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Analiza przemieszczeń roboczej części frezu podczas frezowania stali

Analysis of milling cutter working part displacements during milling of steel

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The aim of research was focused on analysis of tool displacements during milling of hardened steel, conducted with various overhangs. The measurements of displacements were carried out in feed and feed normal directions. Moreover, the measurements of forces, vibrations and surface roughness' parameters were also conducted.

KEYWORDS: milling, dynamics, surface roughness

Displacements and mechanical vibrations of milling cutters during machining are phenomena that should be minimized because they have an adverse effect on process stability, accuracy of workpiece, machined surface quality, tool durability and technical condition of the machine tool. The variability of the geometrical parameters of the surface texture is of great importance for the cutting process dynamics - the variation of the area of cut as a function of the milling cutter rotation angle. This has a direct effect on the phenomena that are inseparably associated with the milling process, such as vibrations, forces and displacements. This in turn affects the roughness of the surface [1]. Knowledge of these issues allows for an in-depth evaluation of the milling process and - as a result - the selection of appropriate machining parameters to achieve the desired technological effects.

The magnitude of displacements depends on many factors, and the most important are the total cutting force and its components. Under the influence of forces, the cutter deforms elastically and creates a shape error [3]. Knowledge of the components of total cutting force [2] and stiffness of the system allows estimating the amount of deflection and displacement of the working part of the cutter, and thus also the roughness of the machined surface [4, 5]. Therefore, the work focuses on the description of these phenomena and the relationship between the studied quantities. In addition, causal relationships regarding mutual relations are presented.

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Scope and methodology of research

The research was aimed at analyzing displacements of the working part of a ball end mill during the machining of hardened steel at different values of the tool's overhang. Measurements were made for tool displacements in two directions: normal and feed. The forces and vibrations were measured, and after milling, the roughness parameters of the machined surface were examined.

The machined material was X155CrVMo12-1 steel (56HRC). The tests were carried out on a vertical milling machine Avia FND-32F. The process of upward milling was carried out. The material was mounted in an APX 125 mm machine vice. The ER32 holder was used to attach the tools.

Ball end mills of the same diameter and working part geometry were used, but with different overhangs (fig. 1, table).

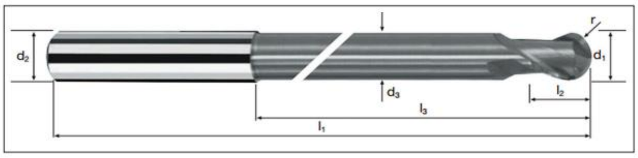

Fig. 1. Ball end milling cutter

TABLE. Basic dimensions of the used cutters

Outreach from holder	d_1 mm	d_3 mm	l_1 mm	l_2 mm	l_3 mm
L1 = 32 mm	10	9,2	72	11	31
L2 = 65 mm	10	9,2	105	11	64
L3 = 95 mm	10	9,2	135	11	94

The same milling parameters were adopted in all tests: rotational speed n = 1400 rpm, effective diameter d_{ef} = 8.83 mm, effective speed v_{ce} = 39 m/min, feed per tooth f_z = 0.03 mm/tooth, axial infeed a_p 0.3 mm, radial infeed a_e = 0.3 mm, the thickness of the machined layer h_{ex} = 0.22 mm, and only the tool overhang L was variable. Nine tests were carried out - three tests for each L value.

The effective cutting diameter and the uncut chip thickness are shown in fig. 2. The workpiece is mounted in such a way that its surface is at an angle of 45 °to the tool axis.

The displacement measuring path of the tool consisted of two Micro-Epsilon optoNCDT ILD1700-10 LL sensors, measuring displacements in the feed direction and perpendicular to the feed direction (fig. 3). Sensors with a measuring range of 10 mm were used, which allowed measuring to an accuracy of 0.5 μm.

Vibration accelerations and components of total cutting force were measured in three directions using standard measuring paths, using piezoelectric sensors.

A Hommel stylus profiler was used to measure the roughness of the machined surface. This measurement was made on a distance of L_T = 4.8 mm, and was repeated five times for each milling pass.

