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PRECISE SHOULDER MILLING WITH AN OPTIMISED 4-AXIS CNC-TOOLPATH GENERATION

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ABSTRACT

End mills with spiral flutes belong to the most frequently used for grooving and shoulder milling. The best progress is presented by the whole-carbide cutters today, but HSS cutters can not be substituted in all applications anyway. However, bigger deflections and more intensive wear can be expected for the HSS cutters due to their lower Young´s modulus and hardness in general. This deflection affects geometry, dimensions and quality of the machined surfaces. Calculations can be based on analytical method or the Finite Element Analysis (FEA). A precise geometrical model of the cutting tool, time series of the loading and material constants are needed for these computations which result in advanced CNC machining that is precise and economical.

KEYWORDS: milling, forces, modelling, FEA

Background

Machining processes like milling, turning, drilling and grinding represent the most frequently used cutting processes. According to the theoretical fundamentals, the productivity and economic efficiency of the manufacturing processes can be substantially increased by an increase of cutting speed and feed today [1-3]. End mills with spiral flutes belong to the most frequently used for grooving and shoulder milling. The best progress is presented by the whole-carbide cutters today, but high speed steel (HSS) cutters can not be substituted in all applications anyway [4-6].

1. THEORY

1.1. Tool Definition

However, shoulder milling tools result in bigger deflections as slim beams and higher deformations can be expected for the HSS cutters due to their lower Young´s modulus in general [4-9]. This deflection affects geometry, dimensions and quality of the machined surfaces. A rising loading of the tools can be expected due to wear development and increase of the passive and cutting forces. Calculations can be based on analytical method or on the Finite Element Analysis (FEA) [10,11]. Both calculations need a precise description of a real cutting tool body and several techniques can be used for such purpose:

- geometry generated with CAD (SolidWorks),
- STL mesh (generated with the scanner ATOS II SO and use of the software ANSYS ICEM CFD (MCAE Systems) for acquisition of finite element mesh – Fig. 1,
- modeling that is generated by reconstructions of the STL file onto plane model by e.g. the program Tebis (MCAE Systems).

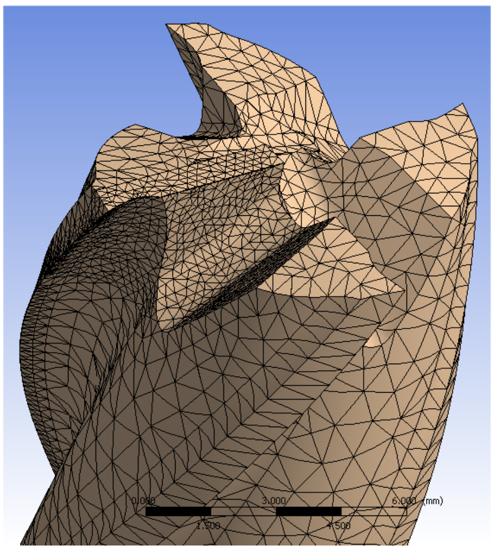

Fig. 1 Example of the mesh of finite elements (tetrahaedrons) of the milling cutter.

1.2. Tool Loading

A total differential of a cutting force for a cutting tool with the spiral flutes, depending on machined material and chip cross-section $\mathbf{A_D}$, that is furthermore function of an engagement angle $\boldsymbol{\varphi}$, tool radius and angle of the spiral inclination [9] can be written as

$$dF_{cj}(\varphi, z) = K_t h_j(\varphi, z) dz \qquad (1)$$

$$dF_{cNj}(\varphi, z) = K_r dF_{cj}(\varphi, z)\,, \qquad (2)$$

where material constants $\boldsymbol{K_t}$, $\boldsymbol{K_r}$ depend on the average chip thickness $\mathbf{h_a}$. For a precise measurement of the tool loading (Fig. 2) - piezoelectric force dynameters are used mostly for their sensitivity, rigidity and high natural frequencies. Standard measurement supposes a PC controlled device with high rate of data acquisition for a statistical evaluation of the time series of the forces and their decomposition according to the orientation of the dynamometer and technological orientation of a cutting edge (ISO).

