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Applications of high frequency vibrations for surface milling

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1. Introduction

The vibrocutting or cutting by using vibrations is obtained after applying ultrasonic frequency vibrations to the cutting tool edge [1]. The absolute value of impulsive forces during vibrocutting is decreasing, which also decreases the average cutting temperature generated in the contact zone (it becomes equal to the room temperature).

New technologies are needed to be introduced for achieving higher manufacturing productivity. Present manufactures require shorter production time and better surface quality of manufactured parts. These factors are influenced by temperature, tool wear and cutting forces during the cutting process.

The first experiments were carried out by using the turning process for different types of materials applying ultrasonic frequencies vibrations [2]. The results turned out to be better compared to conventional turning.

The next step was to apply ultrasonic vibrations in milling process.

One ultrasonic machining application used for machining ceramic materials is by applying water comprising abrasive slurry and small abrasive particles supplied between the tool tip and the workpiece. Material removal occurs when the abrasive particles, suspended in the slurry between the tool and the workpiece, impact the workpiece due to the downstroke of the vibrating tool. Vibrations in this process are only applied in vertical motion, but not rotational, the tool (shaped conversely to the desired hole or cavity) oscillates at high frequency (typically 20 kHz) [3].

The experiments presented in this paper were carried out by applying ultrasonic vibration up to 20 kHz in the rotational and the longitudinal motions.

2. Dynamic model of research system

The theoretical two-degree-of freedom model has been used as a preliminary methodology for understanding the interactive behavior within typical industrial ultrasonic milling components. Ultrasonic energy is generated within a piezoelectric exciter, which is inherently nonlinear, and which is coupled to horn, and to a material cutting tool, for example. The horn/tool configurations are also nonlinear, and within the whole system there are response features which are strongly reminiscent of positive and negative cubic stiffness effects.

It has also been shown experimentally that coupling of ultrasonic components with different nonlinear characteristics can strongly influence the performance of the piezo-horn-tool-workpiece system. Further experiments have shown that a multiple horn-tool configuration can, under certain circumstances, display autoparametric responses based on the forced response of the desired longitudinal mode parametrically exciting an undesired lateral mode.

The actual characteristics of ultrasonic cutting system components depend on many factors which have been recently investigated [4] such as individual component geometry, coupling mechanics such as thread depth, diameter and tightening torque, excitation level, tool shape and workpiece material. These observations clearly show that there are definable system characteristics which can be conveniently and usefully phenomenological modeled by means of straightforward spring-mass-damper systems, as shown in Fig. 1.

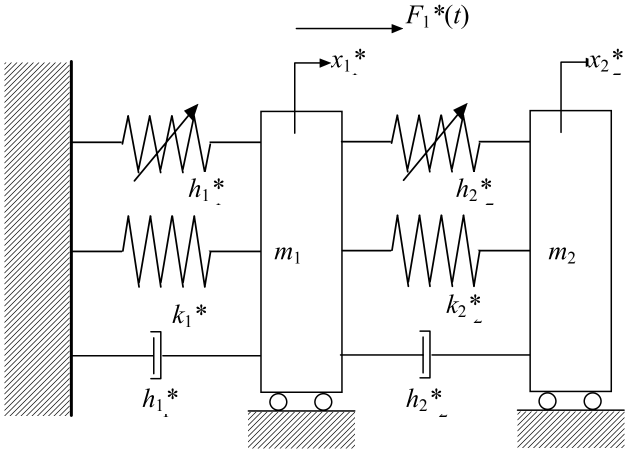


Fig. 1 Dynamic model of ultrasonic cutting system

The equations of motion for this system are derived using conventional principles and after parameterization take the following form [5]

$$\ddot{x}_1 + 2\varepsilon h_1\dot{x}_1 + 2\varepsilon h_2\left(\dot{x}_1 - \dot{x}_2\right) + k_1x_1 + \varepsilon k_2\left(x_1 - x_2\right) + \varepsilon c_1\left(x_1\right)^3 + \varepsilon c_3\left(x_2 - x_1\right)^3 = \varepsilon F\cos\Omega t \tag{1}$$

