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Experimental Investigation on Axial Ultrasonic Vibration Assisted Milling of Cr12MoV

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Abstract. The conventional milling process is difficult due to the high strength and hardness of Cr12MoV, which can cause the rapid tool wear, premature failure, and poor milling quality of work platform. The ultrasonic vibration machining technology has been founded to be effective in the milling process of hard-to-cut materials like die tool steel and nickel alloys. The ultrasonic vibration assisted milling (UVM) technology is carried out the axial milling of Cr12MoV in this paper, and the average impact force F_i is influenced by the vibration amplitude A, the vibration frequency f, and equivalent mass of the vibrating part M. The mean value of cutting force F_x, F_y, and F_z decreases by 25%, 15.04%, and 17.46%, respectively. With the increase of vibration amplitudes, the value of surface roughness firstly decrease and then increase, and it is obviously lower than conventional milling. The experimental results demonstrated that the UVM technology is a feasible method for the low cutting force and high quality process of cutting Cr12MoV.

Introduction

Cr12MoV is one typical and advanced hard-to-cut material used in modern aerospace industry [1-3] because of its inherent properties, such as high hardness, corrosion resistance, wear resistance, and high flexural strength. However, it is known that high strength leads to large cutting force, rapid tool wear, premature failure, and poor surface quality in cutting process [4,5]. The low force, high quality, and stable cutting on Cr12MoV have always been a challenge with the conventional cutting process.

In order to improve the machining quality of hard-to-cut steel, a lot of methods were contributed by many scholars. An analytical method combining finite element simulation with geometric modeling was proposed for predicting cutting forces in shear and plowing, and the validity of the model was verified by micro-milling tests with TiAiN-coated tools on P-20 steel work platform [6]. The effect of different CBN inserts on cutting forces and surface roughness was investigated for turning of AISI H13 die tool steel [7]. An experimental study was conducted on the milling process of hardened die tool steel using coated carbide cutters, and the results showed that main forms of tool failure were chipping and edge spalling [8]. An experimental method was investigated to study the effect of milling parameters on surface roughness during high speed milling of die tool steel [9]. To study the influence of process parameters on the vibration of the work platform during machining, different lengths of high speed steel twist drills were selected for drilling tests on cold work die tool steel, and the influence of tool, work platform material, and machining parameters on the torque of the drilling force was analyzed [10].

The ultrasonic processing technology has attracted the attention of scholars and achieved a lot of results [11]. The ultrasonic vibration assisted cutting is one of promising ultrasonic technique, which showed that have great advantages over the conventional cutting, like lower cutting forces, higher machining stability, less tool wear, and a better quality [12,13]. It has been widely used due to

