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Vibrational excitation of a work piece for drilling force reduction in brittle materials

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1. Introduction

Machining of hard and brittle materials, especially glass is still a major problem because of its lower fracture toughness and higher hardness. Glass tends to crack easily during machining under small stress. Many researchers have tried to develop new methods for machining of brittle and hard materials. Vibration cutting was one of the new methods for this purpose [1]. In the provided paper, the torsional vibration cutting method was proposed to realize ductile mode cutting of glass material. The experimental results show that the proposed method can increase the critical depth of cut for glass material larger than 3μm. It is hypothesized that the main reason for the improvement of critical depth of cut by torsional vibration is the ability of the 3-dimensional compressive stress condition at the vicinity of tool tip to suppress the crack propagation. An approach for surface quality improvement is proposed in the paper [2] by taking into account that the quality of machined surface is related to the intensity of the tool tip (cutting edge) vibrations. This is based on the excitation of a particular higher vibration mode of a turning tool, which leads to the reduction of deleterious vibrations in the machine–tool–work piece system through intensification of internal energy dissipation in the tool material. In the study [3], grooving and cutting tests were carried out to evaluate cutting performance of soda-lime glass using an ultra-precision lathe with a single-crystal diamond tool. Experimental results indicate that with the depth of the coat increasing – a ductile-brittle transition begins to occur, with cutting of soda-lime glass materials. Under different cutting conditions, two types of surfaces are achieved: ductile cutting surface and fractured surface. In the work [4] the ultrasonic vibration diamond cutting of glasses was performed in order to investigate the effect of tool vibration on the brittle–ductile transition mechanism. The effect of cutting speed on the critical depth of cut was studied by groove cutting experiments. The value of critical depth of cut has been found to vary with the ratio of vibration speed to cutting speed. According to the paper [5] cutting performance was found to be improved by applying ultrasonic vibration to the cutting tool. The change in the tribology of the cutting process as well as the alteration of the deformation mechanism of the work material in the cutting zone might be responsible for the reduction in tool wear in vibration cutting. The paper [6] states that overlapping cutting with ultrasound makes it possible to enhance the process chain. We could prove achievement of more suitable chip formation, reduced cutting forces, higher volume removal rates and longer drill lives with this approach. Techniques with combined types of working energies have a significant potential for increases in the cutting performance. Paper [7] presents the design of an ultrasonically vibrated tool holder and the experimental investigation of ultrasonically assisted drilling of Inconel 738-LC. The circularity, cylindricity, surface roughness and hole oversize of the ultrasonically and conventionally drilled work pieces were measured and compared. The obtained results show that the application of ultrasonic vibration can improve the hole qualities considerably. A machining method that combines micro electrical-discharge machining and micro ultrasonic vibration machining is proposed [8] for producing precise micro-holes with high aspect ratios in borosilicate glass. Micro-holes with a roundness value of about 2 μm could be obtained if the appropriate rotational speed was employed.

This paper presents a study to improve machining quality concerning the method of drilling ceramics and other hard and brittle materials. Instead of making the drill vibrate by the ultrasonic actuator, a new design of PZT-driving ultrasonic work piece holder is proposed to ensure the high quality, high efficiency as well as longer life for drilling tools. The aim of this study is to investigate the influence of high frequency work piece excitation, on the drilling forces in drilling of brittle materials, in order to provide guidelines for further investigations of the process. For this paper, ultrasonic work piece holders were first designed by FEA and fabricated experimentally. The ultrasonic holders are used for a series of experiments under different vibration conditions to examine the behaviour of the work piece. First condition considers the sample as a solid structure, meaning that the excitation parameters are evenly dispersed throughout the sample allowing proper analysis of drilling forces. Inversely, second condition considers the sample as a flexible structure, this implies that the excitation parameters are not equally dispersed throughout the sample. Considering such conditions a set of objectives has been established:

1. Perform drilling force measurements on a sample.
2. Propose an excitation model for flexible structure excitation.
3. Verify the adequacy of the proposed excitation model.

The result should demonstrate whether the ultrasonic work piece holder could enhance the quality and efficiency of brittle material drilling. It should also provide guidelines for further drilling tests of solid and flexible structures.

