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ORIGINAL CONTRIBUTION

Grinding, Machining Morphological Studies on C/SiC Composites

Chun-fang Xiao[1] · Bing Han[2]

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Abstract C/SiC composite is a typical material difficult to machine. It is hard and brittle. In machining, the cutting force is large, the material removal rate is low, the edge is prone to collapse, and the tool wear is serious. In this paper, the grinding of C/Si composites material along the direction of fiber distribution is studied respectively. The surface microstructure and mechanical properties of C/SiC composites processed by ultrasonic machining were evaluated. The change of surface quality with the change of processing parameters has also been studied. By comparing the performances of conventional grinding and ultrasonic grinding, the surface roughness and functional characteristics of the material can be improved by optimizing the processing parameters.

Keywords C/SiC compound material · Machining mechanism · Experimental study · AUAG · Study · Processing mechanism · C/SiC · Composite material

✉ Chun-fang Xiao
553017423@qq.com

[1] Changsha Aviation Machinery Manufacturing Institute, Changsha Aeronautical Vocational and Technical College, Ma Zhen Tian River, Yuhua District, Changsha 410124, Hunan, China

[2] Liaoning University of Science and Technology Institute of Mechanical Engineering and Automation, Anshan 114051, China

Processing and Application of C/SiC Composites

Carbon fiber reinforced ceramic matrix composites (CMC) are embedded with tough carbon fiber bundles in the ceramic matrix. Reinforcement of carbon fiber bundles to CMC composites lends excellent properties, such as high temperature resistance, thermal shock resistance etc. Thereby, it is able to provide unique engineering solutions [1–4].

These advanced properties make CMC composites an excellent alternative to advanced ceramics and superalloys [5–9]. For example, carbon fiber reinforced silicon carbide (C/SiC) ceramic matrix composites possess superior mechanical properties as well as oxidation resistance. When compared with traditional metal and semi metallic friction materials, C/SiC composites have the advantages of low density, high temperature resistance, high strength, stable friction, low wear and tear, long service life and so on. It has become a new hot spot in structural materials research [10–12]. The strengthening and toughening of C/SiC composites by continuous carbon fibers not only improve the plasticity of composites, but also retain the advantages of high strength and high temperature resistance of Si and C ceramic matrix. It is a new type of high temperature structural and functional material. It has been more and more widely used in military and civilian fields, such as high temperature components of aircraft engines, combustion chambers of rocket engines, rocket nozzles, space shuttle thermal protection systems, first wall materials of nuclear reactor, etc. [11]. Therefore, the study of mechanical and high temperature properties of C/Si and C composites is of great significance. C/SiC composite is a typically difficult to machine material, which is hard and brittle. It has high cutting force, low material removal rate, prone to edge collapse and results in severe tool wear during machining [7].

Especially when machining C/SiC composites, the traditional machining methods finds it difficult to meet the requirements of dimensional accuracy. Because of the advantages of ultrasonic vibration assisted machining, AUAG machining method is applied to C/SiC composites. The processing mechanism and experimental study of the C/SiC composites were carried out along the fiber distribution direction. The surface quality after machining and the factors influencing the cutting force are comprehensively analyzed and compared. The aim is to propose a good processing scheme to meet the large demand of C/SiC composites in the industrial field.

C/SiC components are widely used in high temperature components of aerospace engines, combustion chambers of rocket, and other important aerospace components. Although the C/SiC component is nearly net shaped, further processing of the workpiece is required in order to form the required geometry, assembly tolerances and surface integrity [8]. There is still a huge problem in processing ceramic matrix composites because of its high hardness and low thermal expansion coefficient resulting in poor machinability. Different mechanical properties lead to different processing problems, such as fiber pull-out, interfacial debonding, matrix and fiber breakage, and so on [7]. Through the simulation analysis of chip forming mechanism, the sub surface damage degree during the composite machining process can be predicted [8, 12]. Ultrasonic vibration assisted grinding has good performance for plastic materials, hard and brittle materials, but ultrasonic grinding of C/Si and C composites has been rarely reported. In this paper, the grinding process of C/SiC composites along the fiber distribution direction is studied. The surface microstructure and mechanical properties of C/SiC composites processed by ultrasonic machining were evaluated, and the change of surface quality with the change of processing parameters was studied. By comparing the performances of conventional grinding and ultrasonic grinding, the surface roughness and functional characteristics of the material can be improved by optimizing the processing parameters.