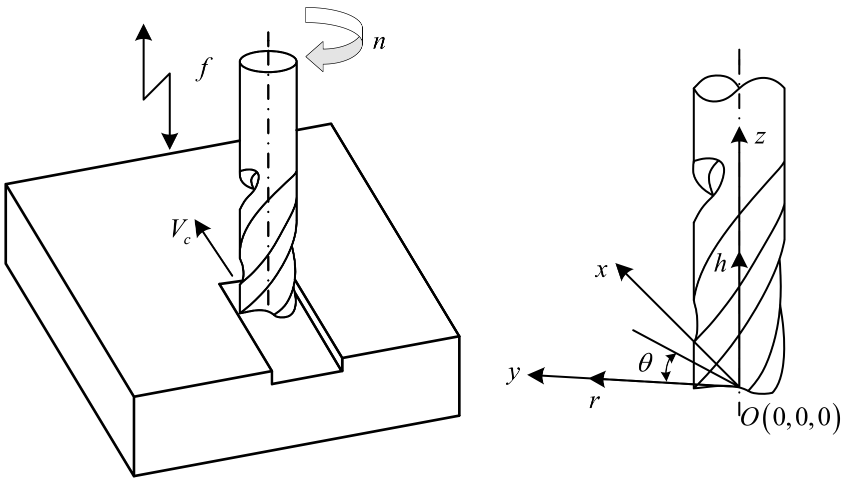


Fig. 1: Schematic of axial ultrasonic vibration milling coordinate system

increase productivity and stability in the machining of the hard-to-cut materials [14,15]. The ultrasonic elliptical vibration cutting (UEVC) can significantly improve the productivity, and it was reported to utilize fully the cutter [16]. The geometrical and mechanical behaviors of machined holes were investigated by helical milling and ultrasonic vibration helical milling Ti6Al4V alloy [17]. Literature [18] carried out a comprehensive experiment on surface integrity in rotary ultrasonic elliptical end milling of Ti6Al4V with various vibration amplitudes and cutting speeds, and the results showed that surface roughness was be risen with increase of cutting speed and vibration amplitude. The ultrasonic vibration cutting technology was applied to the milling process of AISI304 steel [19], and the test results showed that the milling force and the surface roughness were reduced. The effects of ultrasonic vibration milling of 718 nickel alloy was investigated on material surface integrity, tool wear, milling forces, and fatigue resistance [20]. The effects of ultrasonic vibration milling on surface roughness, micro-groove morphology, milling force and chip formation was studied on low speed machining of R-shaped micro-groove [21]. Based on alloy steel AISI4405, and the results showed that the surface roughness, milling force, and micro-groove morphology were improved. Zhang et al. [22] proposed a high speed elliptical ultrasonic vibration milling and tested with titanium alloy webs. Tao et al. [23] mainly studied ultrasonic vibration milling in the feed direction, and a large number of studies has been carried out in the milling force, machining accuracy, surface morphology, and system stability through theoretical analysis and experiments on different materials. Furthermore, A force predictive model and surface roughness predictive model were proposed, and the accuracy of the models was verified based on UVM experiments [24,25].

Although UVM technology has been widely used to the die tool steel, the studies of milling characteristics of Cr12MoV are still poor. In order to improve the milling processing of Cr12MoV, the UVM technology is employed to carry out axial milling in this paper, and the cutting force and surface roughness are analyzed. The principal analysis of UVM process is described in Section 1. The experimental setup is given in Section 2. The results and discussion are depicted in Section 3. The conclusions are drawn in Section 4.

Principe Analysis of Axial UVM Process

The schematic of axial UVM is illustrated in Figure 1. The ultrasonic vibration is applied in the direction of cutting tool axis (i.e., z axis), a rectangle coordinate system $x-y-z$ is established on the work platform, and a cylindrical coordinate system $r-\theta-h$ is established on the cutting tool, the z axis and h axis overlap, the two frames share one origin.

Table 1: Definition of parameters

Symbol	Means	Unit
R	Radium of cutting tooth	mm
ω	Angular velocity	rad/s
t	Time	s
V_c	Feed velocity	m/s
f	Frequency of ultrasonic vibration	Hz
A	Vibration amplitude	μm
Z	Number of teeth on the cutting tool	
ϕ_0	Initial phase angle	rad
i	Number of cutter edge	

In Figure 1, n is the rotary speed (r/min), the motion trajectory equation in axial ultrasonic vibration milling can be defined as [26]:

$$\begin{cases} x_u = V_c t + R\sin(\omega t - \dfrac{2\pi i}{Z}) \\ y_u = R\cos(\omega t - \dfrac{2\pi i}{Z}) \\ z_u = A\sin(2\pi f t + \phi_0) \end{cases} \tag{1}$$

The meanings of the parameters in Eq. 1 are explained in Table 1.

In the traditional milling process, the energy that drives the work platform to move according to the specified geometry and make the tool tip vibrate to produce chips comes from the spindle motor. However, the energy which makes the cutter vibrate to produce chips originates from the ultrasonic generating equipment when using in UVM technology, the energy supplied by the spindle motor only drives the work platform to move in a specific geometric relationship, which improves the chip breaking ability.