2. Work piece excitation experimental set-up

In order to investigate the influence of work piece excitation on the drilling forces in brittle materials, a piezo-ceramic plate of dimensions 30x10 mm was used as a sample (Fig. 1, *1*). The specific ceramic used was lead-zirconate-titanite 4 or PZT 4. It was considered to be suitable for this purpose as it is brittle enough to emulate behaviour of most brittle materials, currently relevant in the industry. At such dimensions the sample is expected to behave like a solid structure, therefore the influence of drilling location is negligible, as the distribution of vibrations is uniform.

Every experiment in this article employs a cylindrical piezo-electric transducer of dimensions 35x27x20 mm as a device for sample excitation (Fig. 1, *2*). The sample is mounted on top of the cylinder with an adhesive, signal for the transducer is generated by the signal generator Agilent 33220A (Fig. 2, *1*) and amplified by the signal amplifier EPA-104 (Fig. 2, *2*).

In order to measure the changes in the forces during the drilling process, experiments employ a force-torque sensor Kistler 9365B. The signal from the sensor is amplified by Kistler 5018A (Fig. 2, *3*) charge amplifier, passed to Picoscope 3424 oscilloscope (Fig. 2, *4*) and subsequently observed on a PC.

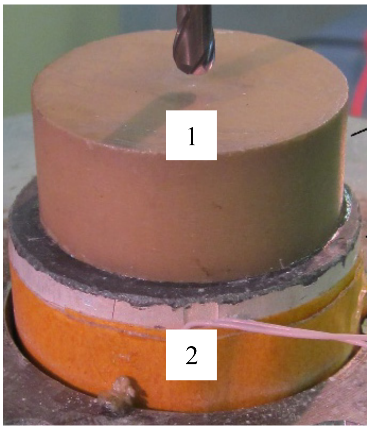

Fig. 1 Solid structure sample setup: *1* – 30×10 mm sample *2* – piezo-electric transducer

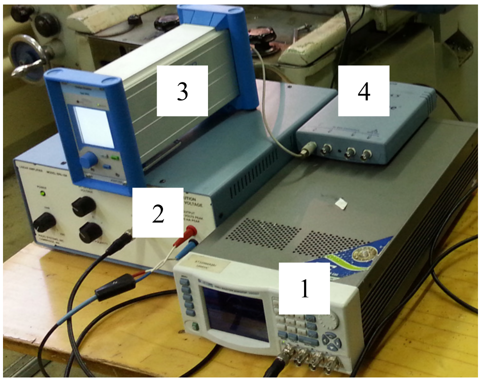

Fig. 2 Vibration generation and observation setup: *1* – signal generator Agilent 33220A, *2* – signal amplifier EPA-104, *3* – signal amplifier Kistler 5018A, *4* – Picoscope 3424

The drilling is performed with a 4 mm drill bit. The feed rate was kept at 0.05 mm/rev. The drilling was performed at speeds of 145, 290 and 580 rpm. The chosen speeds are reasonably spaced apart, therefore drilling with and without work piece excitation was performed at each speed to observe different behaviours of the sample. Provided below are the schematics of the drilling test setup (Fig. 3).

In order to observe the behaviour of a flexible structure when excited at high frequencies (~100 kHz) a piezo-ceramic disc of dimensions 50×2 mm was used as a sample (Fig. 4, *1*). The sample was clamped to the work table by three bolts equally spaced throughout the perimeter of the work piece, at a 120° angle from one another. Holographic vibration analysis was employed to observe different vibration modes of the sample [9]. The samples (Fig. 5, *1*) behaviour was recorded by an optic receiver (Fig.6, *1*) while being excited at different frequencies under an illumination source (Fig. 6, *2*), the process was controlled by the controller (Fig. 6, *3*).

