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APPLICATION OF NUMERICAL SIMULATION FOR THE ANALYSIS OF THE PROCESSES OF ROTARY ULTRASONIC DRILLING

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Abstract

Rotary ultrasonic machining (RUM) is a hybrid process that combines diamond grinding with ultrasonic machining. It is most suitable to machine hard brittle materials such as ceramics and composites. Due to its excellent machining performance, RUM is very often applied for drilling of hard machinable materials. In the final phase of drilling, the edge deterioration of the drilled hole can occur, which results in a phenomenon called edge chipping. During hole drilling, a change in the thickness of the bottom of the drilled hole occurs. Consequently, the bottom of the hole as a plate structure is exposed to the transfer through the resonance state. This resonance state can be considered as one of the important aspects leading to edge chipping. Effects of changes in the bottom thickness and as well as the fillet radius between the wall and bottom of the borehole on the stress-strain states during RUM are analyzed.

Key words

Numerical simulation, Finite element method, Rotary ultrasonic drilling, Edge chipping

INTRODUCTION

In the context of the development of modern technology machinery (1) and equipment, the most recent industrial production processes and the technological processing of new materials with special or modified mechanical properties is required. Due to improved mechanical properties, new materials are usually characterized by complications during the execution of the specific technological processes. Significant problems occur mainly in the processes of machining and welding of such materials. In the case of machining processes, the specific mechanical properties of these materials cause their poor machinability. They are usually hard, with high strength and wear resistance. Simultaneously, these materials are brittle and under critical load will pass from elastic behavior directly into the formation of microcracks and then propagation of cracks and fracture occurs. When using conventional processes for machining such materials occur serious problems, respectively, conventional machining processes for machining such materials are not applicable.

One of the possibilities for machining such materials is the use of non-standard machining methods based on other physical principles than conventional machining methods. Significant achievements in this field can be attained by the application of positive effects of ultrasonic waves in the conventional machining process. As a type of non-conventional machining can be regarded rotary ultrasonic machining (RUM). RUM is a hybrid machining process which uses the machining principle of grinding in combination with the ultrasonic machining by diamond tools. This principle of ultrasonic machining is used extensively especially in the processes of holes drilling. Abrasive particles, typically diamond grains are applied on the active surface of the tool (front surface and side surfaces). The combination of diamond tool movements, i.e. rotation of the tool combined with its axial ultrasonic frequency vibrations, achieves the high efficiency in the drilling hole process. However, some problems arise at the moment when the finalization of drilling through-holes are made, where the effect of ultrasonic excitation of cutting force acting on the bottom of borehole results in unfavorable stress-strain states. As a result of these states, the breaking of the core of the drilled hole occurs and the output edge of the drilled hole is thus unacceptably damaged. This phenomenon is generally called "edge chipping" and its origin includes several factors including the geometric parameters of the tool and drilled hole, material properties and the process parameters of rotary ultrasonic drilling (RUD). From this perspective the main objective of this paper is to analyze and evaluate the effect of the edge radius of the drilling tool and bottom thickness of the drilled hole on the stress-strain states arising in the "edge chipping" region for RUD.

FORMULATION OF THE PROBLEM

Rotary ultrasonic drilling using diamond grinding tools is classified as a special method of material grinding in which a diamond tool performs a rotational movement and at the same time axially vibrates (Fig.1). A rotating tubular tool with bonded diamond abrasives is ultrasonically vibrated in the axial direction and feeds to the workpiece at a constant feed-rate or a constant force. Coolant pumped through the core of tubular tool washes away the removed particles, prevents jamming of the drill, and keeps it cool.