It can be seen that the ultrasonic vibration technology brings additional energy, which makes the energy to increase in the cutting process. Whereas, the high frequency vibration also brings great impact force [27]. The velocity V_z and acceleration a_z of the tool with high frequency vibration could be get as:

$$\begin{cases} V_z = 2\pi f A\cos(2\pi f t + \phi_0) \\ a_z = -4\pi^2 f^2 A\sin(2\pi f t + \phi_0) \end{cases} \tag{2}$$

In axial UVM, assuming $A = 10\,\mu$m, $f = 15.6$ kHz, $a_z = 9.61\times104$ (m/s). According to Newton's second law of motion, the acceleration of an object is proportional to the force exerted on it, which can cause great influence by f and A. Letting M is the equivalent mass of the vibrating part, according to the momentum theorem, the average impact force on the work platform in Δt is approximately as:

$$\begin{aligned} F_i &= \frac{MV_{z_2} - MV_{z_1}}{\Delta t} \\ &= \frac{M}{\Delta t}\{2\pi f A\cos[2\pi f(t+\Delta t) + \phi_0] - 2\pi f A\cos(2\pi f t + \phi_0)\} \\ &= \frac{2\pi f A M}{\Delta t}\{\cos[2\pi f(t+\Delta t) + \phi_0] - \cos(2\pi f t + \phi_0)\} \\ &\approx -4\pi^2 f^2 M A\sin(2\pi f t + \phi_0) \end{aligned} \tag{3}$$

where F_i is the average impact force, and it can be seen that the impact force is related to the quality of vibration parts, the ultrasonic vibration amplitude, and frequency.

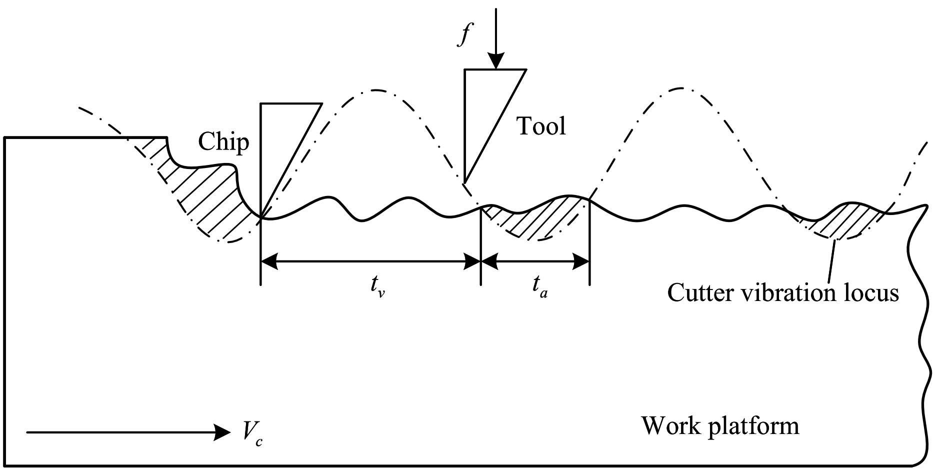


Fig. 2: Illustration of the ultrasonic vibration milling process

Based on Eq. 3, it also can be seen that simply increasing ultrasonic vibration parameters will not achieve better cutting results. For axial ultrasonic milling of thin-wall parts, ultrasonic vibration parameters should be controlled to prevent the great impact force, resulting in the reduction of machining accuracy and surface quality of the work platform.