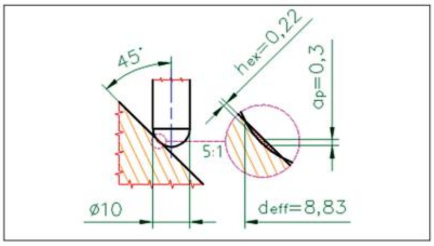

Fig. 2. Area of cut during ball end milling

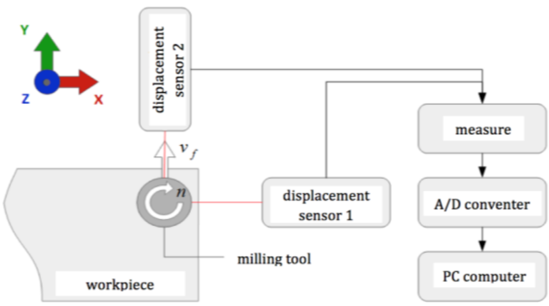

Fig. 3. Diagram of the displacement measurement path

Analysis of results

Fig. 4 presents a graph of changes in static stiffness depending on the diameter of the cutter D and the tool overhang *L*. With the smallest overhang L_1 = 32 mm, the stiffness of the tool is the greatest - approx. *J* = 17 N/μm. However, for the maximum overhang of L_3 = 95 mm, the static stiffness is seventeen times smaller. This means that the effect of tool overhang on the static stiffness is very large, and this in turn is of decisive importance for the displacement values of the working part of the cutter.

Fig. 5 and fig. 6 show the change of displacements X_f (in the feed direction) as a function of cutting time *t* for the overhang L_3 = 95 mm. In fig. 6 the time slice from fig. 5 is shown.

The waveforms show that changes in time displacements for the feed direction are pulsating. This is particularly visible in fig. 6, which shows the duration of one cutter rotation and describes the individual teeth. Similar relations were observed for the second direction - feed normal Y_{fN}. The pulsating character of the changes is also confirmed by vibration patterns, for example shown in fig. 7.

The used ball end mill had two teeth, i.e. the angle of the lateral pitch is Ψ_z = 180°. After taking into account the depth of cut, it is easy to determine the tool angle, which in this case is Ψ = 1.2°.

This means that most of the time, the teeth do not work. Since one turn of the cutter lasts *t* = 0.0428 s, the working time of two teeth for one revolution is *t* = 0.00028 s, which is 0.67% of the time of one revolution. The components of total cutting force have the same type of course. In the case of vibration acceleration, forcing, i.e. entering the tooth into the workpiece and leaving it, is very short and 99.33% of the time needed for one rotation is dominated by free vibrations.

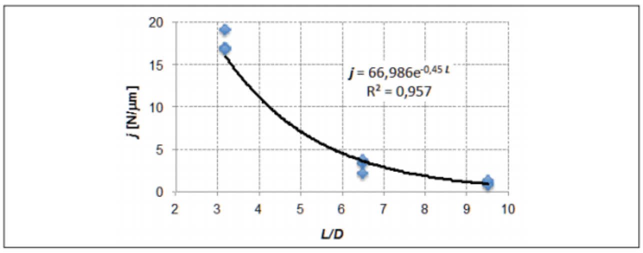

Fig. 4. Static stiffness as a function of milling cutter diameter *D* and tool overhang *L*

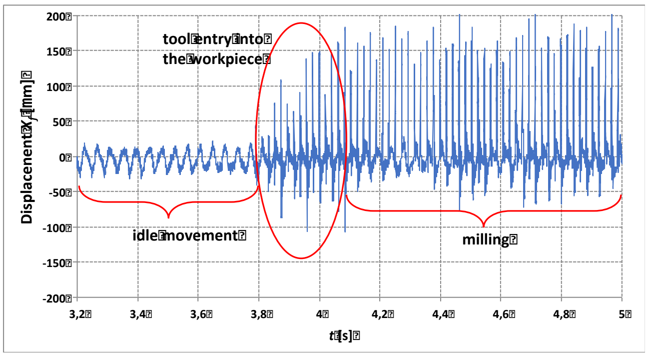

Fig. 5. Course of variation of displacements as a function of time for the L_3 overhang

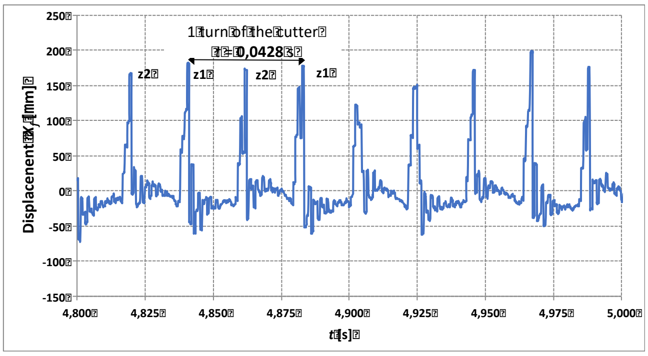

Fig. 6. Section of displacement variation course as a function of time for L_3 overhang

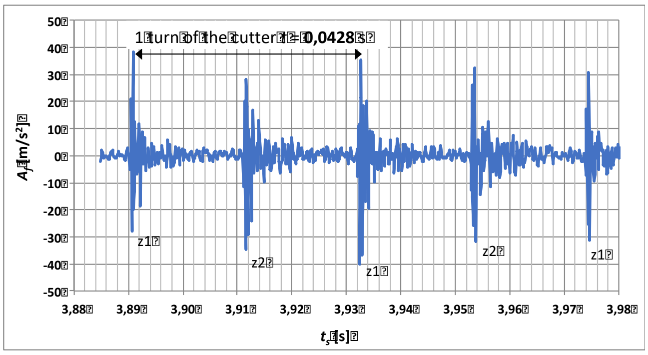

Fig. 7. Vibration accelerations for the feed direction A_f in the function of cutting time t_s

This can be referred to the entire process - i.e. for surface milling in the L_f cutting path, free vibrations dominate and only forced vibration is temporary.

