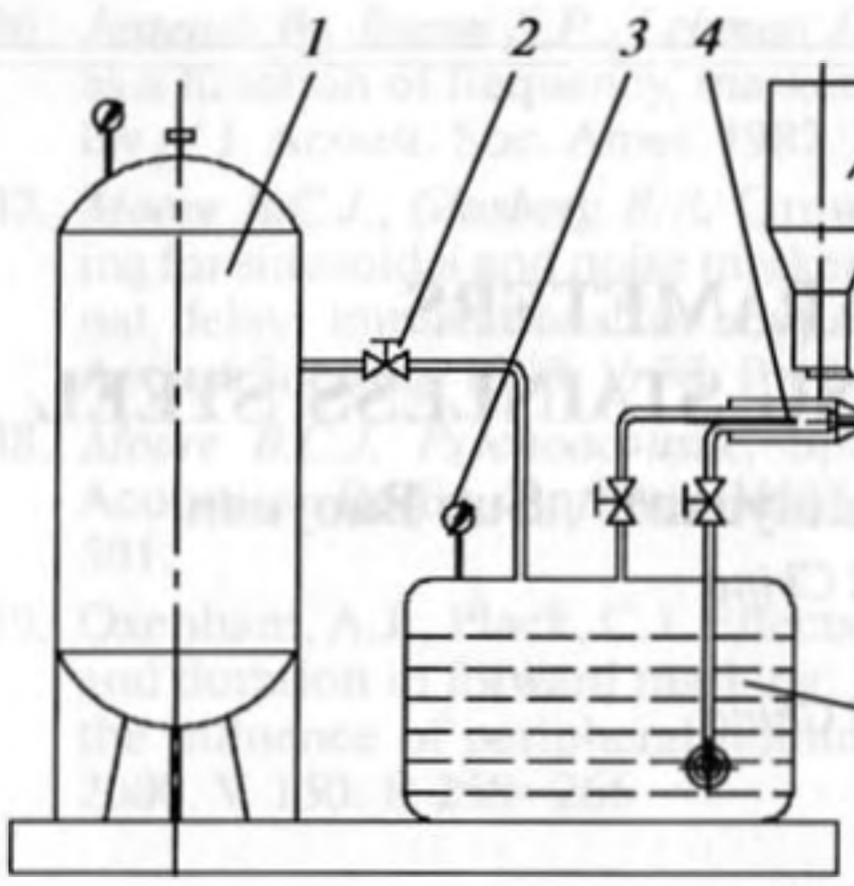

Fig. 1. The gas-fluid atomization device in turning experiment.

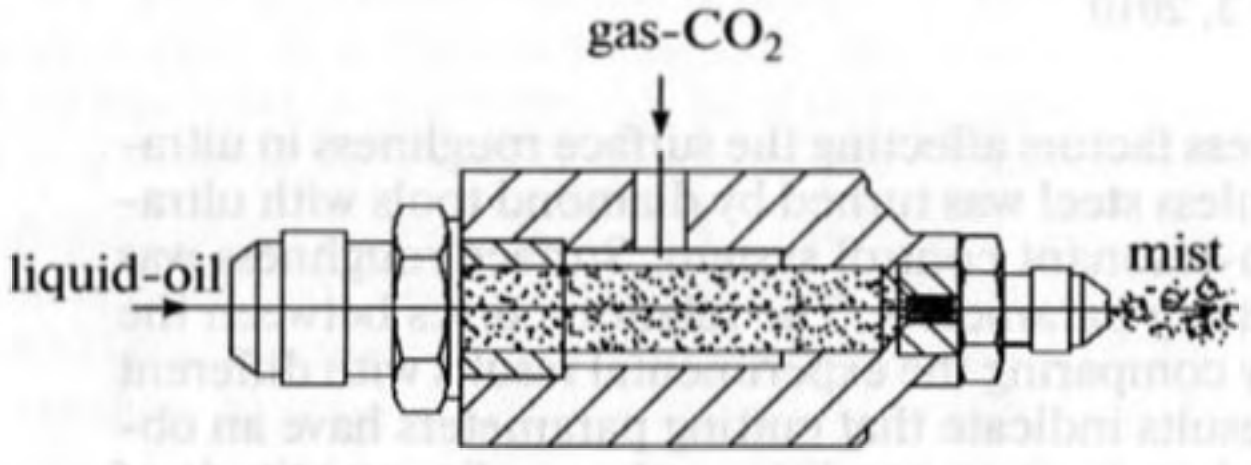

Fig. 2. The nozzle composition and atomization mechanism.

and cooling condition for tools, and rigidity of the machine fixture, tools, and workpiece system. It is important for the turning efficiency and surface roughness to determine proper cutting quantity, ensuring machining quality and reducing machining cost [6]. There are various cutting parameters having effects on the surface roughness, but those effects have not been adequately quantified. In order for manufacturers to maximize their gains from utilizing finish hard turning, accurate predictive models for surface roughness and tool wear must be constructed. The aim of the present research was to create an ultrasonic turning facility to explore the effects of cutting parameters on surface roughness when turning stainless steel by diamond. These results show that the cutting conditions (such as cutting speed, feed rate, cutting depth, tool geometry, and the material properties of both the tool and workpiece) can influence the surface roughness significantly.

