Digital Twins for Micro Machining

Vytautas Ostasevicius[1], Sandra Mikuckyte[2], Rimvydas Gaidys[3], Vytautas Jurenas[4], Vytautas Daniulaitis[5]

[1] Institute of Mechatronics, Kaunas University of Technology, Studentu Street 56, LT-51424 Kaunas, Lithuania; vytautas.ostasevicius@ktu.lt
[2] Institute of Mechatronics, Kaunas University of Technology, Studentu Street 56, LT-51424 Kaunas, Lithuania; sandra.mikuckyte@ktu.lt
[3] Department of Mechanical Engineering, Kaunas University of Technology, Studentu Street 50, LT-51368 Kaunas, Lithuania; rimvydas.gaidys@ktu.lt
[4] Institute of Mechatronics, Kaunas University of Technology, Studentu Street 56, LT-51424 Kaunas, Lithuania; vytautas.jurenas@ktu.lt
[5] Department of Applied Informatics, Kaunas University of Technology, Studentu Street 50, LT-51368 Kaunas, Lithuania; vytautas.daniulaitis@ktu.lt

Abstract. Thanks to digital twins encompassing virtual and physical models, the cutting processes under study are attractive for improving modern manufacturing processes. The aim of this work is to propose an efficient method of controlling the higher buckling modes of a vibration micro drilling tool, which allows to increase the efficiency of this technological process.

Keywords: Data Collection, Vibration Drilling, Buckling Stiffness, Higher Mode, Process Efficiency.

1. Introduction

The dynamics of the micro-drilling system investigated in [1] is focused on the evaluation of the coupling effect between the lateral and torsional vibrations by numerical finite element (FE) method modeling the micro drill as a pre-twisted rotating beam element. The study [2] describes micro-drilling techniques and methods to evaluate the improvement trends of these processes. In addition to the traditional micro-drilling processes, non-traditional electrical, chemical and thermal methods of forming micro-holes are also analyzed. Deformation and critical speed of a micro drill as a pre-twisted beam are investigated in [3] to improve machining quality. As a result of the numerical analysis, it was found that the transverse load decreases as the micro-drill penetrates the workpiece. The analysis of the research sources did not provide data on the influence of the eigen modes of the micro drill and the possibilities to improve the characteristics of the machining processes.

2. Virtual Twin of Micro Drill

The 30x0.6 mm micro drill virtual model was developed to investigate the dynamics of a micro drill. A geometric drill model was developed with the CAD software SolidWorks (Fig.1a) and later imported into the numerical simulation software. The model (Fig. 1b) was developed using the tetrahedral 10-node FE.

Equation describing the drilling process:

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

where $[M]$, $[K]$ - mass and mechanical stiffness matrices respectively; $\{U_N\}$, $\{U_K\}$ - modal displacement vectors; $\{R\}$ - FE nodes reaction forces vector.

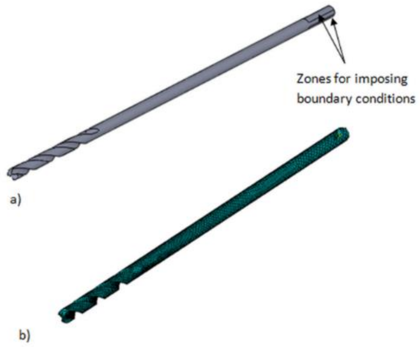


Fig. 1. Chuck-mounted micro-drill (a) and its FE model (b)

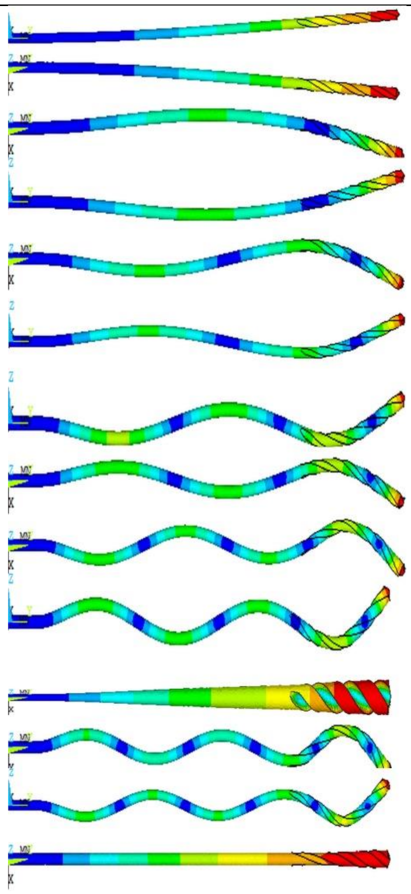
The eigenvalue equation can be written as:

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

where ω^2 – natural circular frequency, [Φ]- the eigenvector representing the mode shapes.

