

Research of Tool Nose Radius in Ultrasonic Vibration Cutting for Difficult-to-cut Materials

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Abstract: Ultrasonic vibration cutting (UVC) as an advanced technique has been widely used in order to increase productivity and stabilities in machining of difficult-to-cut materials. The authors presented a chatter monitoring and signal processing system for turning a slender workpiece. A suitable tool nose radius prevents the tool fracturing occurrence so that the instability of the machining process is markedly reduced by applying UVC. When employing the novel machining method of online monitoring vibration signals and adjusting cutting parameters in real time, there is no occurrence of chatter and the machining accuracy is close to predicted amplitude of vibration during the whole cutting process. At the same time, the tool life improves to some extent.

Keywords: Ultrasonic vibration cutting, Regenerative chatter, Online monitoring technique, Tool life.

1. Introduction

Difficult-to-cut materials which possess high hardness and intensity, low thermal conductivity or others are challenging to machine using conventional cutting methods. Due to their low machinability, it is general to utilize positive rake angle and the smallest possible nose radius of tool in case of exerting large cutting deformation and the regenerative chatter. However a tool with small nose radius still will cause instabilities because the strength of tool edge drastically declines. It is easy to cause tool tipping and cemented carbide-coated layer falling off. Much worse, tool wear is speeding up. Therefore, there is a need for advanced techniques in order to increase productivity and stabilities in machining of difficult-to-cut materials.

2. Influence of tool nose radius on machinability of difficult-to-cut materials by applying UVC

The authors made use of a new cutting model which has been experimentally proven including ultrasonic vibration cutting process to predict the occurrence of regenerative chatter with 2DoF(degrees of freedom) differential equations , where the intermittent cutting force is used to instead of continuous force in the practical cutting methods[1,2,3]. In order to study the mechanism of the occurrence of regenerative chatter, a numerical simulation is given under different cutting conditions according to the regenerative chatter model shown in Fig. 1. Then, the machining stability under traditional cutting and ultrasonic vibration cutting are compared. The simulation results show that when machining low stiffness parts in practical cutting method, the amplitude of the work displacement becomes larger and larger with increasing number of rotations. On the contrary, the amplitude of the work displacement decreases by applying UVC. The simulation predicts the best surface roughness R_y in vibration cutting is $4.3\mu\text{m}$ ($R_a \approx 1\mu\text{m}$) in ideal status. Vibration cutting can suppress chatter significantly although chatter may be caused during conventional cutting process and obviously, vibration cutting achieves a higher cutting stability compared with conventional cutting.

The intermittent cutting machining has a bad effect on the strength of tool edge so that instability of cutting process can still arise. In the simulated results, hypothetically, the same surface between the previous pass and the present pass is cut successively. In fact, the practical turning operations are always not. In order to take the regenerative effect into account, the overlap factor μ is

introduced. The overlap factor is a constant value between 0 and 1, i.e. $0 \leq \mu \leq 1$. Any machining methods, even UVC possibly lead to chatter vibration which is termed regenerative chatter when $\mu \neq 0$. The overlap factor is principally affected by the tool nose radius and side cutting edge angle. For the certain side cutting edge angle, under conventional cutting condition, simulations have shown that the smaller nose radius has the smaller the overlap factor. A slightly increase of the nose radius size makes the machining accuracy worse due to the occurrence of regenerative chatter. So, when the nose radius is kept as small as possible, regenerative chatter can be alleviated. In contrast, simulations show that regenerative chatter is suppressed by UCV even when $\mu = 1$. Therefore it is possible for UVC to use a large tool nose radius to resolve the two problems—the occurrence of regenerative chatter of difficult-to-cut materials and the decline of the strength of tool edge. At the same time, turning tests two hard metals were performed on conventional cutting and ultrasonic vibration cutting with different sizes of tool nose radius. The experimental results showed that under ultrasonic vibration cutting condition when tool nose radius is equal to 0.2mm, the surface roughness attains an approximate value $R_y \approx 4.7\mu\text{m}$, which is closed to the value of $4.3\mu\text{m}$. As a result, a suitable tool nose radius prevents the tool fracturing occurrence so that the instability of the machining process is markedly reduced.