2. EXPERIMENTAL DESIGN AND STATISTICAL ANALYSIS

Fig. 1 shows the photo of processing sites of the ultrasonic vibration turning system used in these experiments. Fig. 2 shows the schematic of vibration turning stainless steel.

The cutting force is measured by Vertical Parallel Octagon and the cutting temperature is measured by tool-workpiece thermocouple method. Surface roughness Ra is measured by comparison with standard surface roughness mass.

The good separation between tools and the cutting scraps in ultrasonic vibration turning, reduces sticking phenomena between them, and breaks the forming condition of the chip build-up and scale-stab [7], diminishes friction force. Meanwhile, the ultrasonic vibration can improve the rigidity and stability of the system. Surface roughness is decreased and geometrical precision is improved for small cutting force, low cutting temperature [8]. When vibration turning, though the tool edge vibrates, the position of the tool edge stays invariable in all moment when tool edge and workpiece contact and produce scraps. Machining precision is improved because of invariability of position with the time when turning the workpiece [9].

The supersonic vibration experiment system of turning stainless steel by natural single crystal diamond is composed of turning lathe, supersonic transducer, and amplitude changing pole, bracket and diamond turning tools. Fig. 2 shows the theoretical sketch of turning stainless steel under the state of supersonic vibration by natural single crystal diamond tools.

2.1. Evaluation of the surface quality and the surface roughness

The surface quality was evaluated by measuring surface roughness along the axial direction of the workpiece [10]. The value of the centre line average (Ra) was used to analyze the surface roughness of machined workpiece. However, other major roughness parameters are also available. The perimeter of the workpiece was divided into five equal parts and five surface roughness measurements were performed on the cylindrical surface. It is a well-established fact that the surface finish of a machined workpiece is extremely sensitive to any changes in the machining process. Hence it is logical to assume that measurement of the surface finish could be used to identify special features of a special manufacturing process and to control the same cases by controlling the identified features [11].

The difference ΔR_{th} between the machining surface roughness Ra_{max} and the geometrical surface roughness Ra is expressed by

$$\Delta R_{th} = Ra_{max} - Ra \qquad (2.1)$$

$$R_{th} = \frac{1}{8}\frac{S^2}{R} \qquad (2.2)$$

$$\Delta R_{th} = \frac{1}{4}\frac{S\Delta S}{R} + \frac{1}{2}\Delta t \qquad (2.3)$$

where s is the feed rate, ΔS is the feeds variation, Δt is the cutting depth variation, R is the radius of the tool cutting point. According to insensitivity vibration turning mechanism, $\Delta t \approx 0$, $\Delta S \approx 0$, so above equations, $\Delta R_{th} \approx 0$. The roughness of machining surface is approximate to R_{th}. It means that the vibration machining surface roughness R_{max} is almost equal to the geometrical surface roughness R_{th}.

Therefore, the measurement of the surface roughness in terms of Ra is used to identify the characteristics of the ultrasonic machining process compared with the conventional machining[12].

2.2. Descriptions of the mechanical and control arrangements

Lathe: S1-222 precise diskette lathe
Workpiece material: stainless steel (1Cr18Ni9Ti)
Workpiece diameter: 30mm
Tools: natural single crystal diamond tools

The auto-resonant system maintains the resonant mode of vibration during the dynamic changes of the load. The maximal level of vibration of the cutting tip was about 12 μm peak-to-peak at 19.7 kHz, and decreased during the turning up to 30–40% depending on the cutting conditions. All surfaces of the workpiece, cylindrical and faces were machined prior to the experiments. After fixing workpiece in the three-jaw chuck, a finish cut with a very small depth was performed using the same insert to be used in the test in order to eliminate any remaining eccentricity. This also allows the insert to get a stable tool wear region before starting each test. The first cut was made with ultrasonic vibration, and as soon as the tool had traversed 15 mm the vibration was switched off, meanwhile the second cut was proceed under the same cutting conditions but without ultrasonic vibration. After changing the cutting speed by changing the spindle rotational speed the next two cuts were performed with and without application of ultrasonic vibration. As for the new workpiece, the insert was changed and the previous steps were repeated.

2.3. Experiment for the effect of cutting speed on surface roughness

When turning with ultrasonic vibration, the cutting speed includes composite speed, which mainly considers the speed of main spindle, main movement of the workpiece, and the speed of vibration relative to the tools which is caused by vibration frequency [12]. The change of cutting speed is achieved by changing the speed of the main spindle, the amplitude and the frequency of the ultrasonic vibration system [13].

2.3.1. Experiment for the effects of cutting speed on surface roughness. The relationship between the cutting speed and the surface roughness both in conventional turning and in ultrasonic turning was studied. The test results are shown in Fig. 3. The test conditions are feed rate 0.056 mm/r, cutting depth 0.10 mm, cutting speed 20–180 m/min.