The cooling and lubricating effects in the process of axial UVM are important on hard-to-cut materials surface quality, tool life, and cutting temperature. The milling process consists of two parts, the vacant cutting and actual cutting. In Figure 2, letting t_a is actual cutting time, t_v is vacant cutting time, and T is ultrasonic vibration period of the cutter tooth, respectively. The conductivity Q can be defined as:

$$Q = \frac{t_a}{T}. \tag{4}$$

According to Eq. 4, the actual cutting state of the tool can be known by the conductivity Q. The actual cutting time t_a is shorter and the vacant cutting time t_v is longer if the conductivity Q is smaller, and so the lower average cutting force and cutting temperature will be achieved in the ultrasonic vibration cutting process. The cutting state between tool cutting edge and work platform cutting surface is not separated when $Q > 1$, it will be finished if $0 < Q < 1$ [28]. The periodically contact and separation of cutting tool and conductivity Q of the ultrasonic vibration milling make the cutting zone interface to open periodically. Therefore, cooling medium effectively enter into the cutting zone interface, and it is significant to improve the cooling and lubrication conditions in the cutting process. Compared with the conventional milling, the cooling lubrication efficiency is greatly increases using UVM technology.

Experimental Setup

In the experimental setup, a typical die tool steel Cr12MoV is chosen, and its size is 180mm $\times$ 180mm $\times$60mm . The physical properties of Cr12MoV are listed in Table 2.

The experimental platforms are set up as Figure 3, it mainly consisted of a CNC machine with cooling system, an ultrasonic power supply, a force measuring system (i.e.,Kistler 9139AA dynamometer and industrial computer), and the CNC machine provided the rotation to the UVM spindle. The cutting tool is rotated and vibrated in z direction simultaneously with high frequency and small amplitude. A piezoelectric dynamometer of Kislter 9139AA is employed to measure the cutting force. The signals generated by the dynamometer are converted into voltage signals, transmitted to the Data acquisition system of Kistler 9139AA, then the obtained digital signals are recorded by the virtue of the Kistler Dynoware software. A 3D digital measuring and scanning microscope Smartzoom are used to observe the wear condition, the shapes, and sizes of the cutting chip.

Table 2: Physical properties of Cr12MoV

Physical properties	Value	Units
Density	7.85×10^3	Kg/m^3
Specific Heat Capacity	4.60×10^2	$J \cdot Kg^{-1} \cdot °C^{-1}$
Poisson Ratio	0.28	
Thermal Conductivity	44	$W \cdot m^{-1} \cdot °C^{-1}$
Elastic Modulus	2.18×10^{11}	N/mm^2