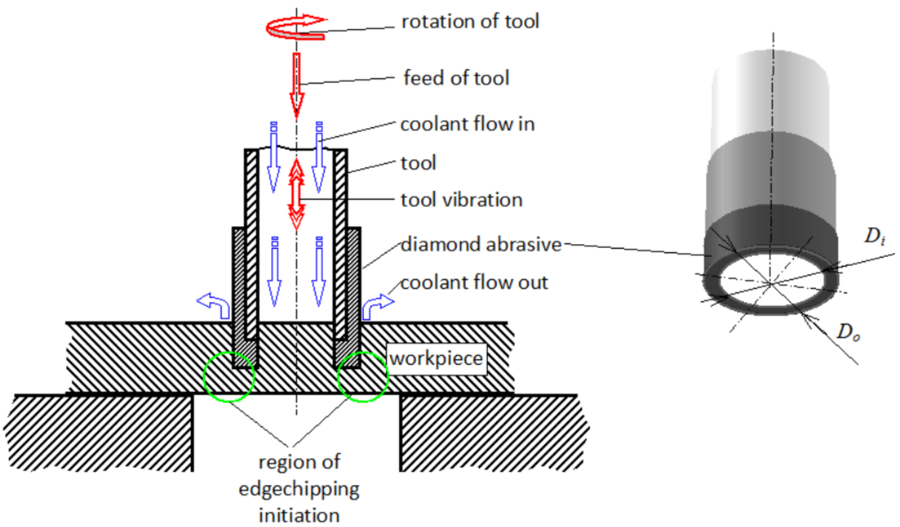


Fig. 1 *Fundamental principle of RUD using a tubular tool (2)*

As already stated, RUM is considered to be a combination of the ultrasonic machining process and grinding. It represents a relatively complex process with many input variables. The main problem is the determination of the cutting force that it is based on different principles. Many abrasive models (4-6) for the determination of cutting force began with an analysis of one abrasive particle. Basic input parameters affecting the process of rotary ultrasonic machining, respectively input data for the development of cutting force model describing the process of RUM are presented in Fig. 2.

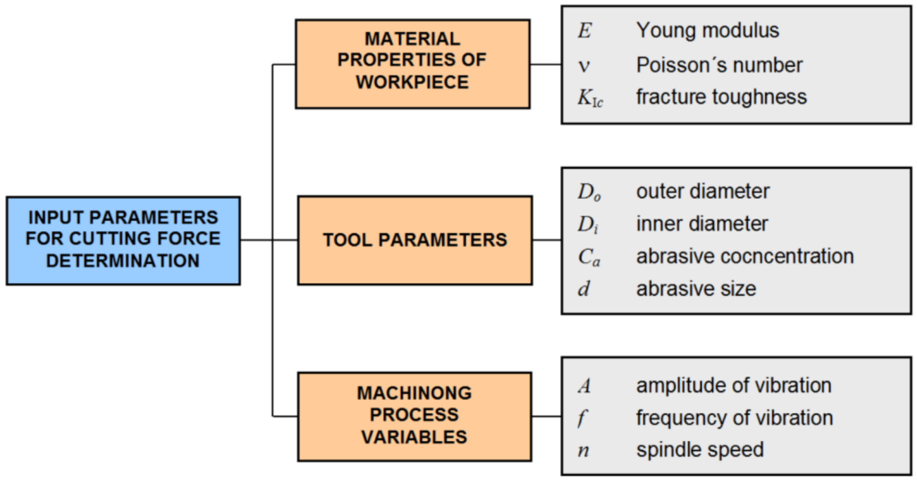


Fig. 2 *Input parameters for determination of the cutting force for RUD*

Cutting force model for process RUM [3] can expressed by the equation

$$F = w^2 \left\{ 2 \tan\beta \sqrt{\tan^2\beta + 2} \left[\frac{1}{2} - \frac{1}{\pi} \arcsin\left(1 - \frac{w}{A}\right) \right] H_v N_a \right\}, \qquad [1]$$

where
- w - maximum depth of abrasive particle penetration into the workpiece [mm],
- β - semi-angle between two opposite edges of an abrasive particle [°],
- N_a - number of active abrasive particles on the end face of a drilling tool [-],
- H_v - Vickers hardness of the work-piece material [MPa],
- A - amplitude of the ultrasonic vibration [mm].

DEVELOPMENT OF A FINITE ELEMENT MODEL

The geometric shape of the workpiece and then the mathematical model was developed and solved using the finite element method. The computational model and numerical simulation of the RUD process were carried out in the environment of the ANSYS software. Determination of stress-strain states arising in the workpiece, which occurs in the RUD process needs to be divided (3) into three phases, i.e. solved in three steps using following analyses:

- *Static analysis* - taking account of contact pressure - distributed pressure on the bottom surface of the drilled hole. The finite element equation takes the form

$$\mathbf{Ku}_{st} = \mathbf{F}_{st} \;, \qquad [2]$$

where K - is the stiffness matrix, $\mathbf{F}_{st}$ - vector of static load, $\mathbf{u}_{st}$ - vector of static nodal displacements.