$$\ddot{x}_2 + 2\varepsilon h_3\left(\dot{x}_2 - \dot{x}_1\right) + k_3\left(x_2 - x_1\right) - \varepsilon c_3\left(x_2 - x_1\right)^3 = 0 \tag{2}$$

where $x_{1,2} = x_{1,2}(t)$ and also noting that $x_{1,2} = x^*_{1,2}/x^{ref}$ given that x^{ref} is a reference displacement. The time t is dimensionless and defined by $t = \omega_{e1}t^*$, where ω_{e1} is the first mode eigenvalue. The damping, cubic nonlinearities and the excitation terms are all ordered to ε^1 based on the reasonable assumption that they can all be contrived to be of similar magnitude in this hypothetical system, thereby leading to readily obtained generating solutions from the zero order perturbation equations. The various coefficients and other quantities within (1) and (2) are defined as follows

$$h_1 = \frac{h_1^*}{2\varepsilon m_1 \omega_{e1}};\ h_2 = \frac{h_2^*}{2\varepsilon m_1 \omega_{e1}};\ h_3 = \frac{h_2^*}{2\varepsilon m_2 \omega_{e1}}$$

$$k_1 = \frac{k_1^*}{m_1 \omega_{e1}^2};\ k_2 = \frac{k_2^*}{\varepsilon m_1 \omega_{e1}^2};\ k_3 = \frac{k_2^*}{m_2 \omega_{e1}^2}$$

$$c_1 = \frac{c_1^* x_{ref}^{*2}}{\varepsilon m_1 \omega_{e1}^2};\ c_2 = \frac{c_2^* x_{ref}^{*2}}{\varepsilon m_1 \omega_{e1}^2};\ c_3 = \frac{c_2^* x_{ref}^{*2}}{\varepsilon m_2 \omega_{e1}^2}$$

$$F = \frac{F^*}{\varepsilon m_1 \omega^2{}_{e1} x_{ref}^*};\ \Omega = \frac{\Omega^*}{\omega_{e1}}$$

Eqs. (1) and (2) are initially solved using the approximation method of multiple scales up to and including first-order terms in the two perturbation series

$$x_1 = x_{10} + \varepsilon x_{11} + \varepsilon^2 x_{12} + \ldots + \varepsilon^n x_{1n} \tag{3}$$

$$x_2 = x_{20} + \varepsilon x_{21} + \varepsilon^2 x_{22} + \ldots + \varepsilon^n x_{2n} \tag{4}$$

Numerical analysis of Eqs. (1) and (2) has shown that both chaotic and steady state regimes of vibrations are possible, depending on the parameters of vibrating system and excitation forces. To solve the problem of electric energy conversion into mechanical vibration one, the steady state vibration regimes with the largest amplitude are of great interest.