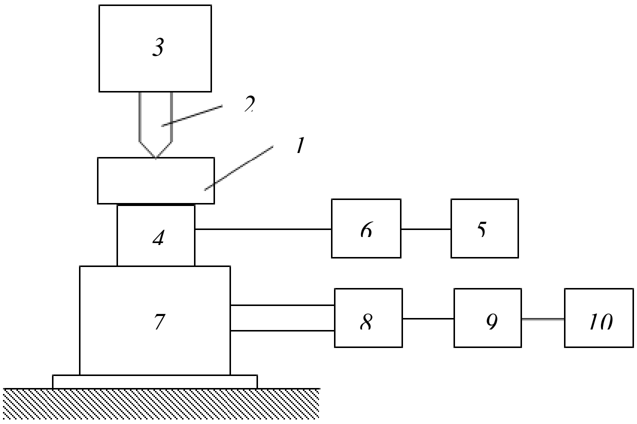

Fig. 3 Schematic representation of the drilling force test setup: *1* – specimen; *2* – drill; *3* – spindle; *4* – piezoelectric transducer; *5* – signal generator Agilent 33220A; *6* – amplifier EPA-104; *7* – force-torque sensor Kistler 9365B; *8* – charge amplifier Kistler 5018A; *9* – oscilloscope Picosope 3424; *10* – PC

Holograms of the sample were taken at high excitation states to enable further evaluation of the adherence of the sample behaviour to the mathematical model as well as observation of behaviour of a flexible structure at high (~100 kHz) frequencies. Confirmation of a resonant vibration mode at 100 kHz would enable further investigation into machining of solid and flexible structures under high frequency excitation.

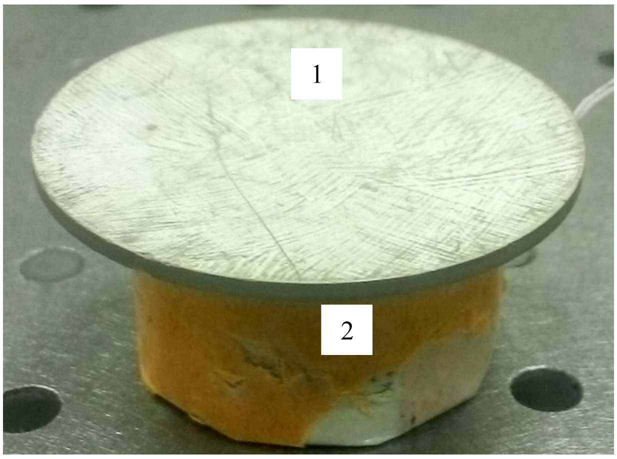

Fig. 4 Flexible structure sample setup: *1* – 50x2 mm sample, *2* – piezo-electric transducer

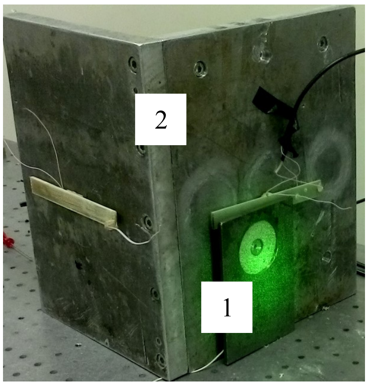

Fig. 5 Holography work area: *1* – excited sample, being scanned *2* – the work stage

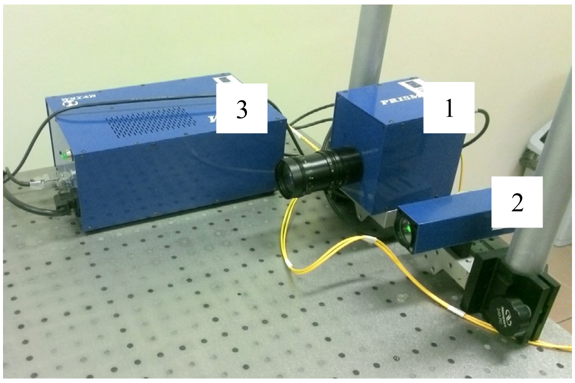

Fig. 6 Prism 100 holography equipment: *1* – optic receiver, *2* – illumination source, *3* – controller

3. Simulation of work piece vibrations

For further investigation of flexible structure behaviour under high frequency excitation, a mathematical model adequate to the real one needs to be developed. The simulations would be used to predict the behaviour of the sample without experimental techniques.