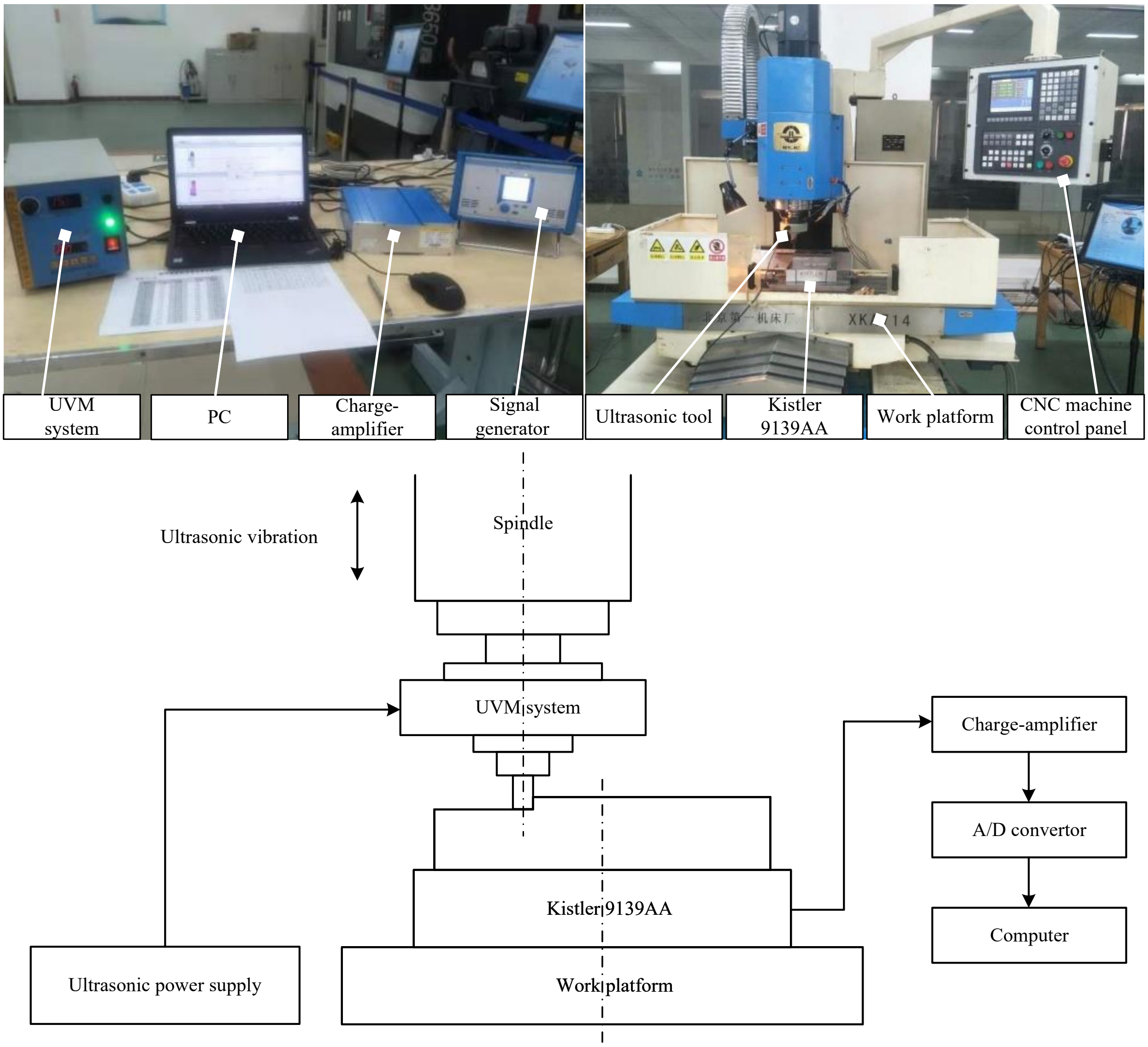
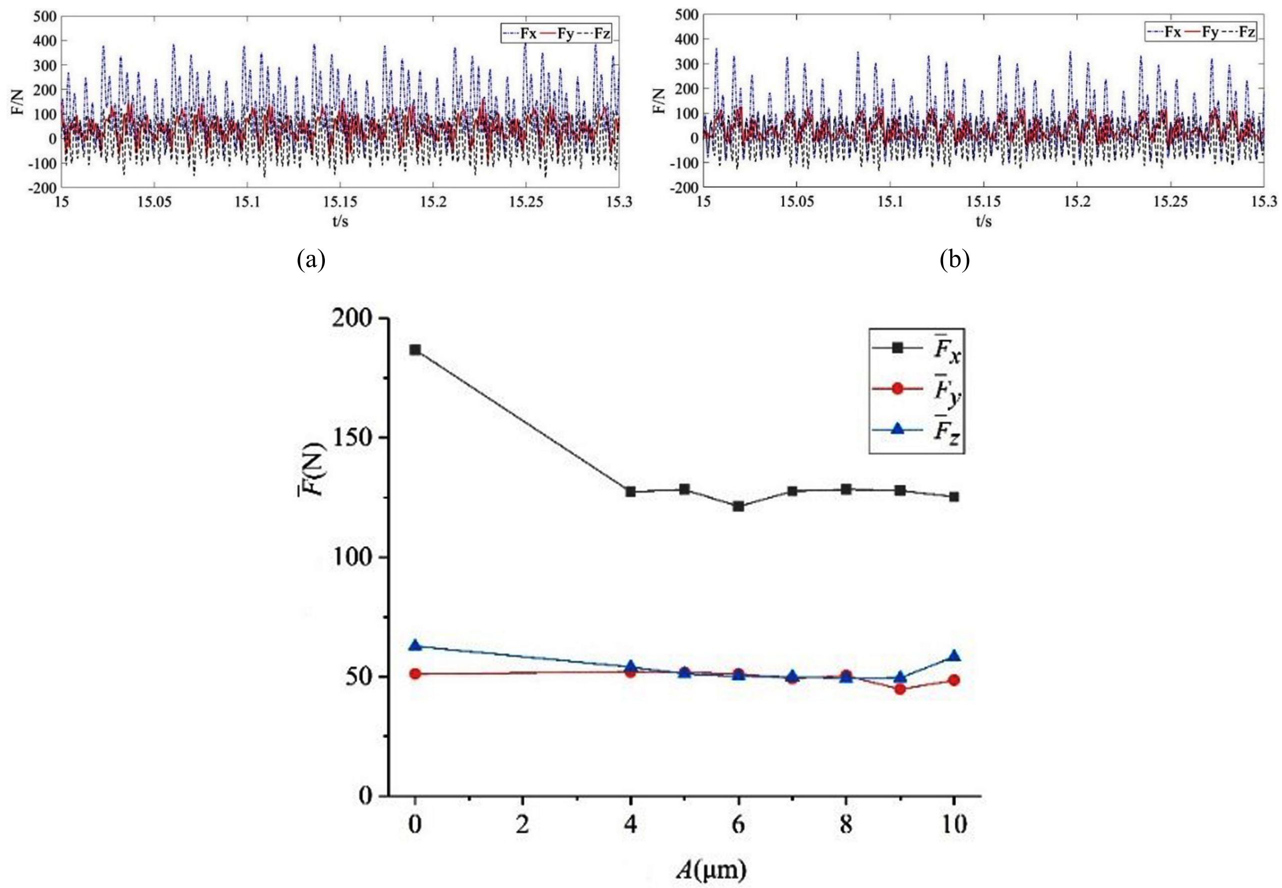