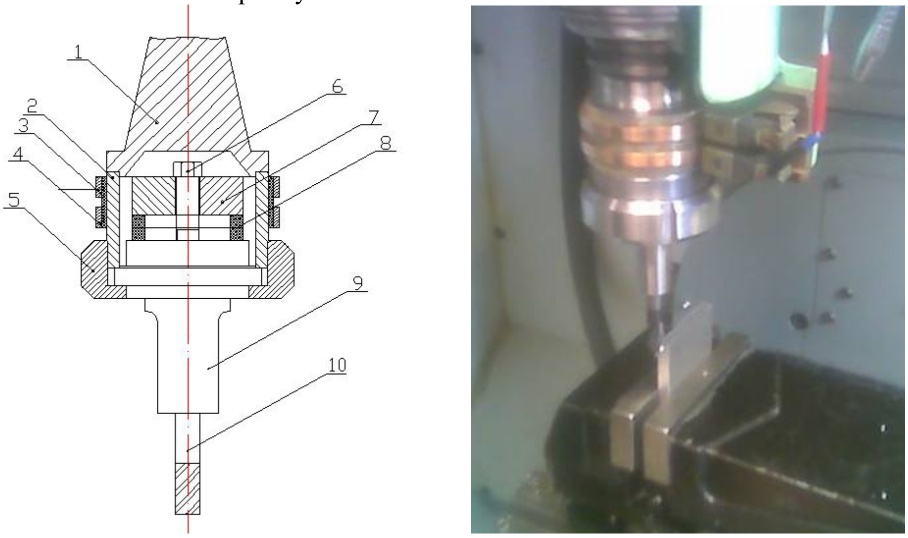
3. Experimental setup

The influence of ultrasonic frequency vibrations was studied during the milling process. Experiments were carried out by using DMU 35M CNC milling machine, with workpieces made of aluminium AlMgSi0,5 (EN AW-6060) and plastic PA6. The special tool holder *1* (shown in Fig. 2) with piezoceramics elements for generating ultrasonic vibrations on the cutting edge of the mill *10* was created [6, 7]. A ceramic stack piezoelectric transducer is the source of mechanical oscillations. It transforms the electrical power received from the power supply. The ultrasonic power supply generates up to 200 W with sinusoidal waveform; a stack of two rings *8* piezoelectric transducer converts the electrical power into mechanical vibrations with a typical 60-70% of efficiency. However, the amplitude of the resulting ultrasonic vibration is inadequate for realization of the cutting process and a waveguide focusing device ("stepped horn-concentrator") *9* is fitted onto the end of the transducer, where it is designed to enhance the vibration amplitude at its output end, with, of course, a corresponding decrease in area. The upstroke of the oscillation can be tuned up to 20 µm. Table 1 summarizes the key performance parameters of ultrasonic transducer and actuator.

Table 1

Ultrasonic transducer and actuator specification

Specification	Value	Specification	Value
Ultrasonic power	200 W	Horn material	Steel
Resonance frequency	18.4 kHz	Mill diameter	10 mm
Transducer impedance	16 Om	Maximum amplitude	20 µm



a b

Fig. 2 Structure of mill holder (a): *1* – standard holder (Weldon) DIN 6359, *2* – cylinder, *3* – textual cylinder, *4* – collector rings, *5* – nut, *6* – bolt, *7* – collet, *8* – piezoceramic rings, *9* – concentrator, *10* – mill. Experimental setup (b)

Table 2

The experimental data

Material	Aluminium AlMgSi0,5								Plastic PA6		
Regimes	1000 rpm; 150 mm/min; 0.5 mm				1500 rpm; 150 mm/min; 0.5 mm						
Experiment	1	2	3	4	5	6	7	8	9	10	11
Excitation amplitudes, V	0	100	150	200	0	100	150	200	0	150	200

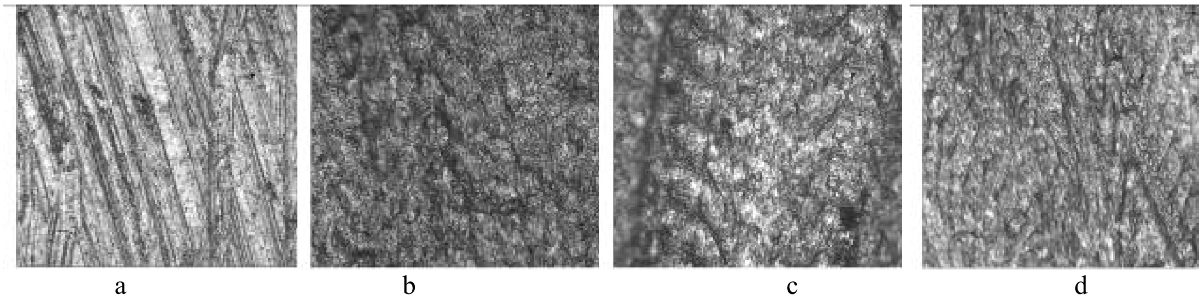


Fig. 3 Structure of aluminium AlMgSi0,5 surface after milling with 1000 rpm: (a) without vibration and with excitation amplitudes of vibrations at (b) 100 V, (c) 150 V and (d) 200 V (image enlarged by 50 times)