Study of the Removal Mechanism of C/Si Composite

The study of the material removal mechanism of plastic materials and hard and brittle materials shows that the material removal methods can be divided into plastic removal and brittle fracture removal, but because of the complex structure and diverse components of carbon fiber reinforced composites, there are various material removal methods of carbon fiber reinforced composites. It mainly includes fiber wear, fiber cutting, fiber pull-out, matrix crushing and other materials removal methods. Based on the different material processing methods, the removal methods of composite materials will change. Grinding along the direction of fiber distribution will lead to breakage of the fiber along the axial direction, and the fiber bundle will be drawn out. Because the ultrasonic vibration assisted machining technology has changed the particle trajectory in the workpiece surface, when the high frequency vibration will produce particle trajectory superposition phenomenon, so it can reduce the fiber breakage and matrix loss cause damage to the surface, improves the surface integrity of the workpiece, lowers roughness.

As shown in Fig. 1, when grinding along the fiber distribution, the entire section of the fiber is drawn out with the movement of the grinding wheel, leaving a fiber groove at the same time.

Research on System Matching in AUAG Processing of C/SiC Composite

According to the system matching model of ultrasonic machining of brittle materials, it is known that the critical state of material removal exists in the process of C/SiC composite processing, and accordingly has the critical ultrasonic frequency.

It is assumed that in the ultrasonic grinding of composite materials, the processing length of the abrasive particles in the single rotation period of the grinding wheel is L_1, and the width of the abrasive groove is Ø. It can get [9]:

$$L_1 = n\phi \tag{1}$$

$$n = 2m + 1 \tag{2}$$

$$L_1 = t_1(vs + vw) \tag{3}$$

$$m = t_1 f \tag{4}$$

Among them, n is the number of debris trajectories, and t_1 is the time that a single abrasive remains in contact with the workpiece in a single rotation period of the wheel, and m is the number of ultrasonic vibration.

Simultaneous formula (1)–(4) can be used to obtain the critical equation of ultrasonic vibration frequency:

$$f = \frac{(v_s + v_w)t_1 - \phi}{2t_1\phi} \tag{5}$$

Representing grinding depth as a_p, the radius of the grinding wheel as R, and the angular speed of the grinding wheel as ω, t_1 can be expressed as:

$$t_1 = \frac{\arccos\frac{R-a_p}{R}}{w} \tag{6}$$

Substituting formula (6) into the formula (5), the critical frequency is obtained as:

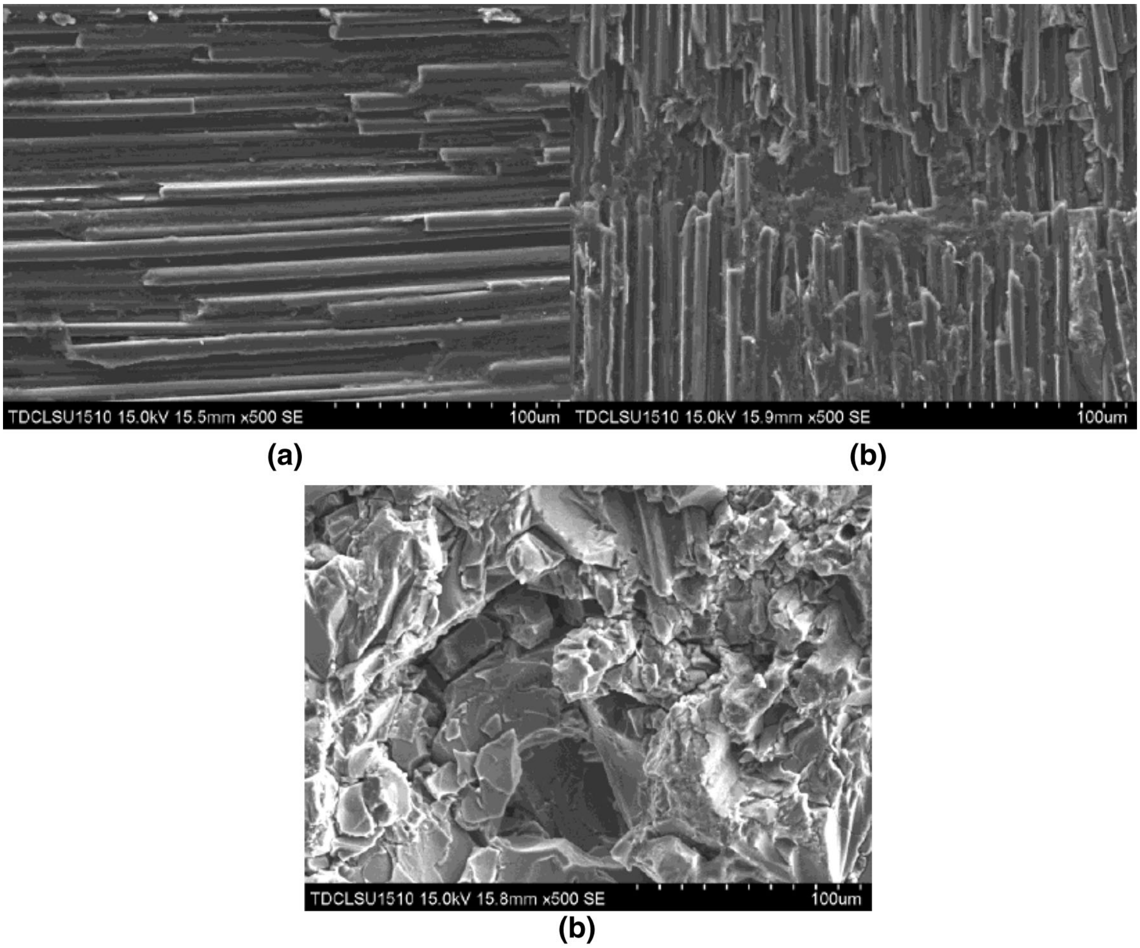

Fig. 1 Material removal mode of C/SiC composites. **a** Fiber pull-out, **b** fiber truncation, **c** matrix breaking

$$f = \frac{(v_s + v_w)\arccos\frac{R-a_p}{R} - w\phi}{2\phi\arccos\frac{R-a_p}{R}} \tag{7}$$

Through the indentation experiment of C/SiC composite, we get Ø = 45 μm. According to the parameters set in actual processing, and substituting in the formula (7), the critical frequency of ultrasonic vibration can be calculated to be 14,000 Hz. The formula of critical ultrasonic amplitude is the same as that of ultrasonic machining of brittle materials. By means of the critical frequency values, the orthogonal tests were designed for 4 factors and 3 levels L9(3^4).

Experimental Results Analysis of Parallel Fiber Distribution in AUAG

In order to obtain reliable data, each experiment was repeated 3 times, and the average value was recorded. The processing parameters and experimental results of orthogonal test are shown in Table 1.

The surface steepness is all greater than 3, which means that the grinding surface is covered by grooves; The surface of skewness is negative, which indicates that the surface of the blade has grinding groove. Some surface support factors greater than 0.608 indicate that the supporting performance of the grinding surface is better than that of the Gauss surface. The oil content in the core area is all greater than 1.56, which indicates that the lubrication performance of the grinding surface is better than that of the Gauss surface.

Range Analysis

Range analysis, also known as visual analysis, has advantages of simple calculation, visual image, simple and easy to understand. It is the most common method for analyzing the results of orthogonal experiments. The range analysis method, abbreviated as the R method, consists of two steps of calculation and judgment. The contents are shown in Fig. 2.

Table 1 Process parameters data and the results of L9(3^4) orthogonal experiments

No	Grinding depth (mm)	Feed speed (mm/min)	Grinding speed (r/min)	Vibration frequency (kHz)	Surface root mean square deviation difference S_q (nm)	Surface skewness S_{sk}	Surface steepness S_{ku}	Surface support index S_{bi}	Core area oily finger mark S_{ci}
1	0.04	600	1800	0	14,123	− 0.05	3.07	0.59	2.35
2	0.04	400	1200	14	13,624	− 2.65	20.65	0.36	1.70
3	0.04	200	600	28	13,932	− 1.16	7.33	0.62	2.01
4	0.03	600	1200	28	14,299	− 0.41	3.78	0.59	2.20
5	0.03	400	600	0	15,561	− 2.05	13.76	0.64	1.79
6	0.03	200	1800	14	12,110	− 1.07	10.70	0.31	2.05
7	0.02	600	600	14	12,018	− 0.59	4.75	0.38	2.11
8	0.02	400	1800	28	13,253	− 1.12	8.09	0.56	2.06
9	0.02	200	1200	0	11,711	− 2.13	21.15	0.33	1.93