- *Modal analysis* - determination of mode shapes and natural frequencies. The equation of motion for modal analysis, which reflects the static pre-stress can be written in the form

$$\mathbf{M\ddot{u}} + (\mathbf{K} + \mathbf{K}_{\sigma})\mathbf{u} = \mathbf{0}, \qquad [3]$$

where $\mathbf{M}$ - is the mass matrix, $\mathbf{\ddot{u}}$ - the vector of nodal accelerations, $\mathbf{K}_{\sigma}$ - increment of stiffness matrix due to static load.

- *Harmonic analysis* - taking into account the effect of periodic pulsating load represented by the uniform distribution of pressure acting on the bottom surface of the drilled hole with a frequency corresponding to ultrasonic vibration frequency of instruments, i.e. 20 kHz. The equation of motion for a mechanical system with harmonic excitation is

$$\mathbf{M\ddot{u}} + (\mathbf{K} + \mathbf{K}_{\sigma})\mathbf{u} = \mathbf{F}_{a} e^{i\omega t}, \qquad [4]$$

where $\mathbf{F}_{a}$ - is the vector of amplitudes of the load, $\omega = 2\pi f$ - exciting angular frequency (f = 20 kHz).

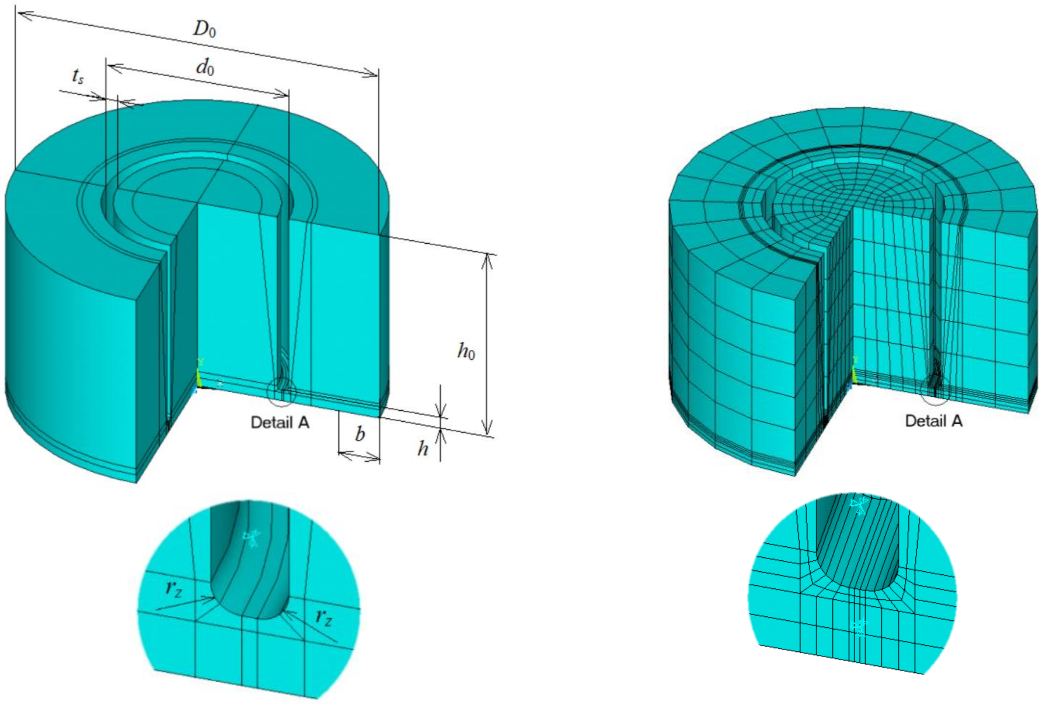
For the development of the finite element model of the workpiece with a hole drilled by RUD, the finite element of the type SOLID95 was chosen from the ANSYS elements library. As shown in Fig. 1, it is assumed that the edge chipping will be initiated in a brittle fracture mode when the maximum stress satisfies the failure criterion. The edge chipping thickness predicted by the FEA model is given by the vertical distance between the location where the edge chipping is initiated and the workpiece bottom surface. The stress failure according to equivalent von Mises stress criterion is used for the prediction of the edge chipping start-up

$$\sigma_{eq} = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2}{2}} \;, \qquad [5]$$

where σ_1, σ_2, and σ_3 are stresses in the principle directions.