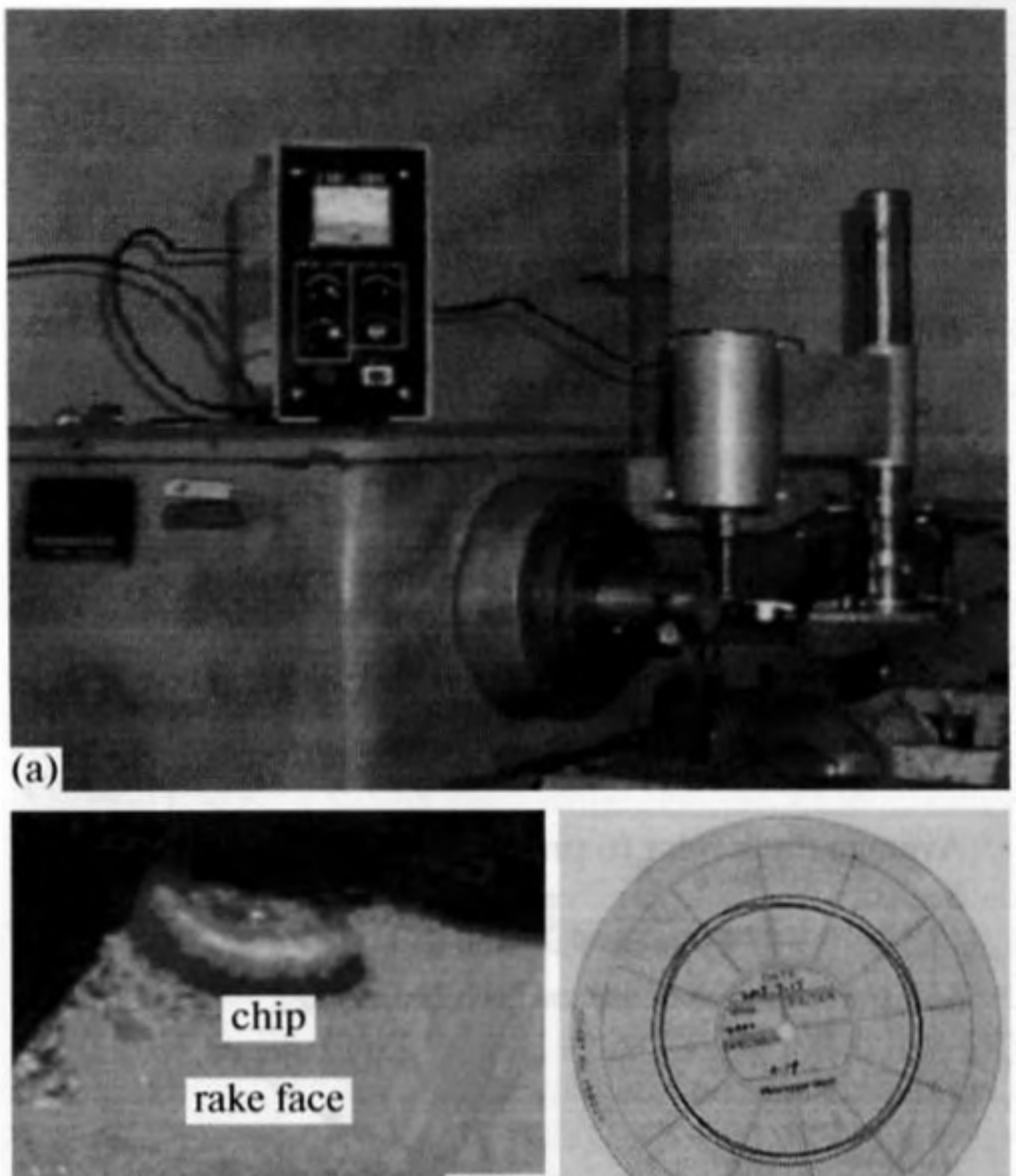

Fig. 3. (a) The photo of processing sites; (b) Microphotographs of the cutting chips; (c) The flatness of the workpiece.

As shown in Fig. 3, by comparing with the conventional turning, the surface roughness with the ultrasonic vibration decreases to about Ra 2.4 μm at cutting speed 50–180 m/min. In conventional turning, it shows that lower speed leads to the larger surface roughness. The results mainly happen from the several build-up edges and scales. In ultrasonic turning, the influence of friction cracks, surface plastic deformation, stick up, and wrinkly and build-up edges is depressed effectively owing to the action of the ultrasonic vibration, as well as the lower speed the chips being discharged in the loose curling strip form.

Therefore, the turning was preceded steadily and the value of the surface roughness was decreased greatly. When the ultrasonic vibration cutting speed is lower than one-third of the critical cutting speed ($v_c = 113.4$ m/min), the surface roughness will hold a small steady value. As it is close to the critical cutting speed, the effect of the surface plastic deformation will increase, which makes the effect of ultrasonic turning fading away. However, the rise of the critical cutting speed can extend the stable machining area and heighten process efficiency. So, the higher the critical cutting speed is, the larger the stable machining area will be. According to the relationship between the speed and the frequency, the best way to increase the