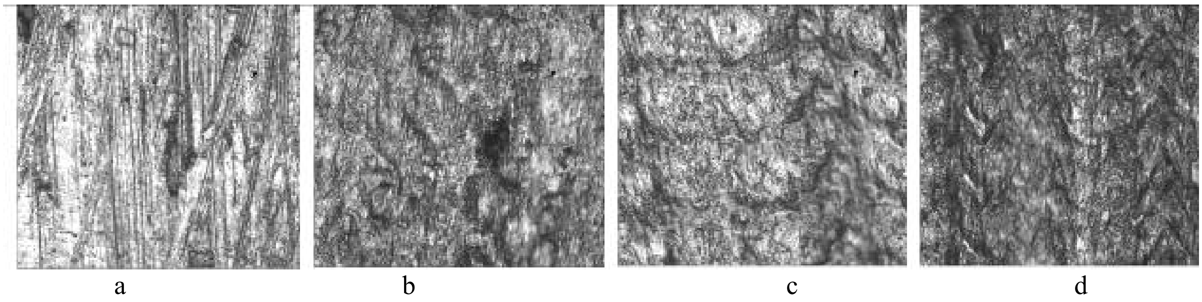


Fig. 4 Structure of aluminium AlMgSi0,5 surface after milling with 1500 rpm: (a) without vibration and with excitation amplitudes of vibrations at (b) 100 V, (c) 150 V and (d) 200 V (image enlarged by 50 times)

The mill *10* attached to the end of the concentrator, therefore the conventional rotation of the tool is superposed by an ultrasonic oscillation in axis direction of the tool. In order to increase the vibration amplitude the vibratory system is designed to be driven at resonance, i.e., its length is equal to an integral number of half-wavelengths at a given frequency. The vibratory system formed by the transducer, concentrator and tool is rigidly clamped to the standard holder *1* at a nodal (zero amplitude) point. This solution prevents losses of vibratory energy through dissipation into the body of the machine. The ultrasonic head is designed for 18.4 kHz operation; a suitable feedback system acts on the generated frequency to track changes of the electromechanical impedance of the piezo-horn-tool-workpiece system.

4. Carried out experiments

The experiments were carried out with this regime: speed at 1000 and 1500 rpm, feed – 150 mm/min and cutting depth at 0.5 mm. Excitation frequencies during all the experiments were kept constant at 18.4 kHz, but excitation amplitudes were variable. The experimental data are shown in Table 2.

5. Results

The workpieces after the experiments were checked by measuring their surface roughness and by taking the surface image with Nikon EPIPHOT optical microscope; the image was enlarged by 50 times. The surface roughness results are shown in Table 3 and the structure of surfaces is shown in Figs. 3, 4 and 5. Dependence of surface roughness on excitation amplitudes of piezoactuator is shown in Fig. 6.

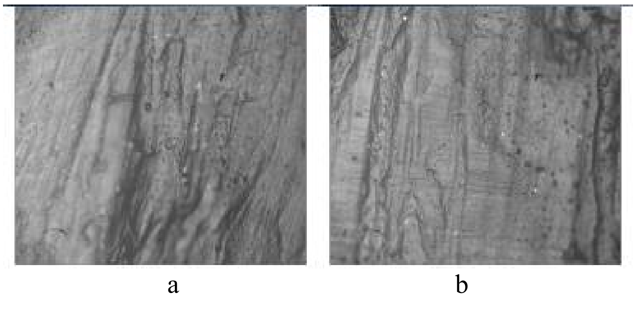


Fig. 5 Structure of plastic PA6 surface after milling with 1500 rpm: (a) without vibration and with excitation amplitude of vibrations at (b) 200 V (image enlarged by 50 times).