This mechanism determines the impulse nature of displacements of the working part of the cutter, which is clearly visible on the spectral characteristics (fig. 8), where two frequencies prevail. The first one is the basic frequency, derived from the rotational speed *n* = 1400 rpm (basic frequency f_0 = *n* / 60 = 23.33 Hz). The second one, with the dominant amplitude, is the frequency of the milling process, i.e. the tool rotational frequency multiplied by the number of teeth z ($z \cdot f_0$ = 46.44 Hz). The following bands are the harmonics of these two frequencies.

The spectral characteristics in the case of forces (fig. 9) and vibrations are slightly different. Harmonics are the dominant frequencies from the point of view of the amplitude values. This does not mean, however, that the pulsating character of dynamic enforcements has changed, which adversely affects the tool life and the machined surface roughness.

In order to present phase diagrams of displacements for the investigated cases, all signals were subjected to digital filtration - in this way, high-frequency components disrupting the course of displacements were eliminated. A low-pass filter with setting f_d = 200 Hz was used to obtain waveforms only from the milling process. In the first place, the displacements during the idle movement of the machine tool were analyzed - the results are shown in fig. 10.

The greatest displacement values were achieved by the milling cutter with L_3 = 95 mm and for the feed direction it was X_f = 27 µm, and for the normal direction of feed Y_{fN} = 29 µm. Similar conclusions can be drawn from the displacement analysis during milling (fig. 11). It is confirmed that the more rigid the tool, the smaller deflection of the milling cutter and displacement and - as a result - smaller shape errors and roughness parameters (fig. 12). Differences in the roughness parameters are very large between the milling cutter running at L_1 = 32 mm and the milling cutter with L_3 = 95 mm - for the R_{max} parameter, the differences in the roughness parameters are up to seven times.

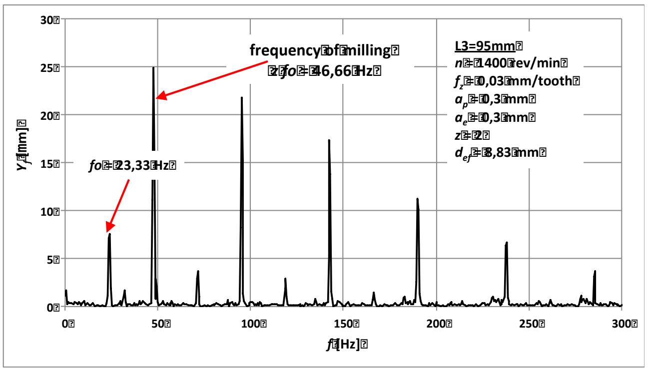

Fig. 8. Spectral characteristics of displacements in the feed direction

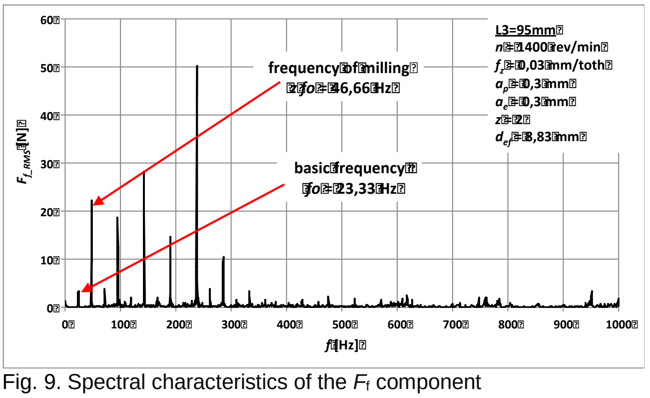

Fig. 9. Spectral characteristics of the F_f component

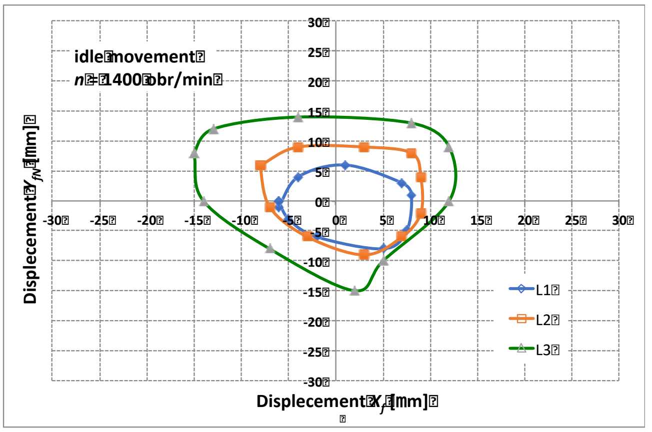

Fig. 10. Graphs of displacements on idle movement in the *X-Y* system of the machine tool (feed and feed direction normal)