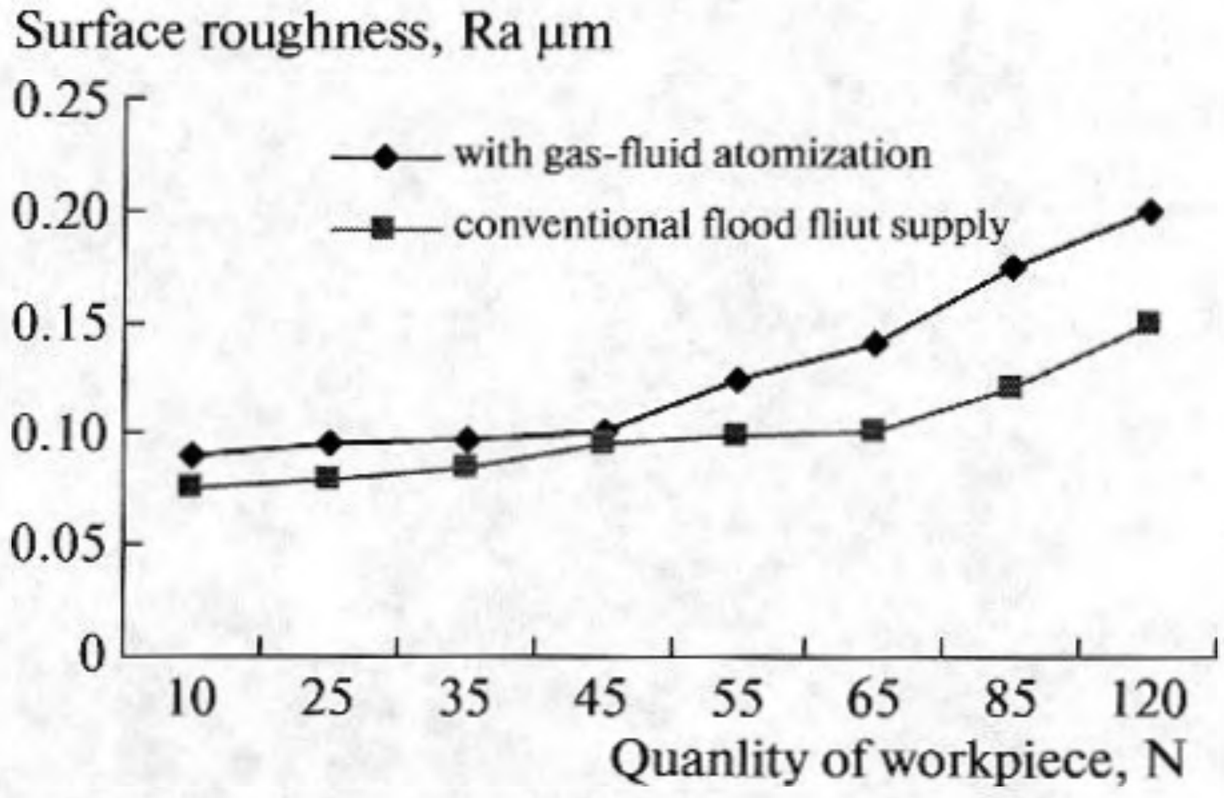

Fig. 4. Relation between the quantity of workpiece and surface roughness.