In the figure, K_{jm} is the test index corresponding to the m factor j of the column factor. $\bar{K}_{jm}$ is a average for K_{jm}. By its size, one can judge the optimal level of j factors and the optimal combination. R_j is the difference of the column j factor, that is the difference between the maximum and the minimum of the index value at all levels of the j column factor.

$$R_j = \max\left(\bar{K}_{j1}\bar{K}_{j2},\ldots\bar{K}_{jm}\right) - \min\left(\bar{K}_{j1}\bar{K}_{j2},\ldots\bar{K}_{jm}\right) \quad (8)$$

The results of orthogonal range analysis are shown in Table 2. The results show that grinding depth is the main factor affecting S_q. The influence order of each factor on S_q is grinding depth > feed rate > ultrasonic parameters > grinding wheel speed. The main factor affecting S_{sk} is feed rate. The influence order of each factor on S_{sk} is as follows: feed speed > grinding wheel speed > ultrasonic parameter > grinding depth, and the influence of each parameter on S_{ku} is the same as that on S_{sk}. The main factors affecting S_{bi} are ultrasonic parameters, and the influence order of each factor on S_{bi} is ultrasonic parameter > grinding wheel speed > grinding depth > feeding speed. The effect of various factors on S_{ci} was consistent with that of S_{sk}.

In Table 2, ki (I = 1, 2, 3) averages 4 trials at the same level, and the best processing states for S_q are A3, B3, C1, and D2. The best processing conditions of S_{ku} and S_{sk} are A2, B1, C1 and D3. The best processing state of S_{bi} is A3, B3, C2 and D2. The best processing state of S_{ci} is A2, B2, C2 and D2.

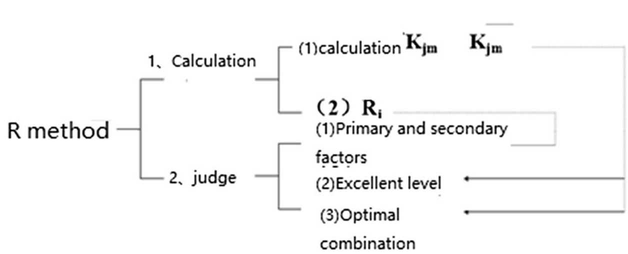

Fig. 2 Range analysis

Table 2 Range analysis of the L9(3^4) orthogonal experiment

Category/factor		A	B	C	D
S_q (nm)	K1	13,890	13,480	13,162	13,798
	K2	13,990	14,164	13,211	12,584
	K3	12,327	12,581	13,834	13,825
	R_j	1662	1564	672	1241
Ssk	K1	− 1.29	− 0.35	− 0.75	− 1.41
	K2	− 1.18	− 1.94	− 1.73	− 1.44
	K3	− 1.24	− 1.45	− 1.27	− 0.90
	R_j	0.11	1.58	0.98	0.53
S_{ku}	K1	10.35	3.87	7.28	12.66
	K2	9.41	14.16	15.19	12.03
	K3	11.33	13.06	8.61	6.40
	R_j	1.91	10.29	7.91	6.25
S_{bi}	K1	0.52	0.52	0.49	0.52
	K2	0.51	0.52	0.41	0.52
	K3	0.42	0.42	0.55	0.59
	R_j	0.10	0.10	0.12	0.24
S_{ci}	K1	2.02	2.22	2.13	2.02
	K2	2.01	1.83	1.94	1.95
	K3	2.01	2.00	1.97	2.07
	R_j	0.003	0.39	0.19	0.11

Factor Response Analysis

Factor response analysis is used to measure the influence of various processing parameters on the surface quality. It can directly reflect the influence degree of each processing factor in the change of grinding surface topography.

