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INVESTIGATION OF THE INFLUENCE OF MAXIMAL CUTTING FORCE ON THE SHPINDLE STATIC STRENGTH OF A MILLING WOODWORKING MACHINE BY FEM

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Abstract: An investigation of the influence of the maximal cutting force on the stresses and strain distribution in a milling spindle with two bearing supports from five-operating woodworking machine KP400 with lower position and console V-belt pulley is carried out by the method of finite elements (FEM) with a CAD/CAE system. The real-acting maximal cutting force on the spindle P^{max} is the maximum cutting force acting on the most laded bit of the cutter and it is 2 times greater than theoretically calculated moment maximal cutting force P_{max}, namely $P^{max} = 2P_{max}$. The 3D milling spindle model was generated section by section with all elements of the real spindle and a static analysis of the spindle 3D model is performed with Autodesk Inventor Professional®. 1-st principal, 3-rd principal and Von Misses stresses, equivalent strains, resultant displacement and factor of safety distribution in the 3D spindle model are obtained and visualized. The results are compared with these for spindle loading with the theoretically calculated moment maximal cutting force P_{max}. Spindle loading with 2 times greater than theoretically calculated moment maximal cutting force causes increase of the stresses, strains and displacements values and reduction of the safety factor – as a result a danger of spindle failure exists. The finite element analysis results must be taken into account in designing of new milling machines with lower position of the spindle. It is recommended increasing of the spindle diameter in the place of the milling cutter location or lower location of the milling cutter and in this case the technological height can be adjusted by the lifting mechanism of the slide.
Keywords: cutting force, spindle, milling woodworking machine, static strength, FEM, CAD/CAE

INTRODUCTION

Primary influence on the strength dimensioning of the spindles of milling machines provide a cutting force acting on each of the bits of the cutting tool. This is the instantaneous maximum force calculated based on the average shear cutting, which is assumed to be the same for all bits (Grigorov, 1985).

In practice, the cutting force of the individual bits is different. The reason for this is the different radius of cutting for each of them. In a study of this force for two bits, the radius of one of which is greater by 0,01 mm has been found that it is two times greater for the one with the larger radius of cutting (Grigorov, 1985).

The reasons why you might get a difference in diameters of the cutting bits are: errors sharpening; radial run-out of the spindle, which according to BDS 3780:1985 is permitted to be within 0.02-0.04 mm; looseness in the fit between the spindle and cutting tool; precession movement of the cutting tool. The first three reasons listed above are geometric in nature and directly affect the radius of cutting the individual bits. Radial run-out of spindle, joint gap between the spindle and cutting tool and own unbalance of the cutting tool caused unbalance of the spindle unit (Vlasev, V., 2013), in consequence of which, in dynamic regime of idle and working stroke precession movement of the cutting tool is obtained. In this regard researches are known on the influence of unbalance of the cutting tool on the accuracy of processing with milling machines (Strenkovskii, 1967). It has been found that the machined surface in unbalance of the cutting tool larger than 17.10^{-5} kg.m is formed by one bit, wherein the location of the unbalance and the bit coincide. Opposite to him bit takes part in cutting but did not participate in the formation of the machined surface.

Other studies on the influence of the unbalance of the cutting tool on the cutting power show that, with its increase the cutting power decreases to 25%. It has been found that this is due to precession movement of the cutting tool. The trajectory, which describes the geometrical centre of rotation is an ellipse, as a result of which the different bits have different radii of cutting (Vlasev, 1990). It follows that with the increase of imbalance the participation of bits in the cutting decreases, or some of them take smaller chips at the expense of others. The latter means that the cutting forces for them are different. The mentioned literature clearly shows that the strength dimensioning of the spindles of milling machines necessary cutting forces for individual bits are of different sizes corresponding to that in real cutting conditions. The precise determination of the magnitude of cutting forces on individual bits is not yet possible.

According to popular literature, hypothetically may be accepted following values for their size for cutter with four bits at the theoretically calculated moment maximal cutting force P_{max}, as follows: for the first cutter /side unbalance/ - $P_1 = 2P_{max}$; second - $P_2 = 0.5P_{max}$; the third - $P_3 = 0.2P_{max}$; and fourth - $P_4 = 1.3P_{max}$.

