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Progress and Prospect of Ultrasonic Vibratory Cutting Research

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Ultrasonic vibration cutting technology for processing difficult-to-cut materials proposed a new machining method to improve the cutting performance, is an effective measure to improve the surface quality and cutting efficiency, widely used in titanium alloys and other difficult-to-cut materials. This paper is based on the development of related technology research at home and abroad, first from one-dimensional ultrasonic vibration cutting, two-dimensional ultrasonic vibration cutting, three-dimensional ultrasonic vibration cutting three dimensions to high-speed ultrasonic vibration cutting to carry out the analysis, and then from each dimension of turning, drilling, grinding and milling and other different ways of cutting mechanism, cutting force, surface quality, device development, tool design and other directions of the systematic analysis and research. The analysis results show that ultrasonic vibration cutting technology provides new technical solutions and methods to solve the problems of low efficiency and low dimensional accuracy in processing difficult-to-cut materials by ordinary cutting technology, and can provide technical support for the processing of difficult-to-cut materials. Finally, it looks forward to the future trend of ultrasonic vibration cutting technology: in the future, the integration with five-axis machining technology, additive manufacturing technology, microscopic inspection technology, 5G communication technology and other cutting-edge technologies will be the development direction of ultrasonic vibration cutting technology.

Keywords: ultrasonic vibration; cutting; cutting force; surface quality; devices and tools

1 Introduction

The dimensional accuracy required for the machining of parts in the above industries is increasing, and the high cutting forces, high cutting temperatures, and severe cutting vibrations generated during the machining process to improve the accuracy have resulted in a significant reduction in the cutting efficiency and accuracy of conventional cutting [1]. As a result, it is difficult to produce parts of hard-to-cut materials with high efficiency and quality, and ultrasonic vibratory cutting (UVC) technology proposes a new machining method for machining hard-to-cut materials.

The vibratory cutting method have proposed in the middle of the twentieth century laid the cornerstone of vibratory cutting theory, on which subsequent researchers realized different processes such as vibration turning, vibration drilling, and vibration milling to form the vibratory cutting theory. The principle of UVC is to apply the force of ultrasonic vibration to the tool of ordinary cutting for intermittent cutting, which is a new technology formed by integrating traditional cutting into ultrasonic technology, especially suitable for hard-to-cut materials. Unlike conventional cutting, this technology applies high-frequency, small-amplitude vibration to the tool to achieve high-precision motion control and intermittent cutting, and the continuously varying displacements between the tool, the workpiece, and the chips lead to an increase in coolant arrivals, which effectively improves cooling and lubrication, and improves tool life. Ultrasonic vibratory cutting is an unconventional machining method, this technique applies ultrasonic vibration to the tool or workpiece along the cutting direction, thus continuously changing the cutting speed and the direction of tool motion.

2 One-dimensional ultrasonic vibratory cutting

Some scholars have proposed the vibration cutting method, in the direction of the cutting speed of the ordinary cutting tool to apply ultrasonic vibration, when the speed of the ultrasonic vibration exceeds the cutting speed, because only in the direction of the cutting speed of the cutting tool to impose vibration, it is also called one-dimensional ultrasonic vibration cutting, as shown in Fig. 1.

The research on one-dimensional ultrasonic vibratory cutting mainly focuses on cutting force, cutting temperature, cutting tool and surface quality. In terms of cutting force, some scholars have developed ultrasonic vibration cutting experiments and simulation studies on titanium alloys. The research shows that ultrasonic vibration ultrasonic vibration cutting reduces cutting force and cutting temperature.

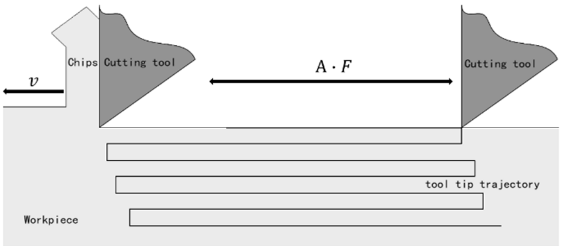


Fig. 1 *One-dimensional ultrasonic vibration cutting*

In terms of cutting tools, Some scholars have analyzed the effect of the radius of the tip fillet on the chatter during ultrasonic vibratory turning, and the results showed that high-pressure polyethylene rake is beneficial to suppress the chatter and increase cutting tool life.

In terms of surface quality, Some scholars have conducted ultrasonic vibratory cutting experiments on titanium alloy, and the experiment shows that compared to conventional turning this method could lower the cutting force and get higher surface quality.

Scholars at home and abroad have studied one-dimensional ultrasonic vibratory cutting. In the ultrasonic vibration milling and ultrasonic vibration drilling research also reached a similar conclusion, effectively reducing the milling force and drilling force.

3 Two-dimensional ultrasonic vibration cutting

One-dimensional ultrasonic vibratory cutting has advantages in cutting titanium alloys and composites. But when it comes to the high-precision cutting of such materials is still insufficient, easily destroys the quality of the processed surface, easy to causes cutting tool chipping and other problems, and can't guarantee the processing accuracy of the final parts. Therefore, some scholars have proposed a two-dimensional ultrasonic cutting technology.