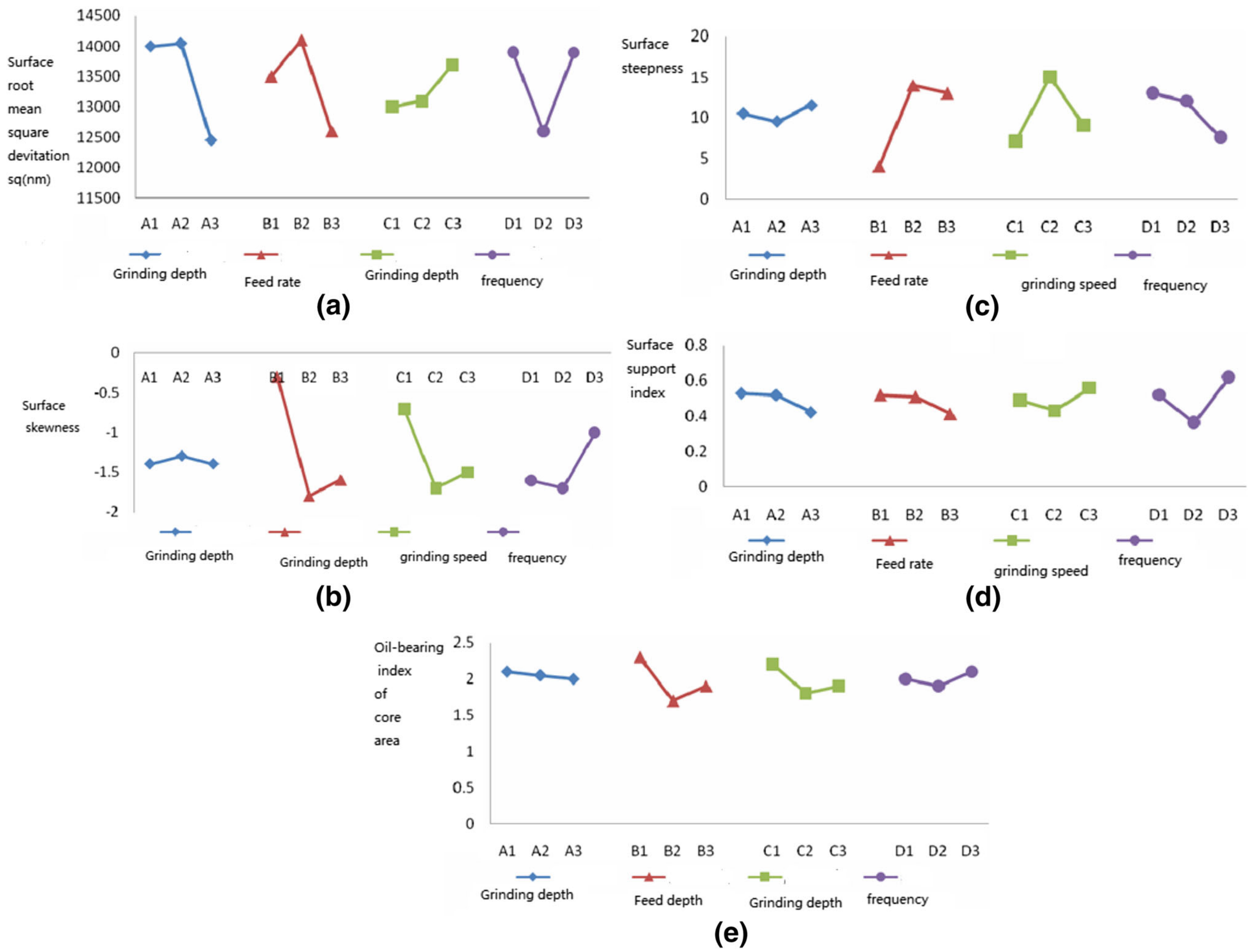

Fig. 3 Factor effect analysis of the L9(3^4) orthogonal experiment. **a** Response curve figure of S_q, **b** response curve figure of S_{sk}, **c** response curve figure of S_{ku}, **d** response curve figure of S_{bi}, **e** response curve figure of S_{ci}

As shown in Fig. 3, the effects of 4 processing parameters on S_q, S_{sk}, S_{ku}, S_{bi}, and S_{ci} are nonlinear. Ultrasonic vibration mainly affects the functional parameters of grinding surface, such as S_{bi} and S_{ci}. The surface roughness is mainly determined by the grinding parameters of machine tools, and the roughness value increases with the increase of grinding depth. The bearing capacity of the grinding surface is mainly determined by ultrasonic vibration parameters. The parameters of S_q, S_{sk}, S_{ku}, S_{bi} and S_{ci} decrease with the increase of ultrasonic frequency. When the ultrasonic frequency exceeds the critical value, the values of each parameter increase with the increase of frequency.