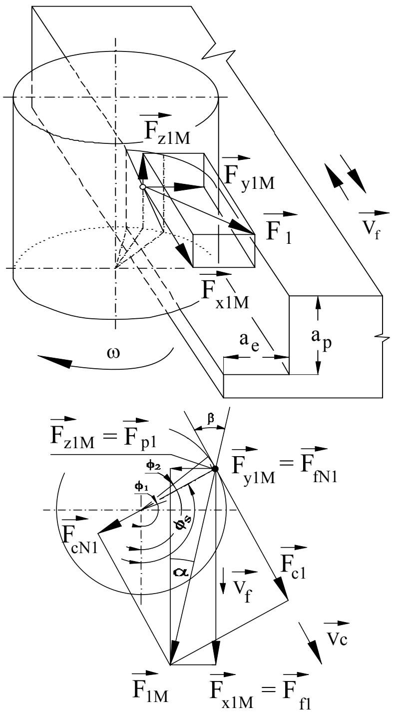

Fig.2 Model of tool loading when milling.

$$\mathbf{F_{1_i}} = \sqrt{\mathbf{F_{x_{1Mi}}}^2 + \mathbf{F_{y_{1Mi}}}^2 + \mathbf{F_{z_{1Mi}}}^2}$$
$$\mathbf{F_{1_i}} = \sqrt{\mathbf{F_{c_{1i}}}^2 + \mathbf{F_{f_{1i}}}^2 + \mathbf{F_{p_{1i}}}^2} \qquad (3)$$

Anyway, the magnitude of the resultat instantenuous force should be the same in all time moments (eq. 3).

2. EXPERIMENTAL WORK

Six short end milling HSSE PM cutters ϕ10/72 mm, with 4 flutes and straight cylindrical shanks (producer ZPS-FN, share company, Zlin, Czech Republic) were used. Cutting speed for down milling was $\mathbf{v_c}$=35 m/min, feed per tooth $\mathbf{f_z}$=0.05 mm, axial depth of cut $\mathbf{a_p}$=4.0 mm, radial depth of cut $\mathbf{a_e}$=2.0 mm, cooling with CIMSTAR HD 650 - 5% emulsion, rate of flow 2 l/min was applied. Statistical assessment of the data was done by Statgraphics v.5. (Statistical Graphics Corp., U.S.A.).

The steel according to the Czech standard CSN 41 5241.9 (R_m = 840-860 MPa) was used as workpiece, in blank dimensions 40x90-300 mm. The force measurement was carried with a piezo-electrical dynamometer KISTLER 9257B, equipped with the charge amplifiers KISTLER 9011A and fully controlled by a PC. A long time constant was set up. The frequency spectrum was checked by the FFT and only one (teeth frequency and their multiplications) were found. None significant influences from outer sources of vibrations or instabilities of cutting process were observed. The deflections of the machined surfaces were measured by the probe Renishaw, OMP400 and SW Productivity+ were used at the CNC machining centre MCV 1210/Sinumerik 840D, ZPS-TAJMAC, a.s., Zlin, Czech Republic in the tool life measurement.

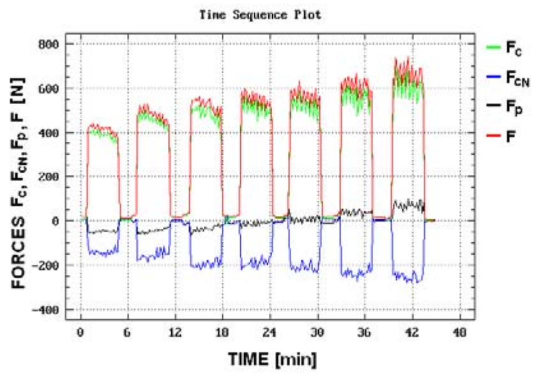

Fig. 3 Statistical time series analysis of the force data.

3. RESULTS

A typical time series of the tool loading due to wear can be seen in Fig. 3. An abrasive mechanism and typical flank wear was observed in the experiments – Fig. 4.

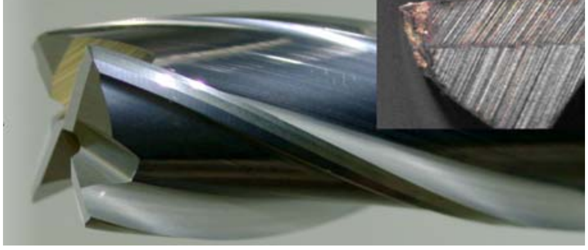

Fig. 4 The new and worn cutting tool (flank wear).

Those phenomena resulted in expected mechanical loading of the milling cutter and deflection of the cutter body – Fig. 5.