NUMERICAL ANALYSIS – RESULTS AND DISCUSSION

The geometrical and finite element models of the workpiece used for numerical simulations with details in the area of the hole bottom are shown in Fig. 3.



a) b)

***Fig. 3** Geometrical model (a) and finite element model (b) of the workpiece with the details from the region of the hole bottom*

Table 1 Drilling parameters

Parameters			Value
outer diameter	D_0	[mm]	16.0
workpiece thickness	h_0	[mm]	9.0
diameter of drilled hole	d_0	[mm]	8.0
bottom thickness	H	[mm]	0.2 ÷ 9.0
width of drilled gap	t_s	[mm]	0.5
edge radius	r_z	[mm]	0.03 ÷ 0.2
width of support	B	[mm]	0.0 ÷ 3.0
Young modulus of workpiece material	E	[GPa]	300.0
Poisson´s number of workpiece material	ν	[-]	0.23
density of workpiece material	ρ	[kg.m^{-3}]	3720.0
tensile strength of workpiece material	R_m	[Pa]	350-580
excitation frequency	F	[kHz]	20.0
amplitude of excitation force	F_c	[N]	200.0

Modal analysis of the workpiece is carried out applying the finite element model illustrated in Fig. 3b. There were studied changes in natural frequencies and mode shapes with respect to the changes of basic geometric parameters that are changing during the execution of the drilling hole by the RUM method. The first two mode shapes are shown in Fig. 4 (a - vertically vibrating core; b - vibration with tilting core).

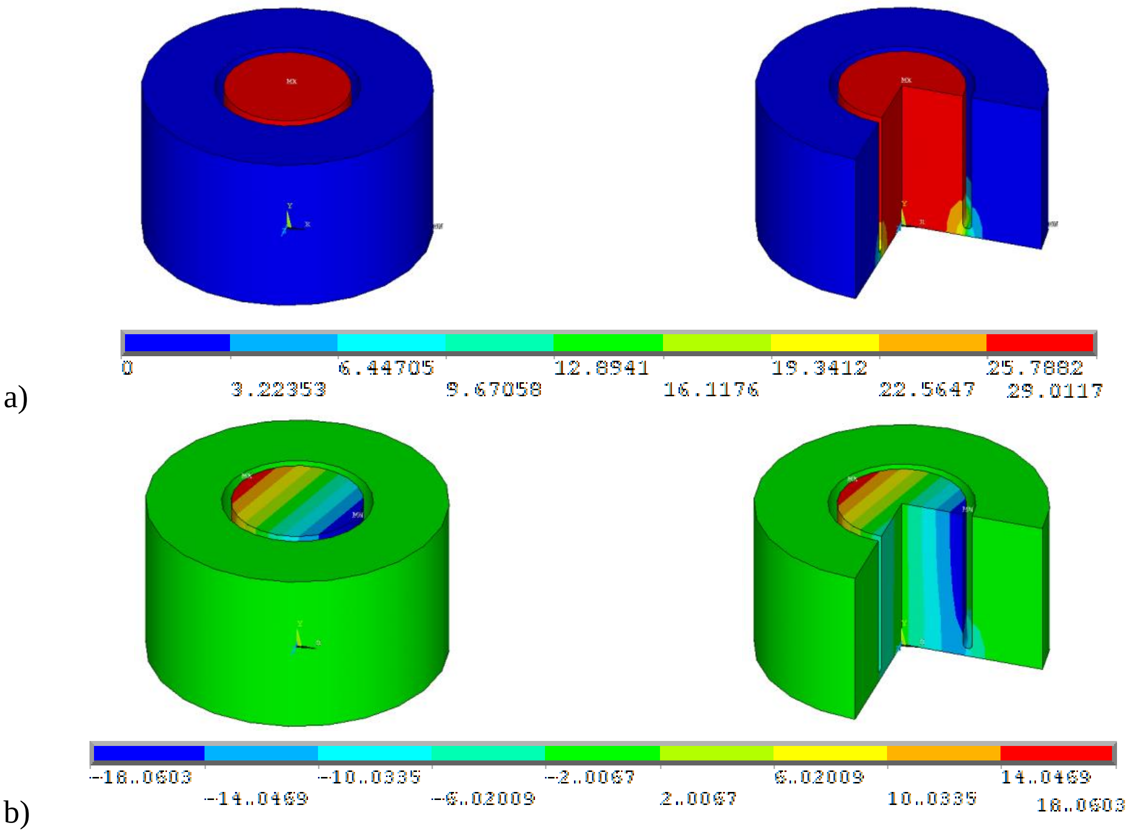


Fig. 4 *Mode shapes of the workpiece vibrations: a) vertically vibrating core; b) vibration with tilting core (h = 0.5 mm,* r_z *= 0.2 mm, b = 3.0 mm)*

Dependencies of the first two natural frequencies on the bottom thickness of the drilled hole are shown in Fig. 5. The values of both natural frequencies decrease with the decreasing bottom thickness of the drilled hole.