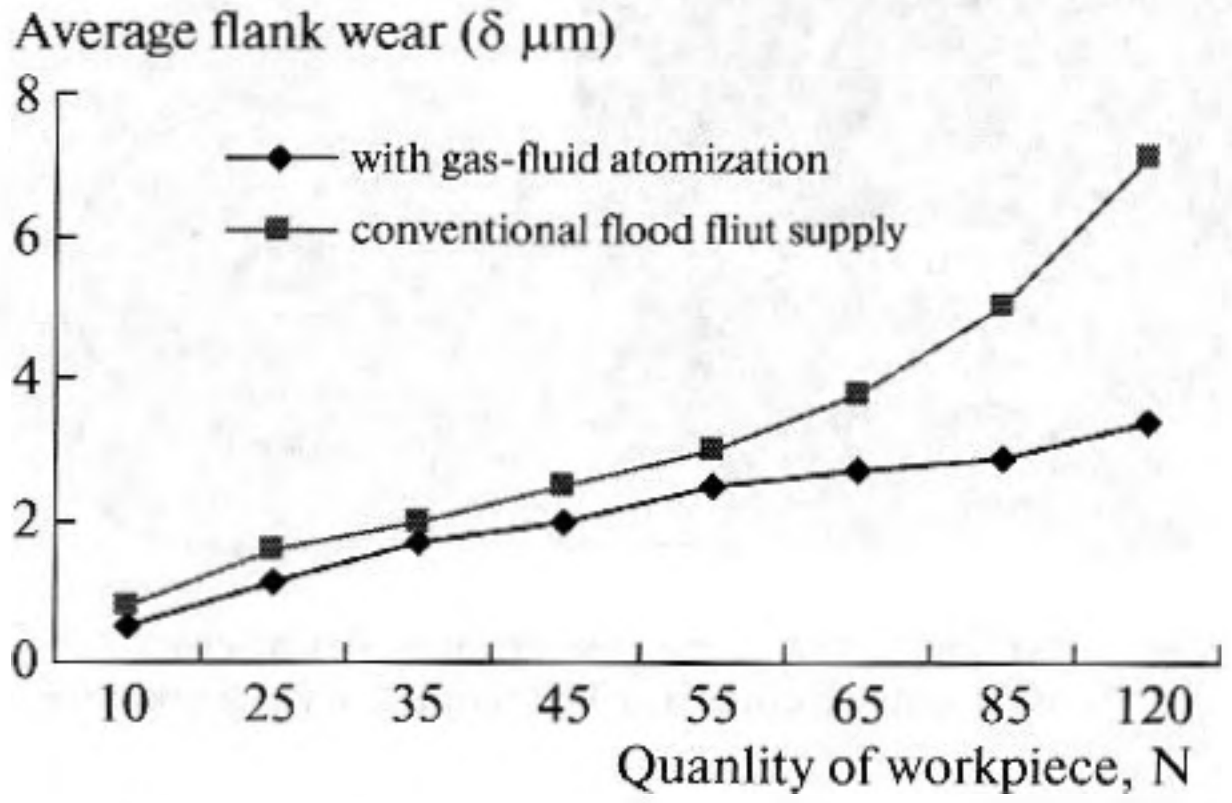

Fig. 5. Relation between the quantity of workpiece and averrange flank wear.

critical cutting speed is to increase the vibration frequency [14].

2.3.2. Experiment for the effect of the main spindle speed on surface roughness. Excessive spindle speed will cause premature tool wear and breakages, and tool chatter, leading to potential dangerous conditions. Proper spindle speed for the materials and tools will greatly affect the tool life and the quality of the surface finish.

Table

a \ v \ f	$f = 20$	$f = 30$	$f = 40$
14	106	158	211
12	90	136	181
10	75	113	151
8	60	90	121
6	45	68	90
4	30	45	60
2	15	23	30

For a given machining operation, the cutting speed will remain constant for most situations; therefore the spindle speed will also remain constant. However, as for the operations on a lathe involving machining with changing diameter, it means changing the spindle speed as the cut advancing across the face of the workpiece; this was harder to do in practice and was often ignored unless the work is demanded.

Fig. 4 shows influence the curve of the main spindle rotary speed on surface roughness of the workpiece. Experiment shows that surface roughness becomes worse with increasing main spindle speed. Surface roughness also becomes worse when the main spindle speed less than 80 r/min. There is no chip built-up and scale-stab when the range of the speed is between 100 r/min and 300 r/min.

2.3.3. Experiment for the effect of ultrasonic vibration parameters on surface roughness. Fig. 5 shows the relation curve of ultrasonic vibration frequency, amplitude and surface roughness. The value of roughness in experimental Table is an average value of surface roughness of three workpiece.

As shown in Fig. 5, the amplitude has the most serious influence on surface roughness when machining stainless steel workpiece by diamond ultrasonic vibration. Surface roughness was decreased when amplitude was increased. With constant amplitude, the effect of the ultrasonic vibration frequency on surface roughness is that the surface quality of the stainless steel was improved with increasing ultrasonic vibration frequency.

2.4. Experiment for the effect of feed rate on surface roughness

Fig. 6 shows the influence curve of the tool feed on surface roughness. As shown in Fig. 3, the feed rate has more effect on surface roughness. Surface roughness increases along with the increase in the tool feed. In experiment, the main spindle rotary speed is 210 r/min, cutting depth is 4 μm, vibration amplitude is 7 μm, and vibration frequency is 20 kHz.

2.5. Experiment for effect of cutting depth on surface roughness

Fig. 7 shows influence curve of cutting depth on surface roughness. As shown in Fig. 7, the cutting depth has evident effect on the surface roughness. Similar to section 2.4, the surface roughness increases along with the increase in cutting depth. In the experiment, main spindle rotary speed is 180 r/min, feed rate is 5 μm/r, vibration amplitude is 7 μm, vibration frequency is 20 kHz.

3. ANALYSIS OF THE EXPERIMENTAL RESULTS: THE RELATION-SHIP BETWEEN THE SURFACE ROUGHNESS AND VARIOUS CUTTING PARAMETERS

In vibrating turning, the cutting depth in cutting direction is a crucial factor which influences not only the machining quality but also the tools wear. During one cycle of vibrating turning, the length along the cutting direction [15]:

$$l_T = \frac{v}{f}, \tag{3.1}$$

v is cutting speed, f is vibrating frequency of tools.

From above experiment, if the cutting speed is fixed, the higher the frequency is, the shorter the l_T is, and the shorter cutting time and better surface quality will be obtained [16].

For the original machining system, only if the vibrating parameter in the process of vibration turning is proper, the vibration of machining system will be alleviated, and the stability of turning will be improved. So it is important to choose appropriate vibrating parameters (especially the ratio of f/f_n vibration frequency f, the instinct frequency of parts f_n).

The analysis of ordinary dynamic equation:

The differential equation of movement of parts in ordinary turning:

$$\frac{d^2x}{dt^2} + \frac{\gamma}{M}\frac{dx}{dt} + \omega_0{}^2 x = P_0 + P(t) \tag{3.2}$$

x is the horizontal displacement of parts;

M is the relative mass of the workpiece in lathe spindle;

ω_0 is relative model frequency of machining system;

γ is viscidity coefficient of machining equivalent model;

P_0 is average force to the parts in turning process;

$P(t)$ is impulse force generated by lathe in ordinary turning process.