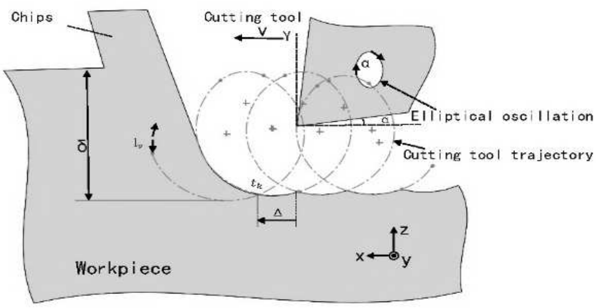


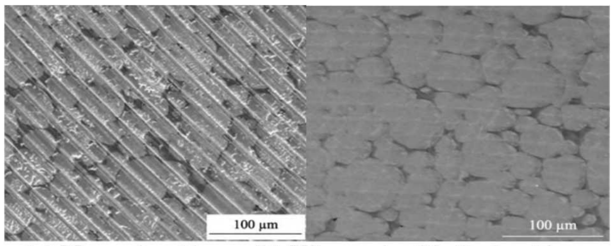
Fig. 2 *Two-dimensional vibration cutting diagram*

3.1 Two-dimensional ultrasonic vibration cutting/turning

In order to solve the one-dimensional ultrasonic vibratory cutting is easy to damage the surface quality of the machined parts and the cutting tool is easy to collapse blade or other shortcomings. E.shamoto et. [2] proposed the cutting speed and depth of cut in two directions of ultrasonic vibration applied to the two-dimensional vibration cutting technology, because its tool trajectory is elliptical, also known as elliptical vibration cutting technology, as shown in Fig. 2. In cutting difficult-to-machine materials Fig. 2. When better than one-dimensional ultrasonic vibration performance, improves the surface quality while reducing cutting tool wear, was quickly applied to turning and other fields, and scholars have carried out experimental research from the cutting force, surface quality, roughness and so on.

In terms of surface roughness, it is developing two-dimensional ultrasonic vibratory cutting experiments on tungsten alloys using a diamond cutting tool, which resulted in lower roughness and improved surface quality when compared with normal cutting, as shown in Fig. 3.

In terms of surface quality, Some scholars have showed that two-dimensional ultrasonic vibration cutting aluminum at a frequency of 18.86 KHz, the edge burr of the workpiece was improved and the surface quality rose.



(a) Normal cutting (b) Ultrasonic elliptical cutting

Fig. 3 *Comparison of surface topography between normal cutting and ultrasonic elliptical vibratory cutting*

Scholars at home and abroad have studied two-dimensional vibratory cutting from different directions such as cutting force etc. The study shows that two-dimensional ultrasonic vibratory cutting can better inhibit the generation of machining surface burrs, improve the surface quality, and obtain nanometer accuracy in precision machining and good durability of the knife.

3.2 2-dimensional ultrasonic vibratory drilling

Drilling is the most commonly used process in manufacturing, but the design of the drill is limited by the length-to-diameter ratio, which restricts the drilling diameter and depth. The introduction of ultrasonic vibration assistance to reduce the axial thrust in the drilling operation can improve the aspect ratio and enhance the conventional drilling capability. It has aroused many scholars to pay attention to ultrasonic vibratory drilling, and carried out research on two-dimensional ultrasonic vibratory drilling in terms of the chip formation mechanism, drilling force and surface quality.

In terms of the chip formation mechanism of ultrasonic vibratory drilling, Some scholars have used ultrasonic vibratory drilling in Ti64 micro-drilling experiments, and compared with ordinary drilling found that the morphology of the chips was improved and became more broken and smaller. In addition, the drilling force decreased and the surface quality was higher.

In terms of drilling force, Some scholars have found experimentally that the drilling force and surface roughness during deep hole drilling of CrNiFe alloys were reduced, cutting tool life increased, thrust decreased by 40%, and machining time reduced by 90%.

In terms of surface quality, Jia D et al. [3] conducted a study on two-dimensional ultrasonic vibratory reaming, which showed that ultrasonic elliptical vibratory-assisted reaming significantly improved the quality and roughness of homemaking compared with conventional reaming.

Scholars at home and abroad have studied two-dimensional ultrasonic vibratory drilling from the formation mechanism of drilling chips, drilling force, surface quality, etc. The study shows that due to the intermittent contact, the drilling temperature is lower, reducing the edge buildup, reducing the exit delamination defects, and forming a smooth surface. Secondly, the presence of axial vibration in ultrasonic vibration-assisted drilling also promotes drilling, resulting in a smoother surface.

3.3 Two-dimensional ultrasonic vibration grinding

Conventional grinding processes usually produce large grinding forces and extremely high temperatures. In contrast, ultrasonic vibratory grinding is a hybrid grinding process, where the reduction of grinding force and the improvement of surface quality give it a great advantage in the grinding of difficult-to-cut materials such as titanium alloys. The force reduction rate is introduced to assess the impact of ultrasonic vibrations. Equation 1 illustrates its expression.

$$P_F = \frac{F_C - F_U}{F_C} \times 100\% \qquad (1)$$

Among them,Fc and Fu are grinding forces in CG and UVAG respectively.

In terms of processing parameters, some scholars have shown that vertical ultrasonic vibration is significantly higher than the axial direction for reducing cutting force. In terms of vibration form, some scholars have showed that after 100 minutes of cutting, the normal and tangential grinding forces at a speed ratio of 0.1 are reduced by about 19 and 17 %, respectively, compared with the speed ratio of 0.8.

Scholars' research shows that compared with traditional grinding, the grinding force of two-dimensional ultrasonic elliptical vibration is significantly reduced, and the generated compressive residual stress is helpful to prevent surface crack propagation in the oxidation process, improve surface integrity, improve surface adhesion and peeling, and reduce defects such as burrs.