Table 3

The surface roughness results

Workpiece material	Aluminium AlMgSi0,5								Plastic PA6		
Experiment	1	2	3	4	5	6	7	8	9	10	11
Excitation amplitudes, V	0	100	150	200	0	100	150	200	0	150	200
Ra, µm	0.94	0.75	0.74	0.64	1.11	0.62	0.73	0.97	1.88	1.9	1.92

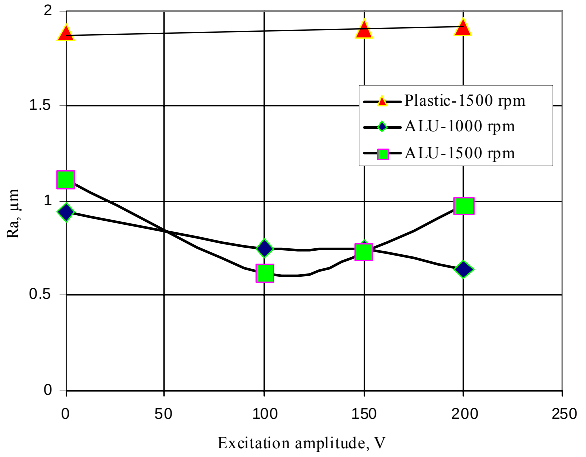


Fig. 6 Dependence of surface roughness from excitation amplitudes

6. Conclusions

The results of the experiments showed that the surfaces of aluminium after the milling process with applied high frequencies vibrations is smoother than milling by the conventional method. Better results can be achieved in the future, if they were carried out by using the vibration resonance control system. The main aim of the experiments to receive better surface quality was achieved by milling aluminium workpieces. But plastic material did not have any difference in the surface quality after milling with and without vibrations. The main reason for it is that plastic absorbs vibrations.

Further experiments will be carried out to find the efficiency of vibrocutting. Also milling process with vibrations has to be tested out on a different type of materials with changing excitation frequencies and amplitudes.

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AUKŠTOJO DAŽNIO VIBRACIJŲ PRITAIKYMAS FREZUOJANT PAVIRŠIUS

Reziumė

Metalų apdirbimas naudojant aukštojo dažnio vibracijas yra racionalus metodas. Buvo tiriamas frezavimo procesas. Tam tikslui buvo sukurtas specialus frezavimo įrankio laikiklis su piezokeraminiu ultragarsiniu vibracijų žadintuvu, kuris suteikia įrankiui sukimosi ir išilgines vibracijas. Rezultatai parodė, kad naudojant vibracijas, detalės paviršius apdirbamas glotniau.

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APPLICATIONS OF HIGH FREQUENCY VIBRATIONS FOR SURFACE MILLING

Summary

Metal cutting by using the high frequency vibrations is a rational method. Research was applied in milling process. For this purpose a special milling tool holder with ultrasonic vibration actuator of piezoceramics was developed to create rotational and directional vibrations. Results showed that by using vibrations the surface quality of machined detail could be improved.

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ПРИМЕНЕНИЕ ВЫСОКОЧАСТОТНЫХ ВИБРАЦИЙ ДЛЯ ОБРБОТКИ ПОВЕРХНОСТЕЙ ФРЕЗОВАНИЕМ

Резюме

Обработка металла резанием используя высокочастотные вибрации является рациональным методом. Исследования проводились при обработке металла фрезерованием. Для этой цели был создан специальный фрезодержатель с ультразвуковым пьезоприводом вибрации для создания вращательных и продольных вибраций инструмента. Результаты показали, что при использовании вибраций получена более гладкая поверхность обрабатываемой детали.

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