In determining the magnitude of the forces is according to their sum within a complete rotation of the cutting tool is constant, according to the formula $P_1+P_2+P_3+P_4=4P_{max}$. Each of these forces is of-phase compared to the previous of angle of $\pi/2$. According to the traditional modes of such dimensioning is necessary to select the maximal value, acting on the most loaded bit, namely $P_1 = 2P_{max}$.

The object of this study was to establish the influence of the maximum cutting force acting on the most laded bit of the cutter on the spindle static strength of 5-operating woodworking machine КР 400 with spindle lower position by the method of finite elements (FEM).

METHODS

Calculation scheme of the cutting spindle

A cutting spindle with two bearing supports (*l*=264 mm) from a 5-operating aggregate woodworking machine K5-400 with lower spindle position and console pulley is considered and 3D modeled. The 3D model of the cutting spindle is created with the modulus "Shaft Generator" of the program Autodesk Inventor® section by section with all elements of the real spindle – key slot, tread for fixing of the cutter, grooves for clip ring, wrench, chamfers, filets, center holes in both ends, etc. The sequence of creation of the 3D geometrical model of the cutting spindle is described in detail in our previous publication (Staneva and Vlasev, 2014).

The spindle is driven by an asynchronous motor with 3 kW power and revolutions of 2860 min^{-1} by a high-speed belt gear with gear ratio i=0.5. The cutting spindle is loaded with a torque and forces calculated according to Filipov, 1979 as pointed on the scheme of loading - Figure 1. The meaning and calculated values are given below in 2.2.

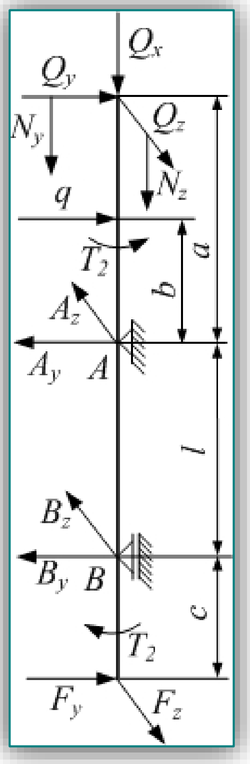

Figure 1. Scheme of loading of the cutting spindle

Static analysis

Recently, the modern CAD/CAE systems for 3D modeling and engineering analyses by finite element method (FEM) of the operating woodworking cutting mechanisms are widely applied (Chaitanya and Kaladhar, 2013; Gok et al, 2013; Marta and Corduta, 2010).

The static analysis of the cutting spindle 3D model is performed by the method of finite elements (FEM) with the CAD/CAE system Autodesk Inventor Professional® (student version) and it is described in detail in Staneva, Vlasev, 2014.

The material "Carbon Steel" was chosen with the following characteristics: yield strength $350 \cdot 10^6$ $N \cdot m^{-2}$; ultimate tensile strength $420 \cdot 10^6$ $N \cdot m^{-2}$; elastic modulus $2.0 \cdot 10^{11}$ $N \cdot m^{-2}$, shear modulus $7.75 \cdot 10^{10}$ $N \cdot m^{-2}$; Poisson's ratio 0.29; density 7870 $kg \cdot m^{-3}$. These characteristics are closest to the Bulgarian carbon steel brand 45 according BDS 2592:1971.

The fixing of the spindle in the 3D model was set: fixed.