The vibrational analysis was performed in the 0–60 kHz range (Table 1).

Table 1 Micro drill eigenmodes

No.	Eigenfrequency, Hz	Mode shape
1.	692	
2.	692	
3.	3753	
4.	3819	
5.	9228	
6.	9568	
7.	18134	
8.	18281	
9.	30523	
10.	32657	
11.	32084	
12.	44217	
13.	45620	
14.	51651	

Assessing the adequacy of the virtual model to the physical the experimental studies of micro drill dynamics were performed using an accelerometer KD91, an oscilloscope PicoScope 4424, the data of which were processed with PicoScope 6.0 software. The physical micro drill free vibration amplitude-time characteristic is presented in Fig. 2.

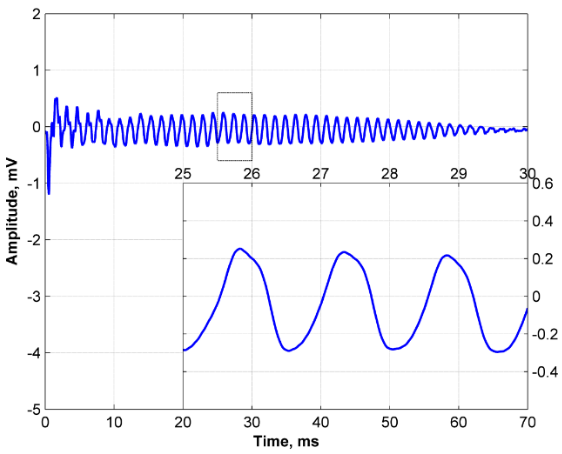


Fig. 2. Micro drill **t**ime **-** amplitude characteristic

The eigenfrequency generated by the virtual drill model at 692 Hz (Table 1) is close to the physically obtained eigenfrequency of 678 Hz (Fig. 2), which corresponds to an error only 3.41%.

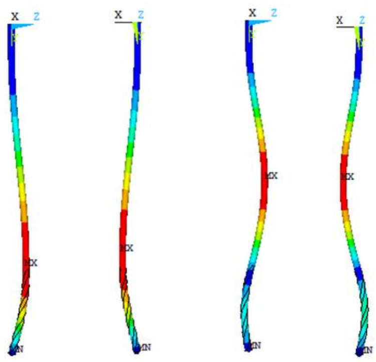
3. Virtual Micro Drill Model for Buckling Analysis

The critical micro drill loads were performed by eigenvalue buckling analysis:

$$([K]+\lambda[\sigma])\{\psi\}=\{0\} \qquad (3)$$

Where [K], [σ]-stiffness and stress matrixes; λ – eigenvalue; {ψ} – displacements eigenvector.

For the same conditions as in previous virtual modal analysis, the first two critical buckling modes of the micro drill were identified, which shapes are shown in Fig. 3. According to the first and second buckling modes, the micro-drill bends under axial loads 23 N and 69 N in the *YZ* plane and 31 N and 72 N in the *XY* plane, respectively, indicating that under the second buckling mode the drill withstands almost 3 times the axial loading.

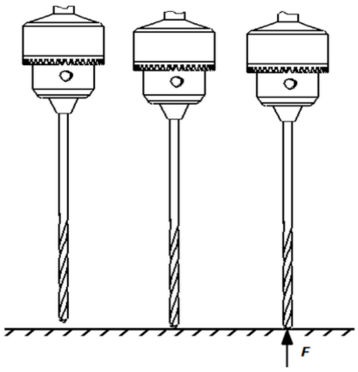


a) b) c) d)

Fig. 3. Buckling modes: in *YZ* and *XY* bending planes the firsts (**a**), (**b**) and the seconds in *YZ* and *XY* planes, respectively