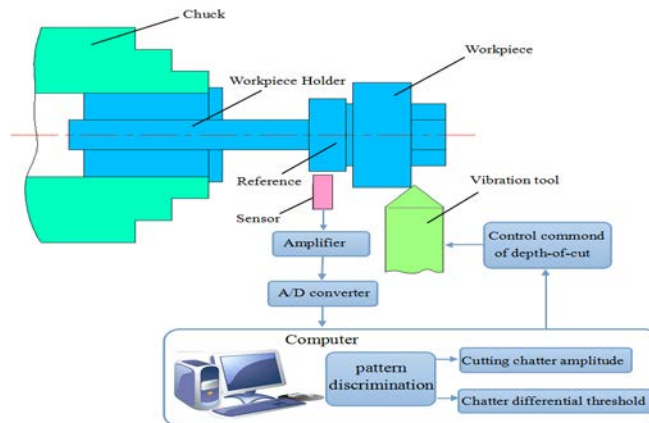


Fig.1 Online monitoring system diagram

3. Making use of online monitoring technology to improve the tool life and reduce tool wear by applying UVC

The authors presented a chatter monitoring and signal processing system for turning a slender workpiece by applying UVC. The work displacement was obtained from vibration signals which were online monitored between tool and the workpiece. Thus, cutting parameters can be adjusted in time according to the feedback. Firstly, we introduce the theoretical basis for this machining method and then, correctness of the theoretical analysis need be proved by the test. In the process of metal machining, with the increase of cutting time, tool nose radius will constantly change in the usual wear situation. The influence of two different sizes of tool nose radius on regenerative effect and cutting forces was shown in Fig.2. Fig. 2 (a) shows smaller nose radius of the new or redressing cutting tool. In a small nose radius, the maximum cutting edge angle (C_s) and the side cutting angle (K_r) are of equal value and the amount of component forces is determined by the side cutting angle (K_r). Fig. 2 (b) shows the larger nose radius after wears. The maximum cutting edge angle (C_s) is determined by the following formula:

$$C_s = \arccos \frac{r - t_m}{r} \quad (1)$$

In the formula(1), r is on behalf of the sizes of tool nose radius. When the cutting depth (t_m) is 0.05mm with tool nose radius increasing from 0.2 to 1mm, The maximum cutting edge angle (C_s) decreases from $41^\circ 25'$ to $18^\circ 12'$. Though the larger nose radius can improve the heat radiation of the tool, strengthen the tool intensity and reduce the surface roughness, thrust force (F_t) in the radius direction will rapidly increases with larger cutting deformation. As a result, the system may lose machining stability, and it is easy to exert regenerative chatter. Finally, the tool life is reduced.

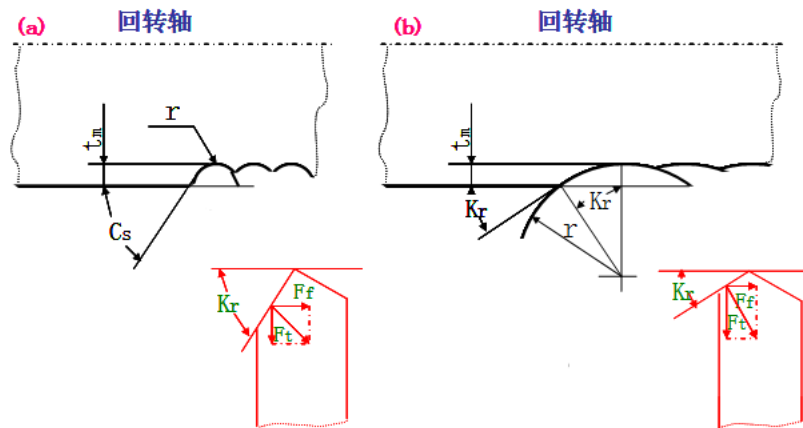


Fig.2 Influence of tool nose radius on the regenerative effect and cutting forces

The formula above shows that tool nose radius has effect on thrust force (F_t) through a specified range of the cutting depth. If the cutting depth relative to tool nose radius is a smaller value, which significantly affects the thrust force, the effect of tool nose radius on cutting forces and chatter is not negligible with increasing nose radius size[4]. Theoretic analysis and experimental results in the previous section indicate that it is possible for UVC to use a large tool nose radius compared with the conventional cutting methods. A suitable tool nose radius can not only improve stability of the machining process, but obtain higher accuracy machined surface. But, in the process of metal machining, with the increase of cutting time, tool nose radius will constantly enlarge due to tool wears. Vibration amplitude between a tool and the workpiece will also enlarge as thrust force continuously amplifies. When the nose radius reaches a certain value, even using the ultrasonic vibration cutting method of high machining stability, chatter will still occur. When the turning process grows from stable to unstable state, the amplitude of cutting vibration or the machining accuracy is gradually changed from a small value to a large one. Once the amplitude of cutting vibration exceeds 10~15 μm , chatter is likely to occur.

It is preliminarily concluded that cutting vibration between a tool and the workpiece will become smaller if the workpiece is turned in the whole process with a suitably larger nose radius value. It is possible to obtain a surface with a machining accuracy of $R_y = 4.3\mu\text{m}$.