$P(t)$ is the force forming the scraps. In the process of turning, because of shaving in machining process, its vibrating frequency ω and $P(t)$ have the following relation:

$$p(t) = p\sin\omega t. \tag{3.3}$$

Dynamic analysis of supersonic vibration turning:

In supersonic turning, the impulse force $P(t)$ can be caused by tiny vibration of tools, its vibrating dynamic equation is expressed as

$$\frac{d^2x}{dt^2} + \frac{\gamma}{M}\frac{dx}{dt} + \omega_0^2 x = P(t). \tag{3.4}$$

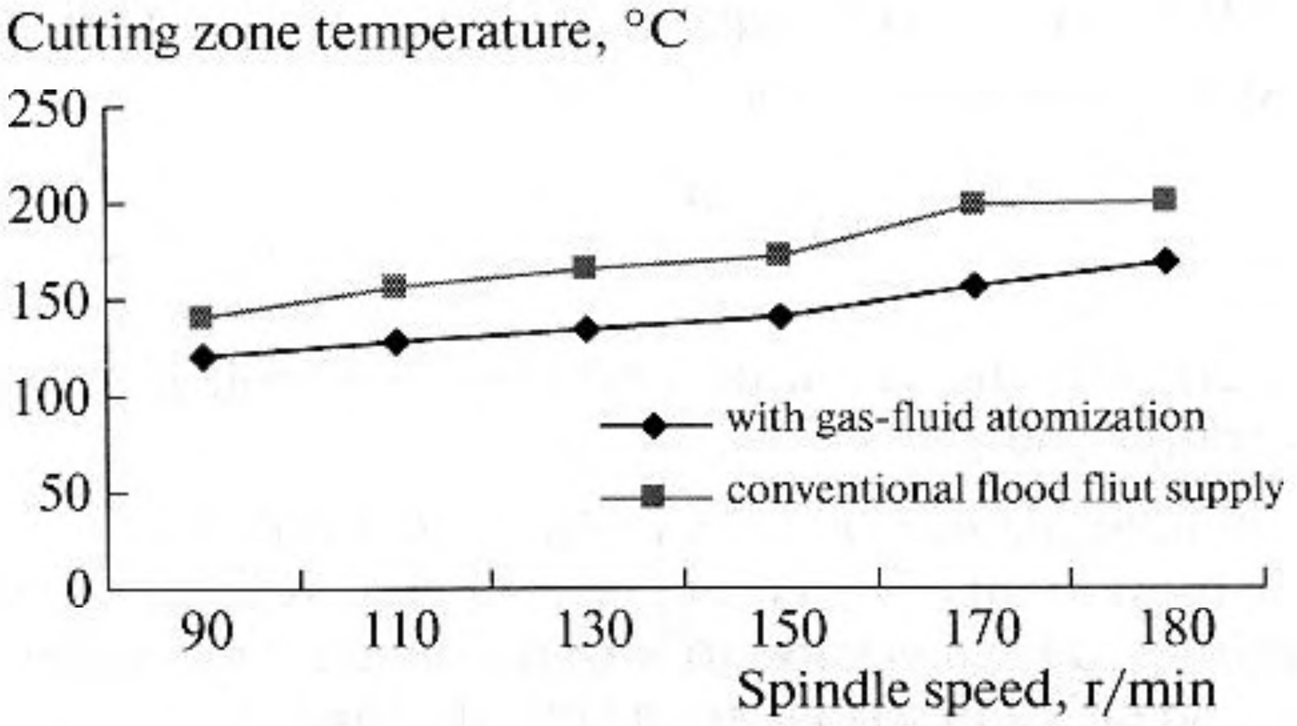

Fig. 6. Relation between cutting temperature and spindle speed.