The dynamics of the circular work piece are described by the equation of motion on a block form by considering that the base motion law is known and defined by nodal displacement vector $\{U_K\}$ (1):

$$\begin{bmatrix} [M_{NN}] & [M_{NK}] \\ [M_{KN}] & [M_{KK}] \end{bmatrix} \begin{Bmatrix} \{\ddot{U}_N\} \\ \{\ddot{U}_K\} \end{Bmatrix} + \begin{bmatrix} [K_{NN}] & [K_{NK}] \\ [K_{KN}] & [K_{KK}] \end{bmatrix} \begin{Bmatrix} \{U_N\} \\ \{U_K\} \end{Bmatrix} = \begin{Bmatrix} \{0\} \\ \{R\} \end{Bmatrix}, \tag{1}$$

where $\{U_N\}$, $\{U_K\}$ are modal displacement vectors. Lower indices $_N$ and $_K$ represent free (unknown displacement) nodes and excited (known displacement) nodes respectively, combination pairs of these indices relate the displaced nodes to their elements and their corresponding positions in property matrices $[M]$, $[K]$, which are mass and damping matrices – the column and row positions of elements in the matrices are denoted by these combinations; $\{R\}$ is vector of unknown reaction forces at nodes under kinematic effect.

In modal analysis un-damped resonant frequencies of the work piece are found by solving equation (2):

$$([K] - \omega^2[M])\{\hat{U}\} = \{0\}, \tag{2}$$

here ω^2 is angular frequency, $\{\hat{U}\}$ is mode shapes vector. The simulations were developed using COMSOL multiphysics suite, Eigen-frequency study. The boundary constraint of the sample is the contour of the piezo-transducer edge, as this part of the sample is rigidly fixed to it. The simulation yields a number of resonant frequencies for further investigation and comparison to the experimentally obtained values.

The graphical representation of the FEM model itself is provided below (Fig. 7). A spring foundation constraint is introduced at highlighted areas. Areas on the top view (Fig. 7, a) represent the clamps and areas on the bottom view (Fig. 7, b) represent the bottom support. The Eigen frequency study of the model is set to return 150 vibration modes in order to cover the expected range of excitation (1-100 kHz).

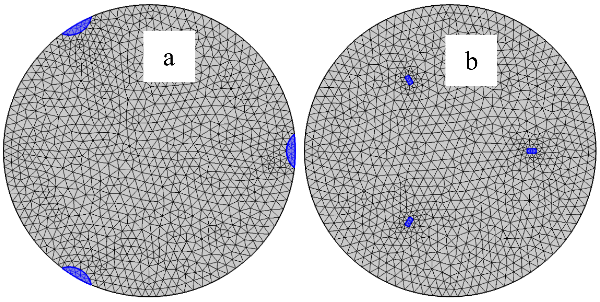

Fig. 7 Visual representation of FEM model: a – top view, b – bottom view

The modal analysis of work piece was carried out in range of 0 - 60 kHz by using Block Lanczos mode extraction method. The results of this analysis are shown in Table. Six modes of work piece vibrations were found in selected frequency range. The first calculated resonant frequency of the work piece is 5200 Hz. Due to verification of the FE model adequacy to physical one, the work piece vibration test was carried out. The work piece modes of vibration were measured by holography interferometry method.

4. Investigation results

During the holographic vibration mode analysis, 6 holograms were made at points of most intensive excitation. The number of experimentally obtained frequencies is lesser than the number of analytically obtained ones, therefore, frequency values closest to one another will be chosen for further investigation (Table).

After comparing the vibration mode shapes two forms (4.9-5.2 kHz and 88.2 and 98.96) were dismissed from further investigation, as they clearly do not match. It can be observed that the flexible structure sample exhibits a resonant vibration mode at a frequency close to 100 kHz (Fig. 8). Also, it can be seen that the behaviour of the material is relatively adherent to its simulations, as the remaining analytically and experimentally obtained vibration mode shapes (Fig. 8, a, b, c, d) appear to be similar in overall distribution of excited areas. However, inconsistencies do exist; for instance, the simulated vibration shape in Fig. 8, c is not excited at the middle of the plate as it can be observed in the hologram. Generally the distribution of excitation areas in the holograms lacks symmetry, which is characteristic of the simulations. The appearance of the deviations suggests that they are in most part caused by the asymmetrical nature of sample clamping and in part by the unavoidable difference between real and ideal cases. The applicability of the model could be improved by either enhancing the accuracy of the sample clamping setup or tweaking the model to accommodate the existing clamping conditions. However, since the resonant vibration mode at ~100 kHz frequency has been confirmed, further investigation of flexible structure machining while under high frequency excitation is available and can be relatively well predicted through the use of the mathematical model.