3.4 Two-dimensional ultrasonic vibration milling

Due to the limitation that ultrasonic vibration assisted grinding can only effectively process circular holes, Amini S et al.[4] have proposed ultrasonic vibration milling is an upgraded version of traditional milling, which reduces the cutting heat of traditional milling and its adverse effects on the surface of the workpiece and cutting tool life. Scholars have begun to study UVAM from the directions of milling force, vibration mode, surface quality and so on.

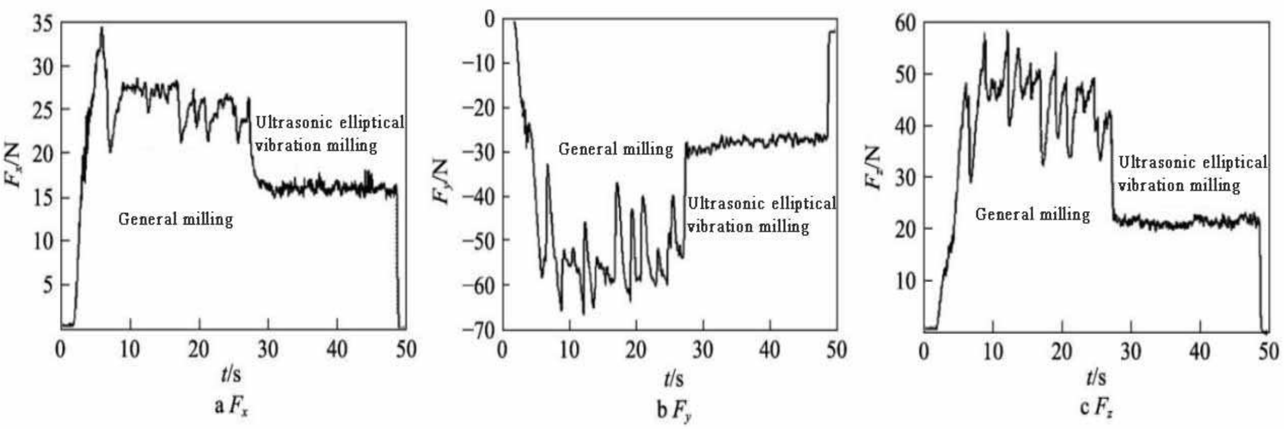


Fig. 4 *Comparison of milling forces between normal milling and ultrasonic vibration milling*

In terms of milling force, Some scholars have introduced two-dimensional ultrasonic vibration to conduct milling experiments on titanium alloy workpieces, as shown in Fig. 4. The research shows that two-dimensional ultrasonic vibration achieves a certain degree of high linear speed, which in turn reduces the milling force by 50%. In terms of vibration modes, Some scholars have studied the cutting force waveform characteristics of two unidirectional vibration modes,this series of studies revealed the effects of parameters related to vibration and machining processes, such as vibration direction, amplitude, and cutting parameters.

In terms of surface quality, Yang ZC et al. [5] used two-dimensional ultrasonic vibration milling to test the mirror surface, and the surface quality obtained was good. Domestic and foreign scholars have studied two-dimensional ultrasonic vibration milling from three directions of milling force, vibration mode and surface quality. The research shows that two-dimensional ultrasonic vibration milling has better surface quality, milling force and milling temperature are also significantly reduced, the surface quality of the workpiece is improved, the vibration mode also reduces the surface roughness.

4 Three-dimensional ultrasonic vibration cutting

At present, due to the good cutting performance of two-dimensional ultrasonic vibration cutting, it has been applied in ultra-precision manufacturing industries such as mold industrial production. The cutting performance of three-dimensional ultrasonic vibration cutting is better than that of two-dimensional ultrasonic elliptical vibration cutting, which has attracted more attention. Some scholars have begun to study turning, milling and grinding, but it is still in the preliminary exploration stage.

4.1 Three-dimensional ultrasonic vibration cutting/turning

Some scholars have established a three-dimensional ultrasonic vibration cutting model. Various types of vibration cutting (a) orthogonal type; (b) Oblique type; (c) intermediate type; (d) with inclination, as shown in Fig. 5.