4. Virtual Micro Drill Model for Transient Analysis

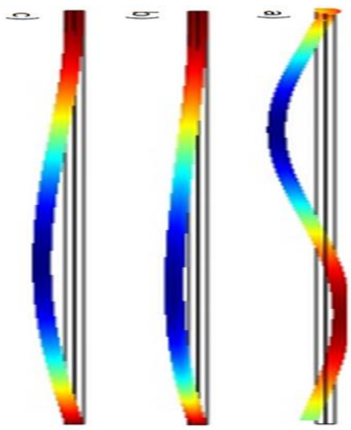
The process of kinematically excited micro-drilling was divided into three stages and modeled by Comsol Multiphysics software: 1) in the time interval 0 - 0.002 s, when the tool does not touch the workpiece (Fig. 4 a) and is excited by a second eigenfrequency of transverse vibrations (Fig. 5 a); 2) in the time interval (0.002-0.006) s, when the tool and the workpiece only touch each other (Fig. 4 b). At that time the nature of the tool vibrations changes and the tool continues to vibrate at the first buckling mode (Fig. 5 b) and 3) from 0.006 s, under the axial load F (Fig. 4c) the tool plunges into



a) b) c)

Fig. 4. Schematic of the analysis of the micro drill: before touching a) and touching b) the surface of the workpiece; (c) plunging into the workpiece

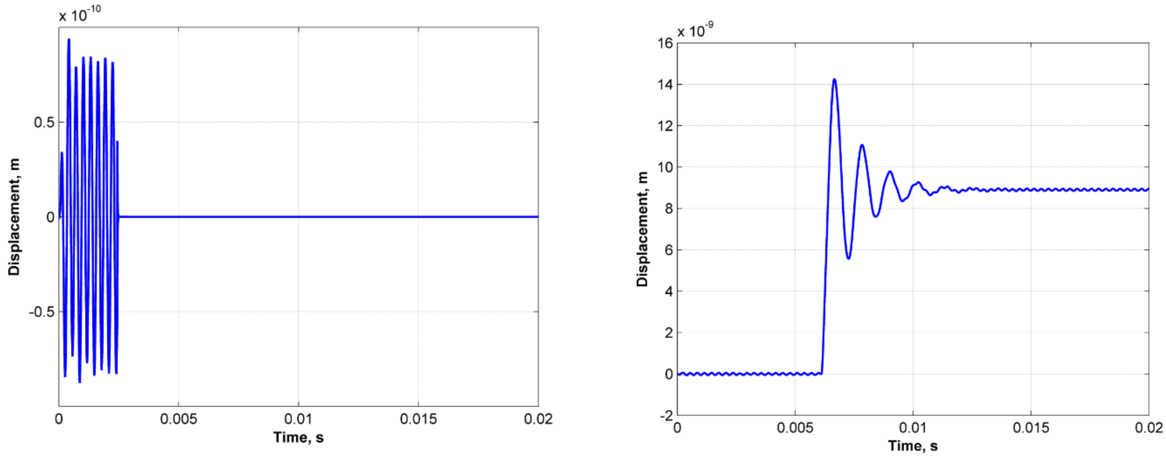
the workpiece vibrating on the second mode (Fig. 5 c). At the third stage, the vibration amplitudes of the nodal point of



a) b) c)

Fig. 5. Modes of micro drill: the second transverse (a); the first (b) and second (c) buckling modes

this mode are negligible (Fig. 6 a) while the amplitudes of the tool tip vibration are significant (Fig. 6 b).



a) b)

Fig. 6. Time-amplitude characteristics of the transient vibrations of the tool midpoint (a) and of the tool tip (b)

From the dependence of the reaction force acting on the workpiece (Fig. 7). At the moment the tool touches the workpiece the transformation of the tool buckling from the unstable second mode to the stable first mode is observed.

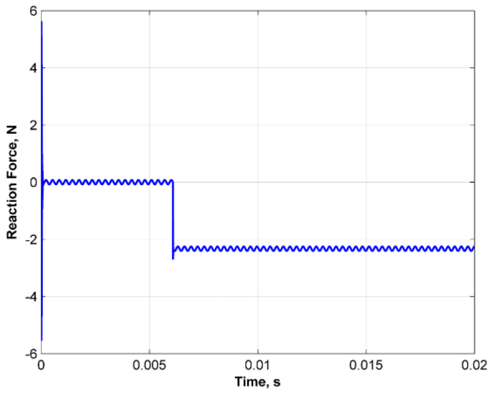


Fig. 7. The reaction force of a micro drill in the transient process

5. Micro Drill Physical Twin and Experimentation

The CNC milling machine DMU-35M was used for the experiments (Fig. 8).