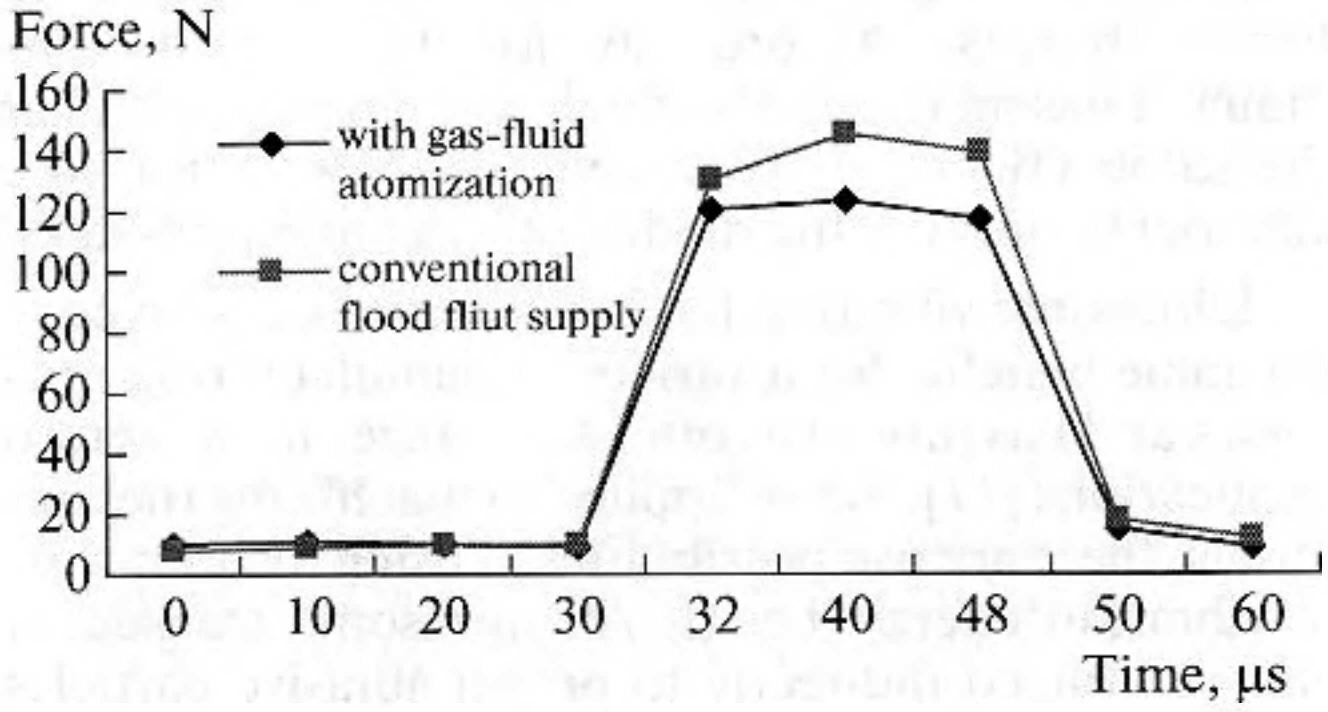

Fig. 7. Relation between the force acting on the cutting tool and turning time.

Unfolding $P(t)$ by the Fourier series , there is

$$P(t) = \frac{t_w}{T}P_0 + \frac{2P_0}{\pi}\sum_{n=1}^{\infty}\frac{1}{n}\sin\frac{t_w n}{T}\pi\cos n\omega t. \tag{3.5}$$

So:

$$x = \frac{t_w}{T}\frac{P_0}{\omega_0{}^2} + \sum_{n=1}^{\infty} NU \tag{3.6}$$

Where

$$N = \frac{P_0/\omega_0{}^2(2/n\pi)}{\sqrt{4\xi^2 n^2\omega^2/\omega_0{}^2 + (1 - n^2\omega^2/\omega_0{}^2)}},$$

$$U = \sin\frac{t_w\pi}{T}\sin\left(n\omega t + \arctan\frac{1 - n^2\omega^2/\omega_0{}^2}{2n\xi\omega/\omega_0}\right).$$

The frequency ratio λ is described as

$$\lambda = \frac{\omega}{\omega_0} = \frac{f}{f_0}, \tag{3.7}$$

where f_0 is inherent frequency of the above experiments which should be chosen less than 2 kHz; f is the vibration frequency of a tool.

When vibration frequency f is much bigger than f_0, Eq. (3–6) could be rewritten as

$$x = \frac{p_0\, t_w}{\omega_0^{\,2}\, T}, \qquad (3.8)$$

where T is the vibration period of the tool; t_w is the turning time.

The value of t_w is 1/3 to 1/10 of T. From Eq. (3.8), the movement of parts decreases obviously in vibrating turning state, it is good to improve machining accuracy and efficient to ensure the cutting quality.

When $\omega/\omega_n > 3$, the dynamic movement of parts in supersonic vibration manufacture is only t_c/T times of the ordinary turning. Actually, this characteristic intensifies the rigidity of workpiece vibrating system in turning process. Accordingly, for the sake of technique, it has increased the clip force of parts which has the same effects of using central bracket and core clamper to improve the rigidity of lathe spindle system.

Ultrasonic vibration has been harnessed with considerable benefits for a variety of manufacturing processes and has proved to offer advantages in numerous applications [17]. When applied to machining the materials, there are two possibilities of using the ultrasonic vibration energy, i.e. (i) An ultrasonic transducer can be utilized indirectly to propel abrasive particles suspended in slurry causing slow erosion at the work surface. (ii) the vibration is applied directly to a cutting tip. The advantages of the second possibility are not obvious. Because normally, the tool vibration has to be vigorously suppressed in most cases. However, different researchers have reported significant improvements in noise reduction, tool wear reduction, etc. By applying ultrasonic vibration during machining operations, especially in turning process, it is necessary to point out the possible advantages of the ultrasonic technology for industrial machining. The present research intends to fill up some existing gaps concerning the applications of the ultrasonic machining the modern aviation materials.

3.1. Analysis of the influence of cutting speed on surface roughness

After investigating the range of the cutting speed, it is known that the mild steel workpiece machined under the application of ultrasonic vibration is superior to the surface roughness of workpiece machined by conventional turning as illustrated by the mean lines drawn to represent these cases. The surface roughness of mild steel workpieces improves 50% more in the whole range of cutting speed under investigation.