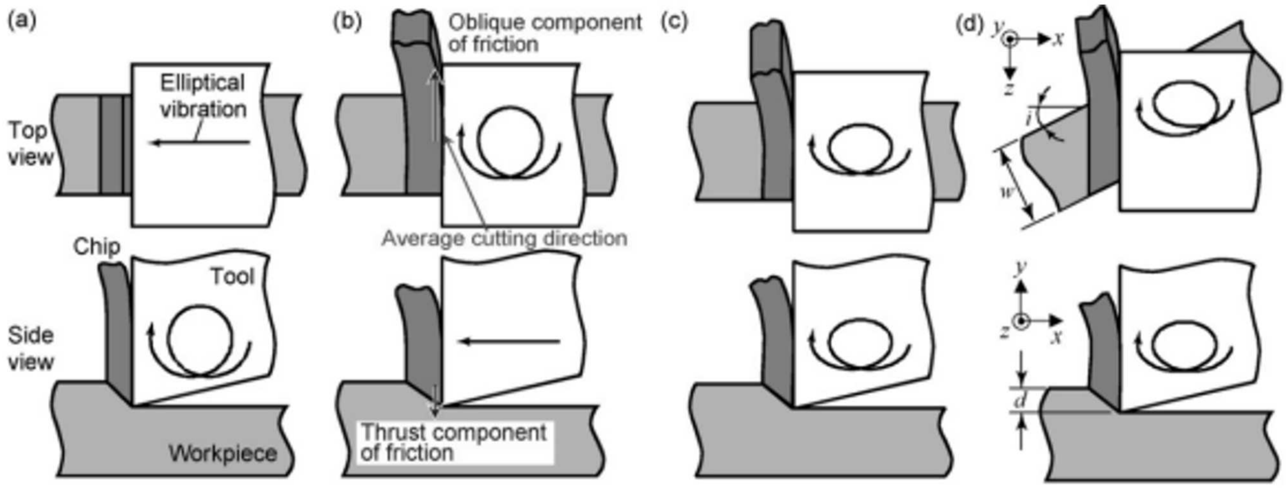


***Fig. 5** (a) orthogonal type; (b) oblique type; (c) intermediate type; (d) with inclination*

There are three kinds of ultrasonic vibration modes in three-dimensional ultrasonic vibration cutting, namely, one-dimensional (LVT), two-dimensional elliptical (2DEVT) and three-dimensional elliptical (3DEVT). The effects of ultrasonic vibration on the tribological properties of the machined surface in ultrasonic vibration assisted turning (UVAT). Bhaduri D et al. [6] conducted experimental research on three vibration modes. The results show that compared with ordinary turning surface, the micro-dimple surface produced by UVAT method can reduce the average friction coefficient, and the maximum reduction is 13, 18, and 21%.

The research shows that three-dimensional ultrasonic vibration cutting technology can improve the surface integrity and roughness, surface tribological properties and wettability when cutting difficult-to-machine materials, and the cutting performance is better than two-dimensional ultrasonic vibration cutting.

4.2 Three-dimensional ultrasonic vibration milling

Nic vibration milling has also carried out related experiments and research. In terms of milling force, Some scholars have first proposed and successfully applied three-dimensional elliptical ultrasonic vibration and horizontal ultrasonic vibration to rotary ultrasonic surface machining (RUSM). The machining performance and surface quality of three-dimensional elliptical ultrasonic vibration, horizontal ultrasonic vibration and non-ultrasonic vibration surface machining were compared.

In terms of surface quality, compared with ordinary turning, ultrasonic vibration can obtain higher microhardness, more uniform surface texture and 6μm grain size. Scholars of three-dimensional ultrasonic vibration milling research is mainly from the cutting force and surface quality of the 2 aspects, the study shows that three-dimensional elliptical ultrasonic vibration can be in the two-dimensional ultrasonic vibration cutting on the basis of further reduction of the cutting force and surface roughness, to obtain a higher quality of the surface of the workpiece.

4.3 Three-dimensional ultrasonic vibration grinding

Three-dimensional ultrasonic vibration grinding (UVAG) is a composite process that combines three-dimensional ultrasonic vibration with grinding wheel dressing during electrolysis to achieve high-efficiency precision machining. In terms of grinding force, because ultrasonic vibration is introduced in three mutually perpendicular directions, the impact force is similar to the larger instantaneous force, which increases the grinding effect, that is, normal, tangential and axial impact. Therefore, the grinding force can be expressed by Equation 2:

$$\begin{cases} F_n = F_{nc} + F_{nf} + F_{nu} \\ F_t = F_{tc} + F_{tf} + F_{tu} \\ F_a = F_{au} \end{cases} \quad (2)$$

Among them, Fnc is the normal force generated by grinding deformation; Fnf is the normal force generated by friction; Fnu is the normal force generated by ultrasonic vibration; Ftc is the tangential force generated by grinding deformation, and Ftf is the tangential force generated by friction. Ftu is the tangential force generated by ultrasonic vibration; Fau is the axial force generated by ultrasonic vibration.

In the study of grinding force model, some scholars have established a three-dimensional ultrasonic vibration grinding force model based on the kinematics of a single sand particle, and compared it through experiments.The research shows that the three-dimensional ultrasonic vibration grinding force is 20~30% lower than the two-dimensional ultrasonic vibration grinding force.

Scholars have studied the three-dimensional ultrasonic vibration grinding technology from the aspects of grinding force, calculation model and surface quality. Experiments and research show that the three-dimensional ultrasonic vibration grinding force is 20~30% lower than the two-dimensional ultrasonic vibration, and the surface roughness is 40~50% lower, which can obtain better surface quality.

5 High-speed ultrasonic vibration cutting

Ultrasonic vibration cutting has made great progress in one-dimensional and two-dimensional, and has been applied in various fields. Three-dimensional is still in the exploratory stage. Ordinary ultrasonic vibration cutting (UVC) is a low-speed cutting method, and its advantages will gradually disappear due to the increase of cutting speed. In order to overcome the critical cutting speed limit related to traditional ultrasonic vibration cutting technology, Some scholars have proposed namely high-speed ultrasonic vibration cutting (HUVC),as shown in Fig. 6, from the direction parallel to the cutting direction to the direction parallel to the feed direction, perpendicular to the direction of cutting speed.