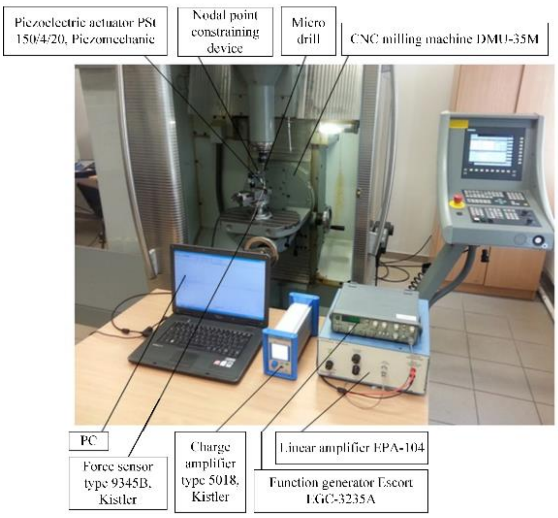
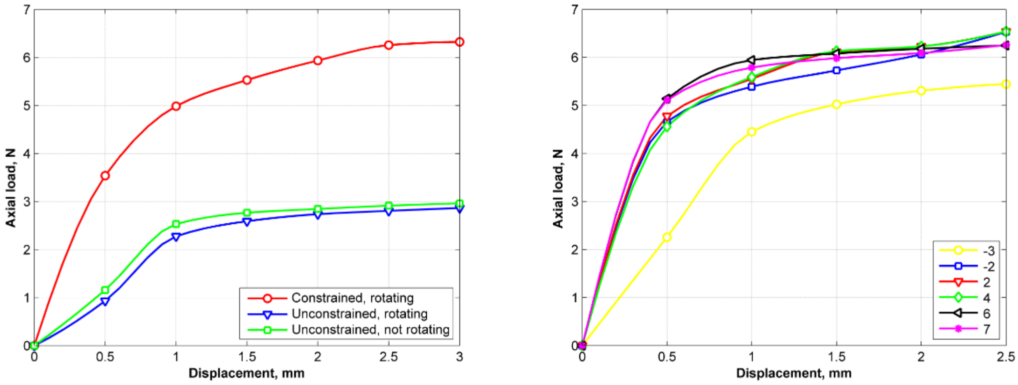


Fig. 8 The experimental set-up

In order to take the buckling advantages, the nodal point of the second mode was constrained. As shown in Figure 9a, the bending stiffness of a rotating (1500 rpm) constrained tool is less than non-rotating and not constrained one. This is caused by the centrifugal force of the rotating tool. Similar results were obtained in the virtual model.



a) b)

Fig. 9. Buckling dependence on the position of the constraint (a) and from its shifting in the diapason from -3 to +7 mm on either side of the buckling node (b)

The bending stiffness dependences shown in Fig.9 a confirm a small effect of the change in the position of the constraint, which allows to perform vibration micro-drilling by excitation of the tool at a frequency of 225 Hz (Fig. 10).

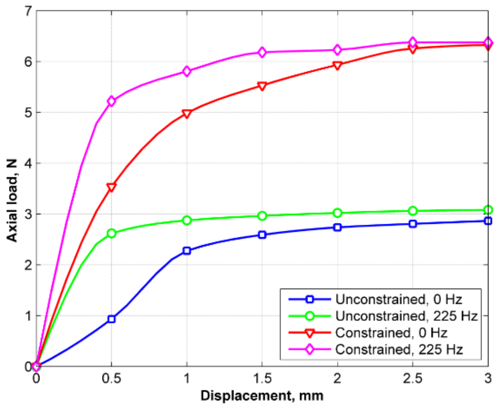


Fig. 10. Dependence of vibration drilling axial load on drill buckling node constraint position

Conclusions

The results of the digital twins investigation of micro-drilling process reveal the possibility to significantly increase the stiffness of the tool by shaping it by the second buckling mode, which allows the increase of the drilling force almost three times.

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