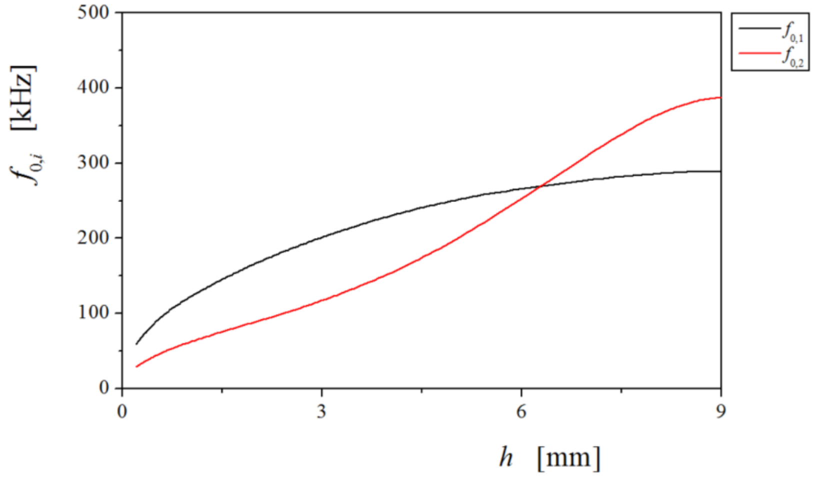


Fig. 5 *Dependency of the first two natural frequencies* $f_{0,i}$ *on the bottom thickness h (b = 3 mm,* r_z *= 0.2 mm)*

The process of forced vibration caused by pulsating force that simulates the effect of a cutting force in the process of RUD is carried out by harmonic analysis. The fields of equivalent von Mises stresses in the hole bottom for the various bottom thicknesses are shown in Fig. 6.