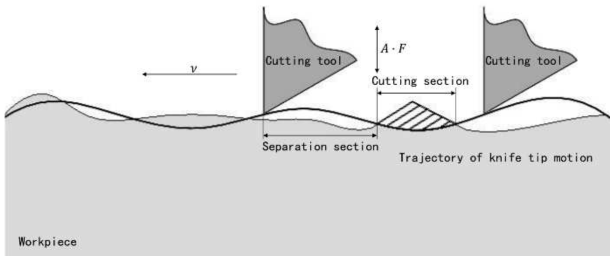


Fig. 6 *Schematic diagram of high-speed vibratory cutting*

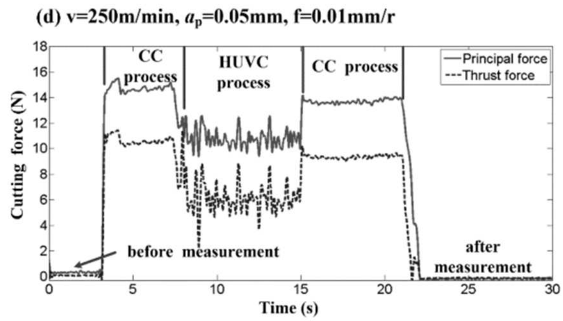


Fig. 7 *Main and thrust forces for different conditions of HUVC and CC*

High-speed ultrasonic vibration cutting (HUVC) is considered to be an effective and successful unconventional cutting process. It has its unique advantages, such as lower cutting force and cutting temperature, longer cutting tool life, better stability and chip breaking effect during cutting, and improved cutting performance. In terms of cutting force, some scholars have carried out high-speed ultrasonic vibration milling research on composite materials. The research shows that when the milling parameters are the same, the introduction of the increase of ultrasonic vibration dimension will gradually reduce the cutting force, as shown in Fig. 7.

In terms of cutting temperature, Some scholars have shown that cutting Ti-6Al-4V at high cutting speeds (200-400 m / min) can extend the cutting tool life by 6.3 times and reduce the cutting temperature by up to 55%. In terms of the machinability of the cutting tool, some improvements can be made by reducing the cutting temperature and increasing the temperature resistance. Some scholars have used the tool-workpiece separation effect to reduce the cutting temperature to a maximum of 30 % compared to conventional cutting (CC). The focus of HUVC's application in titanium alloys is to improve the processing performance. The performance comparison evaluation of HUVC and CC is shown in Tab. 1.

Tab. 1 *Performance changes of HUV compared to CC*

Machinability	Change	Stability	Change	Surface integrity	Variation
Cutting force	Decrease	System energy	Decrease	Surface roughness	Decrease
Cutting temperature	Decrease	Critical cutting thickness	Rising	Deformation layer thickness	Rise
cutting tool life	Rise	Machining accuracy	Increase	Surface micro-hardness	Increase
Material removal rate	Increase	Chatter stability	Rise	Compressive Residual Stress	Rise

In terms of separation characteristics, C. Zhang et al. *[7]* theoretically analyzed and by experimentally verified the influence of side interference and cutting tool wear on the separation process, focusing on the partial separation state caused by side interference. In terms of cutting tool wear influencing factors, under the traditional cooling method, the cutting tool wear of HUVC with the same cutting speed is lower, and the cutting tool life can be extended to three times that of CC, as shown in Fig. 8.

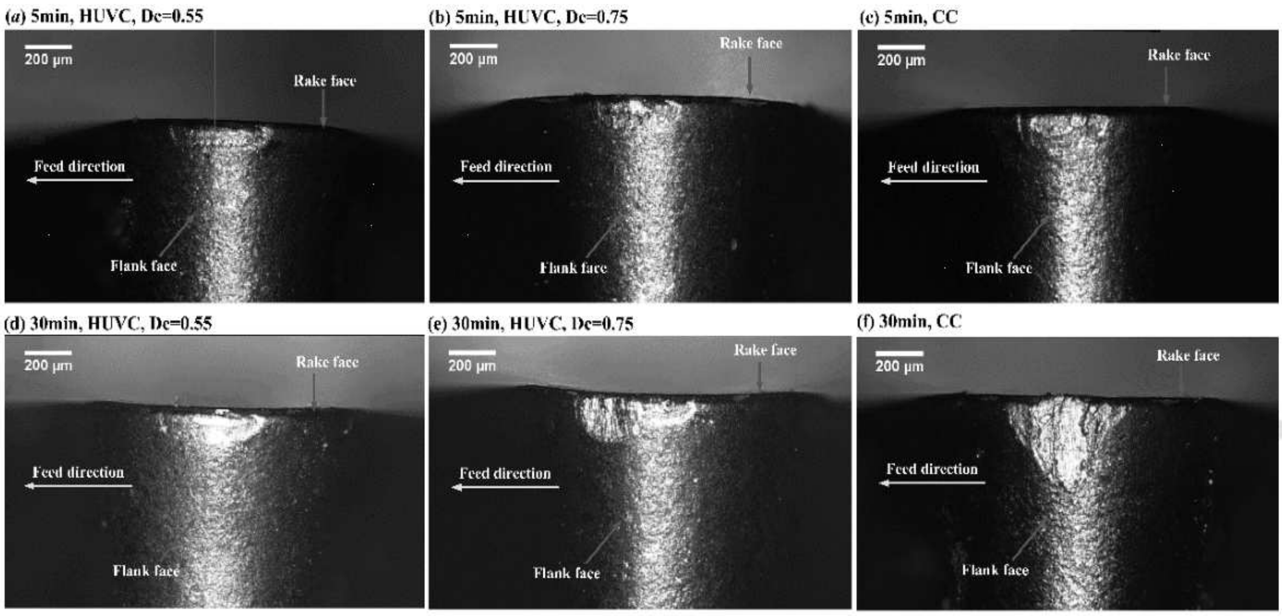


Fig. 8 *Comparison of HUVC and CC cutting tool wear*

In terms of surface integrity, Jiang Xinggang et al. [7] have designed a phase difference control system for high-speed ultrasonic vibratory cutting, with the assistance of which a surface roughness of less than 0.4 μm was obtained. Domestic and foreign scholars have studied high-speed ultrasonic vibratory cutting in terms of cutting force, cutting temperature, cutting tool machining performance and surface integrity, the focus of the research can be summarized as(1) improved machinability, (2) improved process stability, and (3) improved surface integrity. HUVC breaks through the original critical speed limitations, increasing the cutting speed from the original 40 m/min to 200-400m/min, which significantly improves the cutting efficiency.