Analysis of Variance

Analysis of variance, also known as ANOVA or F test, was invented by R. A. Fisher and used for significance tests of mean differences between two and more than two samples. Because of the influence of various factors, the data obtained from the study presented a fluctuation. The causes of fluctuations can be divided into two categories, one is uncontrollable random factors, and the other is the controllable factors that influence the results in the study.

Multivariate analysis of variance was used to examine whether two or more two control variables produced significant changes in the observed variables influence. Here, because of the influence of multiple factors on observational variables, it is called multivariate analysis of variance. Multivariate analysis of variance can not only analyze multiple independent factors for the observed variables, it is also possible to analyze whether the interaction of multiple control factors can have a significant effect on the distribution of observed variables, and finally find the optimal combination for the observed variables.

ANOVA is used to study the significance of the 4 processing parameters, and the analysis results are shown in Table 3. It can be seen that the grinding depth and feed

Table 3 The results of variance analysis

	Analysis result				
	Factor	Sum of squares of deviations	Freedom	F than	Saliency
S_q	A	5,216,387	2	1.63	Y
	B	3,699,339	2	1.15	Y
	C	841,731	2	0.26	N
	D	3,015,397	2	0.94	N
	Error	12,772,856	8		
S_{sk}	A	0.019	2	0.5	N
	B	0.019	2	0.5	N
	C	0.022	2	0.57	N
	D	0.09	2	2.42	Y
	Error	0.15	8		
S_{ku}	A	5.51	2	0.05	N
	B	191.72	2	2.03	Y
	C	107.64	2	1.14	Y
	D	71.28	2	0.75	N
	Error	160.42	8		
S_{bi}	A	0.019	2	0.5	N
	B	0.019	2	0.5	N
	C	0.022	2	0.57	N
	D	0.09	2	2.42	Y
	Error	0.15	8		
S_{ci}	A	0	2	0	N
	B	0.23	2	2.92	Y
	C	0.06	2	0.81	N
	D	0.02	2	0.26	N
	Error	0.32	8		

speed are significant to S_q. At the same time, the feed rate is significant to S_{sk} and S_{ci}, the feed speed and the grinding wheel speed are significant to S_{ku}, and the ultrasonic parameters show significant dependence on S_{bi}.

Summary of This Article

In this study, orthogonal experiments are used to optimize the surface grinding quality of C/SiC composites. The influence of 4 grinding parameters on 5 evaluation parameters is studied in detail. Through the comparison of the surface quality and grinding force under different grinding parameters, and the overall processing of the direction of fiber distribution, the following conclusions are obtained:

In the direction of fiber distribution, ultrasonic grinding of C/SiC composites is done. The main factor affecting S_q is grinding depth. The influence order of each factor on S_q is grinding depth > feed rate > ultrasonic parameter > grinding wheel speed. The main factor affecting S_{sk} is feed rate, The influence order of each factor on S_{sk} is: feed rate > grinding wheel speed > ultrasonic parameter > grinding depth. The influence of each parameter on S_{ku} is the same as that on S_{sk}. The main factors affecting S_{bi} are ultrasonic parameters, and the influence order of each factor on S_{bi} is ultrasonic parameter > grinding wheel speed > grinding depth > feeding speed. The effect of various factors on S_{ci} was consistent with that of S_{sk}. The effect of ultrasonic vibration can effectively improve the surface grinding quality and reduce roughness.

Under the condition of ultrasonic machining parameters 14,000 Hz frequency and 5 µm amplitude, better surface quality can be obtained. The effect of ultrasonic vibration can reduce the surface damage of materials, but it will backfire in high frequency and large amplitude.

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