Table

Natural frequencies of simulated and experimentally obtained vibration modes

Vibration mode	Hologram frequency, kHz	Simulation frequency, kHz
1	4.9	5.2
2	6.3	5.6
3	12.3	12.89
4	43.1	40.1
5	88.2	98.96
6	99.8	101

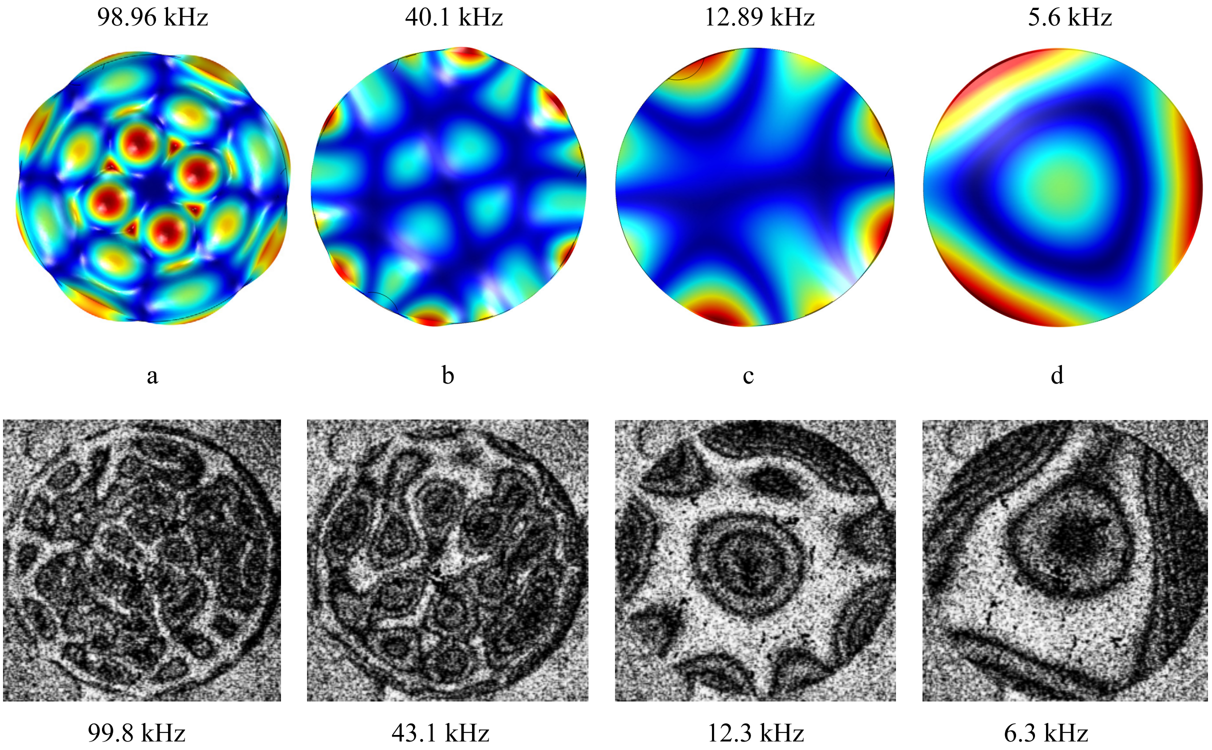

Fig. 8 Corresponding vibration modes: *a* – 99.8/98.96 kHz, *b* – 43.1/40.1 kHz, *c* – 12.3/12.89 kHz, *d* – 6.3/5.6 kHz

The results obtained from the drilling experiment demonstrate that there is a slight difference between torque forces when drilling a still and excited work piece at a low speed of 145 rpm (Fig. 9). However, cutting forces are significantly lower for excited pieces when drilling at higher speeds.