Tab. 2 *Main research directions and progress of ultrasonic vibration cutting*

Dimension	Cutting mode	Research direction	Specific content	Conclusion
One-dimensional ultrasonic vibratory cutting	Turning/Cutting	Cutting Mechanism	Chip Breaking Cutting	Low cutting forces, high cutting quality
		Cutting force	Compared to conventional turning	Significant reduction of cutting forces
		Cutting temperature	Cutting temperature simulation analysis	Cutting Temperature Significantly Reduced
		Cutting tools	New type of bevel cutting	Surface quality and cutting tool life increase
		Cutting tool wear	Turning wear experiment	Reduced cutting tool wear and increased cutting tool life
		Surface quality	Turning experiments, model analysis	Significant improvement in surface quality
	Milling	Milling experiment	Compared with traditional milling	Less cutting force
	Drilling	Drilling experiment	Finite element model	Significant reduction in drilling force
Two-dimensional ultrasonic vibration cutting	Turning/Cutting	Cutting mechanism	Elliptical cutting	Improved surface quality and reduced cutting tool wear
		Cutting force	Cutting force experiment	Reduction of tangential and radial components of cutting force by 70-75% and 71-88%, respectively.
			Cutting force modeling	Reduced deformation, significant reduction in cutting forces, slight increase in temperature
		Surface roughness	Comparison with normal cutting	Lower surface roughness
		Surface quality	Alloy precision cutting	Reduced burrs, lower roughness, higher surface quality, and
	Drilling	Chip formation mechanism	Compared to conventional drilling	Significantly lower drilling forces, better surface finish
		Drilling force	Drilling test	Reduced cutting forces
		Vibration amplitude	Influence of vibration amplitude on cutting force	After a certain limit, the amplitude is detrimental to the drilling performance.
		Surface quality	Ultrasonic vibration drilling experiment	Reduced drilling forces and improved surface quality
	Grinding	Grinding mechanism	Hybrid process	Reduced grinding forces and improved surface quality
		Grinding forces	Comparison of simulation and experiment	40.5% and 38.7% reduction in grinding force and grinding heat, respectively
		Machining parameters	Vibration parameters	Vertical vibration has a higher impact on cutting forces
		Type of vibration	Rotary vibration	Reduced grinding force, slower wear
		Surface quality	Compared to conventional grinding	Significant improvement of adhesion and peeling on the machined surface
	Milling	Milling mechanism	Upgrading of conventional milling	Reduction of the negative effects of conventional milling
		Milling forces	Effect of cutting speed	Cutting forces reduced by more than 70%
		Vibration modes	Vibration in the feed direction and perpendicular to the cutting tool	Cutting forces in the feed direction represent impulse cutting characteristics, micro-amplitudes in the perpendicular direction improve surface roughness.
		Surface quality	Mirror milling test	Obtaining better surface quality
3D ultrasonic vibratory cutting	Turning/Cutting	Cutting Mechanism	Cutting Model	3D UVC cutting performance is better
		Cutting force	Friction	Cutting forces are further reduced
		Vibration Modes	1D, 2D-elliptical and 3D-elliptical	Improved surface quality, smaller defects
		Surface Quality	Compared to conventional boring	Typical feed marks are virtually eliminated
	Milling	Milling force	3D ultrasonic, horizontal ultrasonic	Further reduction of cutting forces
		Surface quality	Impact of surface integrity	Obtaining a more uniform surface texture
	Grinding	Grinding force	Grinding force calculation	Grinding force 37.64% lower than conventional
			Magic Grinding Force Modeling	Three-dimensional grinding is about 20% to 30% lower than two-dimensional grinding force
		Surface quality	Surface roughness	Surface roughness reduction of up to 10%
High-speed ultrasonic vibratory cutting	Cutting	Cutting Mechanism	Unconventional cutting process	Improved cutting performance and efficiency
		Cutting force	Comparative pilot study	20-40% reduction in cutting forces
		Cutting temperature	High cutting speeds	Up to 55% reduction in cutting temperature
		Cutting tool machinability	Compared to conventional cutting	2.5 times longer cutting tool life compared to CC
		Separation characteristics	Separation process	Further analysis of the separation state of the lateral interference section
		Cutting tool wear	Cutting tool wear	Extension of cutting tool life by a factor of 3-7.3
		Cooling method	High-pressure cooling/coolant	Improved surface quality, increased cutting tool life
		Surface Integrity	Versus conventional cutting	HUVC improves surface roughness and topography

6 Ultrasonic vibration cutting device and cutting tool

In ultrasonic vibratory machining, the study of cutting devices and cutting tools has always been one of the hot spots of experimental research.

6.1 Two-dimensional vibration cutting device

Since the first generation of ultrasonic mechanical tools in the 1950s, various types of ultrasonic machining devices have appeared. In terms of cutting device design, Some scholars have designed a dual longitudinal ultrasonic vibratory cutting device, as shown in Fig. 9, and carried out modal and harmonic response analyses to verify the reasonableness of the structure, and the results show that the system can synthesize ultrasonic elliptical trajectories, trajectory is regulated by the phase difference of the excitation signal.