Three significant places of the stress concentration, (identical for a sharp and worn mill tooth) were found:

- *a root of the tooth* - which is loaded from the whole tool the intersection of flank and rake surfaces makes a stress riser where local stress is high;

- *a grinding run out of the flute,* – at the flank part of the tooth, close to the shank. The stress state comes from the bending, change of dimensions and sharp corner;

- *the place of clamping;* but an influence of this place can be expected lower in reality due to certain elasticity of the holder, so the stress peaks would be lower than calculated. However, the maximum calculated values of the stresses were lower being compared to the limit strength of HSS. The reduced stresses according to HMH theory reached at the root and for a sharp edge in the beginning of cutting 380 MPa (100%), the run out 230 MPa (60%), and place at tool holder about 270 MPa (70%), approximately.

The same worn out edge (after 40 minutes of machining) and the same places of loading reached the following values 590 MPa, 350 MPa and 410 MPa, respectively. However, it was a static calculation anyway, so for dynamic impacts the total stress can be regarded as higher.

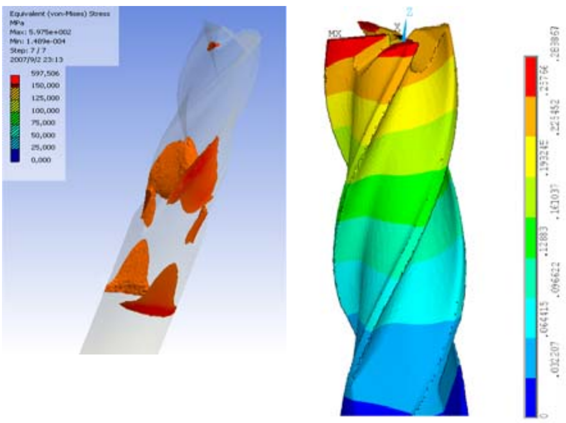

Fig. 5 Von Mises stress state and tool deformations.

A compensation of the tool deflection can be solved for example by:

- an adaptive rotation of a milling head (with another requirements on the adaptive system),

- by rotation and translation of the workpiece (at 4-5 axis CNC tables) with an use of a CNC programme.

The second technique was used and Sinumerik 840D control system was effective to compensate the wall deviations from theoretically perpendicular planes – Fig. 6. The actually measured data are displayed in the Fig. 7.

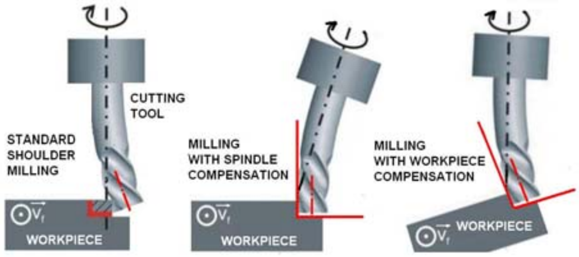

Fig. 6 Tool deflections and various ways of their compensations.

4. DISCUSSION

Modelling of milling operation seems to be more complicated due to many reasons [11]. However, every repeated cutting path means extra time and costs for machining. For these reasons a prediction of the cutting tool behaviour can result in a better interface, lower contact pressures with a flat contact compared to a sharp edge with a wiping (scraping) effect. A better tribology and longer life of the counter-contacting surfaces and possibly all mechanism can be expected.

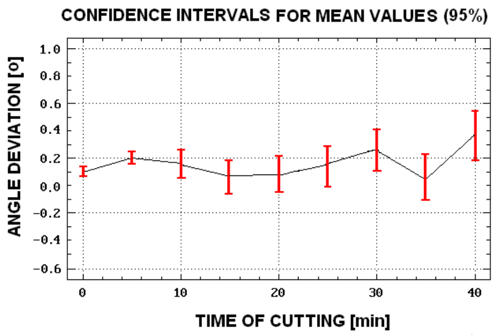

Fig. 7 Measured values of the wall angle deviations from the perpendicular direction.

5. CONCLUSIONS

From the analytical and experimental works results:

- STL geometry of a real cutting tool can be used for stress and deformation calculations relatively easily;

- a time consumption for the design measurement and calculations is shorter compared to the reconstructed model and approximately the same calculating accuracy acquired (20 minutes compared to several hours at powerful workstation HP9300);

- a shoulder milling with advanced CNC procedure of compensation of tool deflection seems to be relatively precise and economical and can be effectively in such cases, where finishing technologies (e.g. grinding) cannot be effectively used.

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