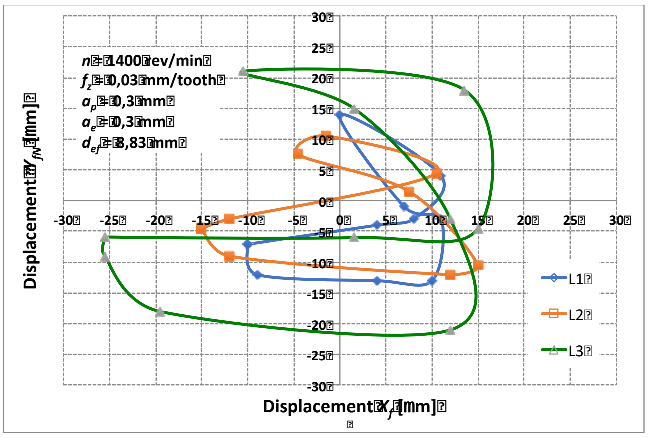

Fig. 11. Displacement graphs during milling in the machine's *X-Y* system (feed and feed normal direction)

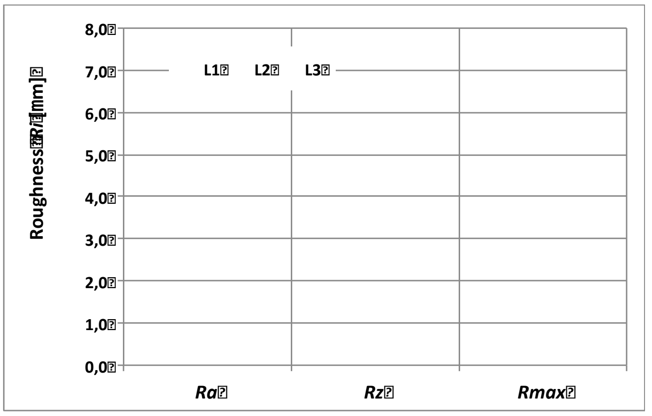

Fig. 12. Roughness parameters for the tested cutter overhangs

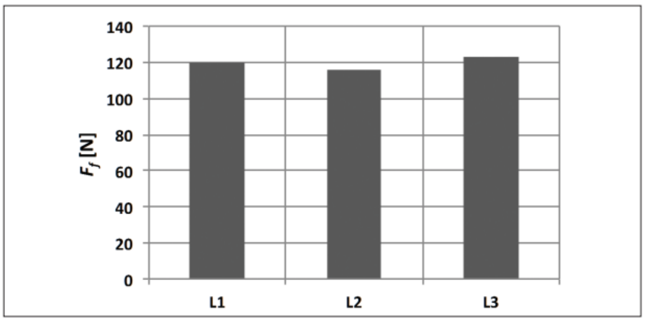

Fig. 13. Feed component for various cutter overhangs

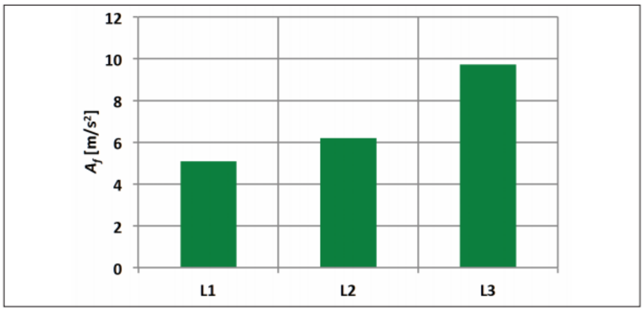

Fig. 14. Vibration accelerations for the feed direction for different cutter overhangs

However, the removal of the milling cutter does not significantly change the value of the tested force amplitudes (fig. 13), but has a significant effect on the level of vibrations in the examined directions (fig. 14).

Conclusions

Changing the rigidity of ball end mills by changing the tool overhang has a significant impact on the displacement of the working part of the cutter. This affects directly to the values of vibration amplitudes, and thus the roughness parameters of the machined surface. This, in turn, does not affect the amplitude values of the forces. The deep pockets should be machined with the largest diameter cutters to ensure the highest rigidity of the tool.

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