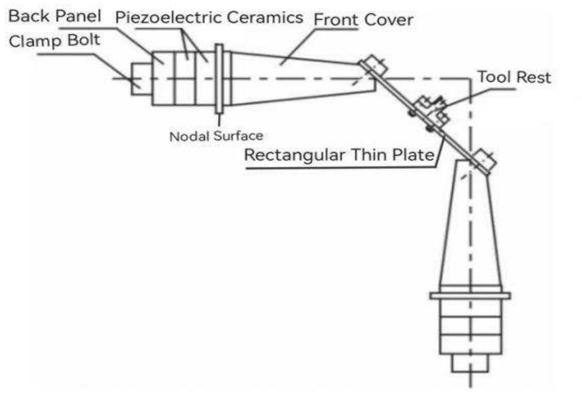


Fig. 9 *Double longitudinal and the shape of the ultrasonic vibration cutting device*

Two-dimensional ultrasonic machining device is mainly divided into two-dimensional vibration device and two-dimensional vibration system, both of the respective development of ultrasonic vibration device and system were experimented, and the experimental data show that the use of vibration device can make the cutting tool wear and roughness decrease, improve surface quality, and extend the service life of the cutting tool.

6.2 Three-dimensional vibratory cutting platform

Based on the research of 2D ultrasonic vibration device, Kim G D et al. [8] proposed a 3D ultrasonic vibration device to apply vibration to the tool in both directions of cutting speed and depth of cut, and feed along the surface of the 3D workpiece to carry out 3D carving experiments. The 3D vibration device can generate arbitrary elliptical motion in space compared to the 2D vibration device.

In terms of cutting platform design, some scholars have proposed an innovative decoupled three-dimensional ultrasonic vibration-assisted cutting (EVC) mechanism and developed a finite element model to simulate and analyze its kinematics and amplification. Experiments show that the performance of the developed 3D ultrasonic EVC mechanism meets the requirements, as shown in Fig. 10.

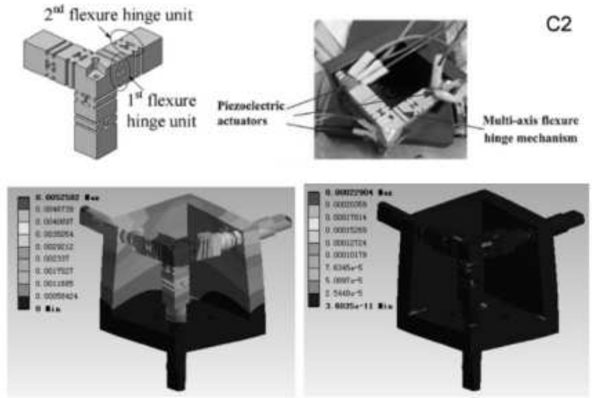


Fig. 10 *3D ultrasonic vibration cutting mechanism*

In terms of cutting system design, some scholars have proposed a control method based on the function and control law of fuzzy sliding mode control for the developed 3D vibratory cutting device, and the experiments show that the robustness of the cutting system is relatively strong using this control method.

Domestic and foreign scholars have proposed a variety of three-dimensional elliptical vibration auxiliary systems, through the experiments show that the performance of the designed device to meet the requirements of the proposed control strategy experiments show that the surface quality of the processed workpiece is good.

However, the current ultrasonic devices, systems and platforms are still lack of practicality and low efficiency, which is the main obstacle to the popularization and application of ultrasonic vibration cutting technology. In the future, with the continuous development and improvement of ultrasonic machining technology and equipment, ultrasonic vibration cutting technology can be widely used in equipment manufacturing, which is important for precision machining.

6.3 Ultrasonic vibration cutting tool

In order to promote and popularize the application of UVC technology, many researchers have also carried out experimental research on the cutting tools used in ultrasonic vibration machining. In terms of cutting simulation, Some scholars have used two-dimensional UVC technology to carry out cutting simulation experiments on TC4 titanium alloy, cutting force is lower, cutting deformation coefficient is also lower, but the cutting temperature has been slightly increased.

In terms of cutting tool geometry parameters, Some scholars have discussed the effect of cutting tool geometry parameters such as cutting edge, nose radius and front angle on the cutting tool chatter process, and found that a proper nose radius is conducive to obtaining excellent surface quality during milling, but too large a nose radius will lead to chatter, while a large front angle is conducive to suppressing chatter.

In terms of machining quality, Kim G.D.et al. [8] carried out a study on the cutting characteristics of two-dimensional ultrasonic vibration of diamond cutting tools and found that the ultrasonic vibration cutting force was significantly reduced, and although the burrs were much shallower than those of conventional diamond cutting, they still existed in the bottom and edge regions of the machined surface.

In terms of cutting tool wear, Some scholars have carried out ultrasonic vibration cutting experiments using alloy cutting tools, and the experiments showed that the main type of wear is abrasive wear, and compared with ordinary cutting abrasive wear and bonded wear is lower, and the cutting tool wear is effectively reduced to prolong the service life. The results show that: in the case of the same amount of cutting tool wear, elliptical vibratory cutting force, cutting temperature slope of the curve is greater than 0 and is smaller than the ordinary cutting, the cutting tool life is longer.

In terms of cutting tool design, G.L. Chern et al. [9] designed and fabricated a boring cutting tool capable of generating linear ultrasound. By comparing with the conventional boring process, this ultrasonic cutting tool can reduce surface roughness and burr formation.

In terms of cutting tool system design, Zhang Yundian et al. [10] designed a new and efficient ultrasonic vibratory turning system, and the experiments showed that this system is stable and reliable, and has met the conditions for industrial applications.

Scholars from various countries have studied the theoretical study of ultrasonic vibration cutting tools, geometric parameters, machining quality, cutting tool design and cutting tool system, etc. In ultrasonic vibration cutting with the selection of suitable machining tools, the cutting force will be significantly reduced, the rate of cutting tool wear in the cutting process will be delayed, the surface roughness and burr formation will be reduced, and the surface quality will be improved.