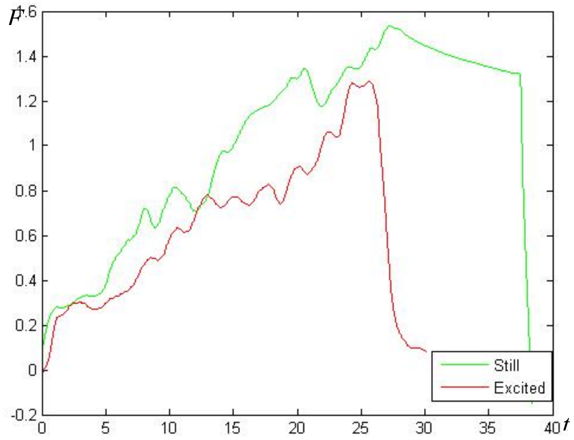

Fig. 9 Cutting force graph at 145 rpm

From Fig. 9 above it can be seen that the plots differ only slightly. The averages of cutting force (before maximum peak) differs by 24%.

When drilling at a higher speed (290 rpm) the distance between the plots is a lot more consistent (Fig. 10). However the difference between the averages of cutting force (before maximum peak) is similar to the previous attempt – 22%.

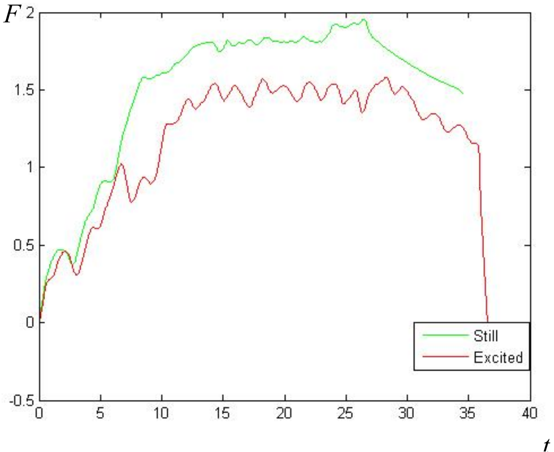

Fig. 10 Cutting force graph at 290 rpm

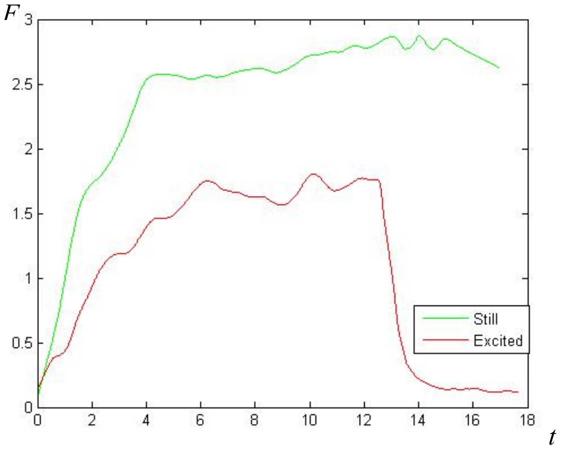

Fig. 11 Cutting force graph at 540 rpm

With an increase in drilling speed of up to 540 rpm (Fig. 11) the difference between the plots becomes more obvious. In this case the difference between averages of cutting force is 40%.

According to the obtained results – a trend can be observed. The decrease in torque is larger and more consistent at higher speeds. It is important to mention, it is not only the drilling speed that changes along with each attempt – the feed rate (0.05 mm/rev) also changes its absolute value with each step-up in speed. Therefore, feed rate should be taken into consideration in further investigations as well, as it should have had a significant influence on the drilling forces. Based on the results, further investigations should focus on higher drilling speeds and lower feed rates. Such considerations occur due to an apparent increase of the force difference between drilling of excited and stationary sample at higher speeds.

5. Conclusions

1. After performing the drilling experiment on a sample, a decrease in drilling forces was observed when exciting the work piece at a 100 kHz frequency. The decrease appears to be more prominent at higher drilling speeds – the average difference in cutting forces was:

1. 24% at 145 rpm;
2. 22% at 290 rpm;
3. 40% at 540 rpm.