Fig. 3: Diagram and picture of experimental setup



(a) (b)

(c)

Fig. 4: Change trend of cutting force; (a) Partial drawing of cutting force of UVM when $A = 0$ μm, (b) Partial drawing of cutting force of UVM when $A = 8$ μm, (c) Influence trend of amplitude on milling force

Results and Discussion

The single factor experiments of cutting force and surface roughness are conducted in laboratory, and the experimental parameters are chosen as the tool rotary speed $n = 1600$ r/min, cutting depth $a_p = 0.8$ mm, cutting width $a_e = 2$ mm, $A = 0, 4, 5, 6, 7, 8, 9, 10$ μm, and $f = 15.6$ kHz, respectively. The comparison of axial milling cutting force are shown in Figure 4 (a) and (b). As can be seen from the figure, the cutting force of ultrasonic vibration milling is reduced for varying degrees, and the range of cutting force is also reduced compared with conventional milling. And the fluctuating density of the cutting force curve is significantly greater than that in conventional milling, which could be explained by the periodic separate-contact type mechanism. Absolute values of cutting force in milling process increase first from zero to the maximum and then decrease from the maximum to zero with the variation of cutting conditions. Thus, the average values of axial cutting force are generally used to evaluate the size of cutting force. The average cutting force of x, y and z direction in conventional milling ($A = 0\mu$m) and UVM ($A = 4, 5, 6, 7, 8, 9, 10\mu$m respectively) of Cr12MoV shown in the Figure 4 (c), and the values of F_x, F_y and F_z, especially the F_x in UVM is significantly lower. The mean value of F_x, F_y, and F_z are decreased by 25%, 15.04%, and 17.46%, respectively. The average value of F_y and F_z are very closed to that of conventional milling, and as the amplitude increases, the cutting force curve of F_z decreases first and then increases when $A > 7\mu$m. The reason for this phenomenon is that as the ultrasonic vibration amplitude increases, the cutting impact force also increases according to the Eq. 3, which weakens the advantage of ultrasonic vibration milling technology in reducing the axial cutting force.