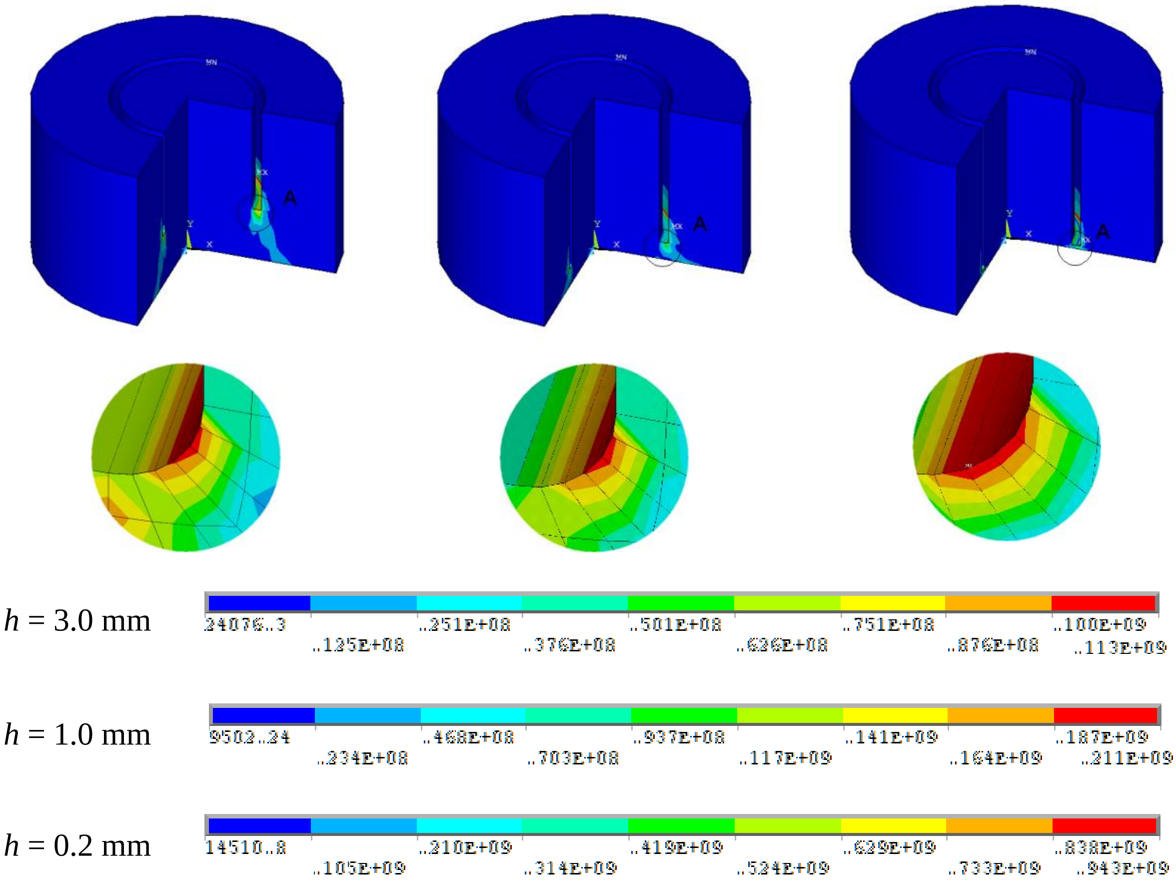


Fig. 6 *Equivalent von Mises stresses [Pa] (r_z = 0.1 mm, b = 3.0 mm)*

The values of the maximum von Mises equivalent stresses depending on the bottom thickness h for different radii of curvature r_z and support width of b = 3.0 mm are shown in Fig. 7.

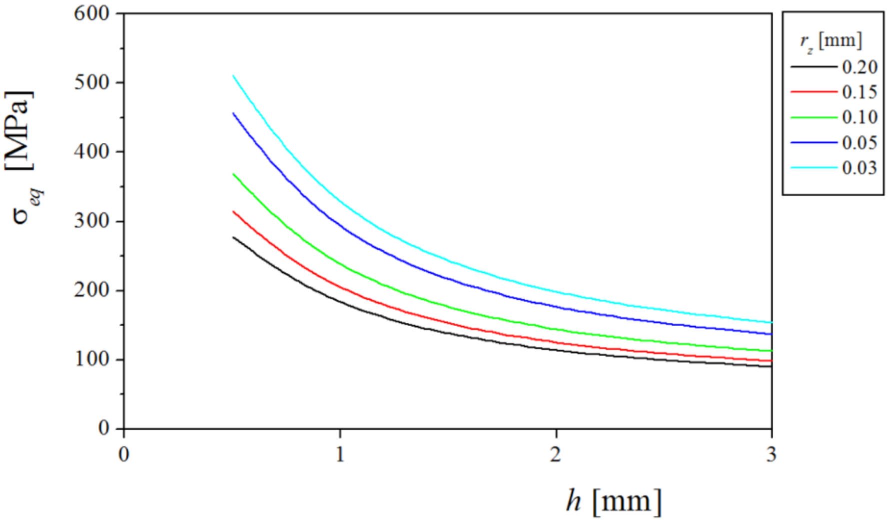


Fig. 7 *Dependence of equivalent von Mises stresses σ_{eq} on the bottom thickness h for different radii of bottom curvature r_z (b = 3.0 mm)*

CONCLUSION

The reason for the occurrence of the phenomenon called edge chipping that occurs in the process of rotary ultrasonic drilling is studied in this paper. Many of material and processing parameters are involved in the development of the phenomenon. The influence of individual parameters, especially the hole bottom thickness and bottom radius, was studied by numerical simulations using the finite element method. Decreasing the thickness of the hole bottom and decreasing the radii of the curvature bottom results in increasing the value equivalent (von Mises) stress. Then as the critical value can be considered, the equivalent stress σ_{eq} takes the value that is greater than the tensile strength (Table 1) of the drilled material. That means if the condition

$$\sigma_{eq} \leq R_m \qquad [6]$$

is not fulfilled, at the point of maximum equivalent stress, the material loses the integrity, i.e. cracks can arise and propagate – the phenomenon of edge chipping occurs.

Using the numerical simulations and procedures presented in this paper, the edge chipping phenomenon can be predicted.

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