Considering such trend – further investigations should focus on drilling at higher speeds and preferably lower feed rates.

2. In order to observe, the excitation conditions that would apply to a flexible sample, a model for simulation of vibration modes was developed. The modal analysis was conducted using Block Lanczos mode extraction method. The simulations were conducted using COMSOL multiphysics suite,

3. Holographic vibration mode analysis of a flexible sample demonstrates a sufficient sample excitation at frequencies close to 100 kHz. When compared to the simulated vibration modes at similar frequencies, the mode shapes differ considerably – such deviations most probably occur due to the asymmetric nature of sample clamping during the holographic vibration mode analysis. If this issue was addressed the model could find practical applications in future research.

6. Recommendations

Since high frequency excitation appears to have a positive effect on both – solid and flexible structures, further drilling experiments can be carried. In order to achieve a proper drill placement when drilling the flexible sample, the proposed model of flexible structure vibrations could be used, if asymmetric sample clamping issue is addressed – either in the model, or the experimental technique itself. Considering the results of the drilling experiment, further drilling experiments should be carried out at higher drilling speeds, as there appears to be a correlation between the decrease of drilling forces and increased drilling speed.

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VIBRACINIS BANDINIO SUŽADINIMAS SIEKIANT GRĘŽIMO JĖGŲ SUMAŽINIMO TRAPIOSE MEDŽIAGOSE

Reziumė

Straipsnyje tiriama gręžimo jėgų sumažinimo trapiose medžiagose, bandinį sužadinant aukštais dažniais, galimybė. Analizuojamos dvi sužadinimo sąlygos: 1. bandinys sužadinamas kaip standus kūnas; 2. bandinys sužadinamas kaip tamprus kūnas. Bandinio sužadinimo poveikiui gręžimo jėgoms tirti buvo atlikti gręžimo bandymai. Buvo matuojamos ir lyginamos gręžimo jėgos sužadinant ir nesužadinant bandinio. Gręžimai buvo atliekami skirtingais greičiais – 145, 290 ir 540 aps./min. Didėjant gręžimo greičiui, vidutinis gręžimo jėgų skirtumas tarp sužadinto ir nesužadinto bandinio gręžimo pakilo nuo 24 ik 40%. Antros sąlygos analizei buvo atliktos bandinio vibracijų režimų simuliacijos. Simuliacijų adekvatumas buvo patikrintas atliekant holografinę vibracijų analizę – simuliacijų rezultatai ne visiškai atitinka eksperimentinius. Tai gali sąlygoti nesimetriškas bandinio prispaudimas holografijos metu, atsižvelgiant į tai tūrėtų būti pakoreguotas arba simuliacijų modelis arba eksperimentinė technika, kad būtų galimas praktinis modelio pritaikymas tolimesniuose tyrimuose.

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VIBRATIONAL EXCITATION OF A WORK PIECE FOR DRILLING FORCE REDUCTION IN BRITTLE MATERIALS.

Summary

Article investigates the possibilities of reducing drilling forces in brittle material drilling, through high frequency excitation of a work piece. Two excitation conditions are analyzed – first, when the sample acts as a solid structure and second, when the sample acts as a flexible structure. In order to analyze the effect, work piece excitation has on drilling forces, drilling experiments were conducted, drilling forces were measured and compared between the case when the sample was drilled in a conventional way and when the work piece was excited. Drilling was conducted at different speeds – 145, 290 and 540 rpm. With the increase of speed, average difference between forces of conventional drilling case and drilling of an excited work piece has increased from 24 to 40%. In order to analyze the behaviour of a flexible structure when subjected to excitation, vibration mode simulations of the sample were developed. To test their validity, holographic vibration analysis was conducted – the simulation results do not completely correlate with the experimental ones. Such deviations may be caused by assymetrical clamping of the sample durring the holographic vibration mode analysis. With regards to this, either the experimental technique or the simulation model should be tweaked to enable its practical application in further research.

Key words: work piece vibrations, solid structure, flexible structure, holographic interferometry.

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