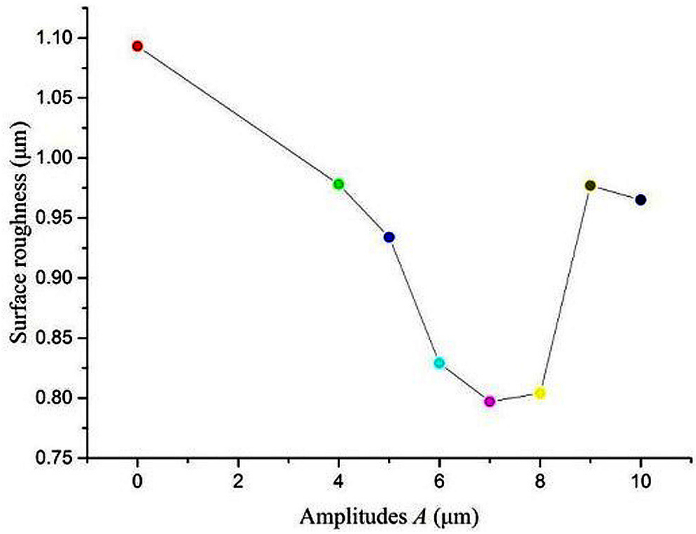


Fig. 5: Illustration of the ultrasonic vibration milling process

The above figures verified that the UVM technology can greatly reduce the cutting force in the cutting process, which will contribute to lower cutting tool wear and longer tool life. And the main reasons for the remarkable effects of UVM are the periodical and dynamic contact and separation mechanism and the effective lubricating and cooling in the cutting process. At the same time, it is important to control the ultrasonic vibration parameters to avoid the generation of excessive ultrasonic impact force.

Surface quality is a crucial indicator used to measure and evaluate the quality of the components, which also has a great impact on the service life and reliability of the parts. The surface roughness is measured by the SJ-210 handheld roughness meter. A single variable method was studied the influence of different amplitudes on the surface roughness of the processed surface.

Figure 5 shows the values of the mean surface roughness. The mean value of the surface roughness in the three different points in the finished surface. It can be found that with the increase of the amplitude A, the mean values of surface roughness after UVM ($A = 4, 5, 6, 7, 8, 9, 10$ μm, respectively) were obviously lower than conventional milling ($A = 0$ μm). Hence, the surface quality of the finished surface is greatly improved compared with conventional milling. Due to the contact-separation mechanism, there are thousands of contact and separation between the cutter and the work platform in the direction of ultrasonic vibration. The cutter with sinusoidal oscillation produces intensive impact on the machined surface, which causes stamping effect and is helpful to obtain good surface processing quality. The value of surface roughness decreases firstly, and reaches the minimum value when $A = 7$ μm, and then increases along with $A = 8, 9, 10$ μm respectively, which is due to the impacting caused by excessive amplitude. The impacting results in micro-dimples on machined surface that deteriorated the surface roughness and integrity. But that are still significantly lower than conventional milling. The results revealed that the UVM of Cr12MoV could effectively reduce the surface topography height of finished surface so as to improve the surface quality compared with that in conventional milling [29].

Conclusion

The UVM technology used to the axial milling of Cr12MoV was employed and an experiment was performed in this paper. Based on the experiment analysis and result, the main conclusion can be drawn as follow:

1) After theoretical derivation, the impact force caused by ultrasonic vibration was related to the quality of vibrating parts M, the frequency f and amplitude A of ultrasonic vibration. Moreover, the impact force had influence on the axial cutting force.

2) In comparison to the conventional milling of Cr12MoV, the UVM technology can effectively reduce the cutting force and obtain the better surface quality, which works together to improve the machining quality of Cr12MoV.
3) The technical method about UVM of Cr12MoV was credible and effective, and the machining effects were excellent, which provides a basis for milling hard die tool steel.

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