Obviously, the fluctuations in the surface roughness caused in conventional turning are greater than those caused in ultrasonic turning especially over the range of speed. The reason for being able to reduce the fluctuations is that the machining process becomes more stable with the application of ultrasonic vibration. The conventional turning process is an unstable cutting process. Therefore, the values of the roughness may vary in a large range .This was proved by the observations made during the turning tests with application of ultrasonic vibration, such as: reduction of noise, formation of continuous chip and abolition of built-up-edge, some of which are inherent features of stable turning. Several authors have made similar observations for different materials in previous researches.

The ultrasonic turning is a strongly non-linear vibro-impact process. There are three independent principal directions in which ultrasonic vibration can be applied during the turning process: feed direction, direction of cutting speed and radial direction. Significant advantages were obtained when the usual continuous interaction between the cutting tip and the workpiece was replaced by intermittent turning [9]. However, when the cutting tip is vibrated ultrasonically, the following limitations are imposed:

In the cutting speed direction:

$$V = \pi n d < V_t = 2\pi a f \qquad (3.9)$$

In the feed direction:

$$s_n < V_t. \qquad (3.10)$$

The calculations show that for the contemporary commercially available bolted Langevin type transducers ($\alpha \approx 14$ μm, $f \approx 20$ kHz) the vibration tip speed can't exceed about 150 m/min. Moreover, reduction of tip speed also occurs during the turning process owing to the cutting tip interaction with the workpiece [6] so the upper limit on surface speed is further reduced. Thus the efficient ultrasonic turning with vibration applied in the direction of cutting speed is $V_t = 2\pi a f$, as shown in table 1.

Workpiece diameter: 30 mm.

$$V = \pi n d = 16 \text{ m/min} \qquad (3.11)$$

and

$$V_t \gg V. \qquad (3.12)$$

It can be achieved only for low diameter workpiece or low rotational speed. For example, n is limited to be less than 160 r/min when $d = 30$ mm and the condition $0.2V_t = V$ is required. However, application of ultrasonic vibration along the feed direction enables the cutting parameters used in manufacturing industry for most materials to be reached independently of the workpiece diameter. For example, n is limited not to be less than 20.000 r/min when $s = 1$ mm/r and condition $0.2V_t = S_n$ is required. Therefore, the tool vibration in the feed direction seems to be more suitable for industrial ultrasonic turning requiring high levels of productivity. We will call it sweep turning.

The higher the cutting speed is, the higher the labor productivity is. Selection of cutting speed is based on the durability of the cutting tool, roughness and precision of machining surface. Chip build-up and scale-stab is an important factor affecting surface roughness during machining the metal. Parallel furrows with different depths and widths are produced along direction of cutting edge with respect to the movement of the workpiece by the chip build-up. However, cutting speed is an important factor influencing the ebb and flow of the chip build-up and scale-stab. The chip build-up and scale-stab are easily formed under middle or low cutting speed. The general countermeasure adopted is to increase cutting speed to avoid forming areas of chip build-up and scale-stab. Chip build-up and scale-stab don't appear in experiment because of pulse turning during ultrasonic vibration turning [11].

The experiment shows that under certain machine tool rotary speed and certain extension, the higher the ultrasonic vibration frequency is, the smaller the cutting length is, the shorter turning time and the more perfect machining effect are achieved. The larger amplitude does favor to improve machining quality. The higher cutting speed intensifies tools diffusion abrasion, leading to increase in surface roughness. With the enhancement of rotary speed, the ratio of the cutting speed to vibration frequency increases, the efficiency of vibration turning was lower than the efficiency of conventional turning. When rotary speed is low, the poor rigidity of machine tool system is the main reason of the surface roughness.

3.2. Analysis of influence feed rate on surface roughness

Feed rate is one main factor of cutting parameters influencing machining productivity. The increasing feed rate results in contact surface temperature's rise. Cutting speed must be decreased when increasing feed rate. A less feed rate and a lower height of residual area will make a better surface quality. However, when feed rate is too small, with the thin cutting depth, the extrusion of cutting edge blunt radius on machining surface is intensified to increase cooling hardening effect.

3.3. Analysis of influence of cutting depth on surface roughness

Cutting depth, as a geometric factor, has no effect on ripple shape and surface roughness. Cutting depth has a obvious influence on surface roughness when the conditions, such as cutting temperature, cutting layer distortion, rigidity of fixture of machine tool, cutting intension and protruding peak transformation caused by the scraps, are changed. So considering above factors synthetically, best cutting depth is gained as ultrasonic vibration machining stainless steel workpiece.

4. CONCLUSIONS

1) The improvements on surface roughness achieved for the aviation materials tested in recommended conventional turning conditions by application of ultrasound vibration were up to 25–40% compared to conventional turning.

2) The spindle speed, amplitude and frequency of tool's vibration have effects on the surface roughness in ultrasonic vibration machining.

3) Feed rate have the most significant effect on the machining quality among all cutting parameters.

5. ACKNOWLEDGMENT

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ПОПРАВКА

к статье О.Э. Гулина “Моделирование распространения низкочастотного звука
в нерегулярном мелководном волноводе с жидким дном”,
опубликованной в томе 56, № 5:

На стр. 644 в правой колонке, 7-8 строки сверху следует заменить “**если плотность в слоях среды изменяется непрерывно**” на “**если плотность в слоях среды постоянна**”, там же на 13 строке удаляется фраза, “где в общем случае $\rho_k = \rho_k(z)$”.