According to the research literature at home and abroad, the theoretical study of ultrasonic vibration cutting machining tools, cutting tool design, tool machining quality and cutting tool systems and other major research directions and research conclusions are summarized in comparison, as shown in Tab. 3.

Tab. 3 *Ultrasonic vibration cutting device and cutting tool research direction and progress*

Equipment type	Research direction	Specific content	Conclusion
Two-dimensional vibratory cutting device	Device Design	Dual longitudinal vibration device	Trajectory shape adjusted by phase difference of excitation signal Improved "tool-work separation" and surface roughness up to 22nm.
		Multi-stage amplification function elliptical vibration device	
		Parallel elliptical vibrator	Improved cutting performance due to decoupled motion
	System design Design	Single excitation ultrasonic vibration turning system	Analyzing its separation characteristics and testing the feasibility of single excitation commutation method for trajectory generation Cutting performance rises, improving surface quality and accuracy
		Rotary vibratory end milling system	
Three-dimensional ultrasonic vibration platform	Device Design	Three-dimensional vibratory cutting device	Generates arbitrary elliptical motion
	Stages Design	New three-dimensional vibrating stage	Adjustable features such as amplitude and frequency improve processing efficiency in needle tip-based nanofabrication. Multiple vibration modes can be realized The adjustable characteristics of amplitude and frequency improve the machining efficiency of needle tip-based nanofabrication. Multiple vibration modes can be realized.
		Decoupled elliptical vibration mechanism	
	System control method design	Fuzzy sliding mode control	Realize strong robustness
		Gray prediction and fuzzy control	Good machining surface quality
Ultrasonic vibration cutting tool	Cutting tools Research	Cutting Simulation	Two-dimensional UVC cutting force is lower, small cutting deformation Turning tool: large front angle for chatter suppression Diamond cutting tools: cutting force decreases, burrs still exist on the bottom and edge of the surface.
		Tool Parameters	
		Machining quality	
		Cutting tool wear	Reduced cutting tool wear and work-hardening, reduced grinding and bonding wear
	Cutting tool design	Cutting tool design	Boring cutting tools: reduce surface roughness and burrs Turning cutting tools: reduce cutting forces and surface roughness Turning system: good stability and reliability.
		Cutting tool system design	

7 Outlook

In summary, substantial research has been conducted on UVC, with scholars both domestically and internationally examining its cutting mechanism, cutting force, surface quality, device development, cutting tool design and other areas. These examinations have spanned multiple directions, including one-dimensional UVC, two-dimensional UVC, three-dimensional UVC, high-speed UVC, and various methods of turning, drilling, grinding and milling within each dimension. Research has shown that ultrasonic vibration cutting technology provides a solution for the low machining efficiency and low dimensional accuracy issues typically faced with traditional cutting. The research on the mechanism of ultrasonic vibration cutting can be summarised by the following trends for future development. It is important to note that technical term abbreviations will be explained upon first usage. The language used will remain formal, clear, and objective while also abiding by standard grammar and spelling conventions. The structure will be formatted in a logical and balanced format that avoids bias and emphasizes precise word choice. Footnote style and citation will be consistent throughout.

- 1) Ultrasonic vibration cutting causes the cutting tool to leave the workpiece periodically, facilitating chip-breaking cutting and fostering a comprehensive comprehension of the chip formation mechanism and process control. The amalgamation of additive manufacturing technology and ultrasonic vibration technology in the future has the potential to mitigate the metal structure defects and elevate the structural properties of the material, which is a promising research avenue.
- 2) The continuous variation in displacement during ultrasonic vibration cutting improves heat dissipation between the workpiece and cutting tool, and allows the coolant to increase contact with both, leading to better cooling and decreased cutting temperatures. In the future, the study of cooling mechanisms and machining energy will be a topic of great interest.
- 3) The mechanism of ultrasonic vibration cutting is distinguished by energy concentration and instantaneous cutting, resulting in an enhancement of the severe cutting vibration during machining. Furthermore, it significantly diminishes the cutting force in comparison to regular cutting. In upcoming times, finite element simulation technology will combine with ultrasonic vibration cutting technology to establish UVC kinetic analysis as well as mathematical models. This will produce a quantitative description of the interaction between the cutting tool and the workpiece, analyze the machining process's cutting force, power, and other signal changes, and extensively examine the cutting mechanism.
- 4) Ultrasonic vibration cutting enhances cutting force and reduces cutting temperature, resulting in improved surface quality and integrity. In the future, the integration of five-axis machining technology and vibratory ultrasonic technology may enable high-quality processing of intricate surfaces. Combining polishing and microscopic inspection technologies in micro-surface applications can improve processing quality, which is a future trend.
- 5) Additionally, high-speed ultrasonic vibratory cutting can overcome the limitations of critical speed, enhance machining performance and stability, and improve surface integrity. In order to develop a comprehensive cutting parameter database, a significant quantity of cutting test data needs to be collected in the future. Additionally, the theoretical application of high-speed ultrasonic vibration cutting technology in precision machining of hard and brittle materials should be studied to further enhance the quality and efficiency of cutting in the production of parts.
- 6) Currently, the designed and researched ultrasonic vibration cutting device is capable of meeting the design requirements. However, it suffers from low efficiency and lacks a practical and effective cutting system. In the future, the exploration of the ultrasonic vibration system will undoubtedly require a highly efficient transducer that can adjust to the amplitude and frequency of the intelligent

spindle's automatic feedback. Meanwhile, the intelligent spindle has the potential to be integrated with wireless communication and 5G technology to mitigate electronic control system latency.

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