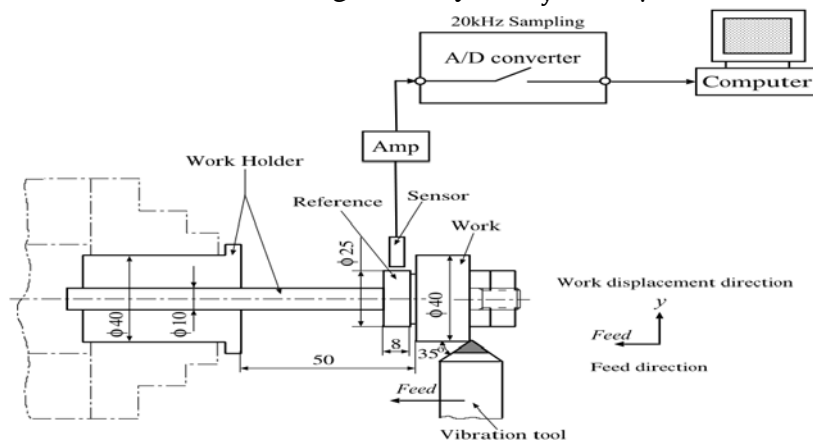


Fig.3 A chatter monitoring and signal processing system for turning a slender workpiece by applying UVC

The work displacement in the y direction is measured, compared with a critical value in real-time, and cutting parameters is adjusted rapidly in the process of ultrasonic vibration cutting as shown in Fig.3. Vibration signals are acquired periodically by a contactless electric capacitance transducer. Then calculate their amplitude of vibration signals and perform signal-processing on the input signals. By comparing the critical value based on predicted amplitude of vibration ($R_y = 4.3\mu\text{m}$), the system automatically adjusts the cutting depth in order to control or suppress cutting chatter. The real-time

adjustment can avoid overlage nose radius size caused by tool wears. Through this approach, the amplitude of vibration and thrust force are decreased and tool life is lengthened as long as possible. With signal-processing time short, controllers simple and response speed fast, the novel method also possesses precautions and suppression of occurrence of chatter.

The authors have performed experiments on difficult-to-cut materials of stainless steel SUS304 and nickelbase alloy of Incone1600. The following conclusions were obtained as shown Fig.4. A stable and precise surface finish is achieved by using the suitably large nose radius of 0.2mm in a large range of cutting length. In addition, the cutting tool life enhances greatly. However, the instability of the machining accuracy with an initial nose radius of 0.02mm appears at a short cutting length, which, to a certain extent, affects tool life. When employing the novel machining method of online monitoring vibration signals and adjusting cutting parameters in real time, there is no occurrence of chatter and the machining accuracy ($R_y \approx 5\mu\text{m}$) is close to predicted amplitude of vibration ($R_y = 4.3\mu\text{m}$) during the whole cutting process. At the same time, the tool life improves to the maximum extent.

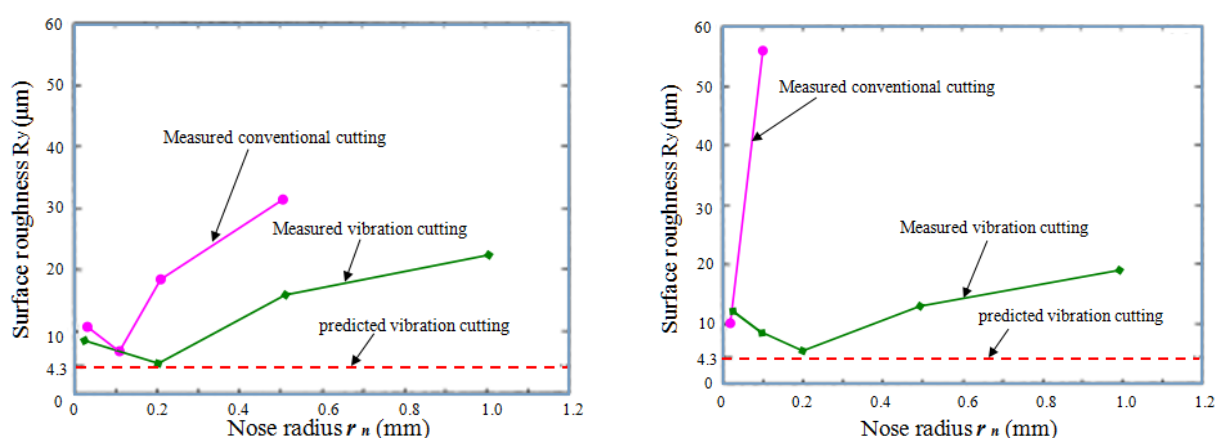


Fig.4 Comparison between predicted and experiment surface roughness R_y versus nose radius, (a) for stainless steel of SUS304, (b) for nickelbase alloy of Incone1600

4. Conclusions

The authors presented a novel vibration cutting method of online monitoring vibration signals and adjusting cutting parameters in real time after a series of theoretical and experimental analysis. With signal-processing time short, controllers simple and response speed fast, the novel method also possesses precautions and suppression of occurrence of chatter. Through the online monitoring technique, the amplitude of the cutting vibration signal is maintained at a smaller one so that damage and worn effect of tools is insignificant and occurrence of larger vibration is prevented. The mentioned online monitoring technique has achieved such a goal of suppressing occurrence of chatter, increasing tool life to the maximum extent, and obtaining accurate surface machined profile.

5. References

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