The following loads according to the scheme of loads (Figure 1) were calculated and set for the simulations:

- torque, T_2 =5.01 N·m;
- forces, initiating at cutting process, determined from maximal cutting force acting on the most

loaded bit of the cutter P^{max} and it is 2 times greater than theoretically calculated maximal moment force P_{max}: $P^{max} = 2P_{max} = 1368$ N and the maximum radial cutting force $R^{max} = 1368$ N (for milling cutter with 160 mm diameter and two cutters): $Q_x = 1963.62$ N – axial force along x-axis, sum of the components P_x, R_x and the mass of spindle and assembled parts; $Q_y = 632.46$ N – radial force directed along y-axis, sum of the components P_y, R_y and the centrifugal force from unbalanced moving masses; $Q_z = 1221.04$ N - radial force directed along z-axis, sum of the components P_z and R_z (a=73.5 mm); $N_y = 932.20$ N and $N_z = 932.20$ N – axial remote forces, received from the decomposition of forces P_x and R_x along the axes y and z and summation of corresponding components;

- force, with which the gauge is clamped to the guide roller: q = 616.82 N, radial force directed along the y-axis (b=50.0 mm);
- stretching forces from belt gear: $F_y = 31.5$ N – radial force directed along y-axis, which includes the centrifugal force from belt pulley unbalance because of fit inaccuracy; $F_z = 469.69$ N – radial force directed along z-axis (c = 38.0 mm).

Specified forces and torque are shown on Figure 2 in such a way as they are visualized by the system Autodesk Inventor Professional®.

Figure 2. Loading of the spindle

The following characteristics of the finite elements mesh were set: average element size 0.1; minimum element size 0.2; grading factor 1.5; maximum turn angle 60 deg; curved mesh elements; The created mesh for the model has 27184 numbers of nodes and 17618 numbers of finite elements. For the solver the following were set: maximum number of h refinements 3; stop criteria 10%; h refinements threshold 0.75.

RESULTS AND DISCUSION

Some of the results from the static analysis of the cutting spindle are represented on Figure 3 to Figure 8. In order to understand where deformation is occurring an exaggeration effect is provided with "Adjust Displacement Display" – Adjusted x 2 (Autodesk Inventor Professional®, Online User's Guide & Help Files).

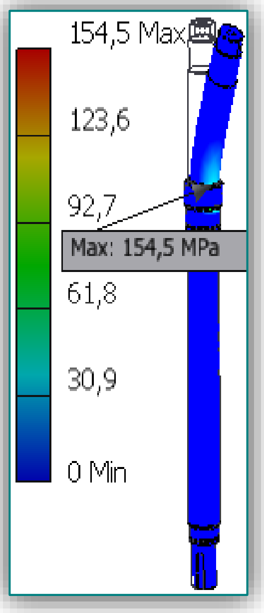

Figure 3. Distribution of the Von Mises stresses

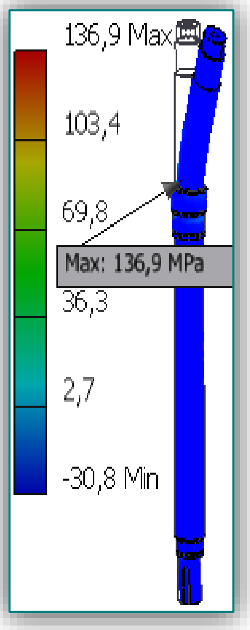

Figure 4. Distribution of the 1-st principle stresses

The distribution of equivalent Von Misses stresses in the cutting spindle 3D model is represented on Figure 3. The maximal value of $154.5 \cdot 10^6$ N·m^{-2} is received and localized near to the bearing shoulder "A" on the side of the cutter. In the same place the maximum $136.9 \cdot 10^6$ N·m^{-2} of the 1-st principal stress (Figure 4) and maximal strain are received.

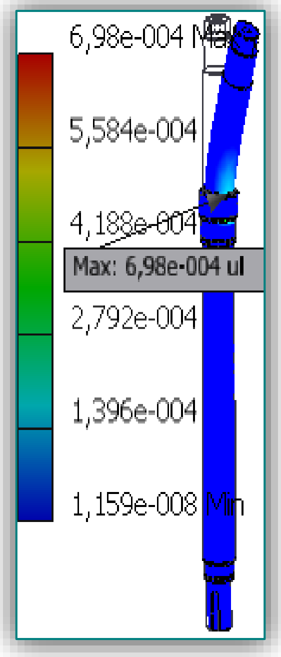

Figure 5. Distribution of equivalent strain

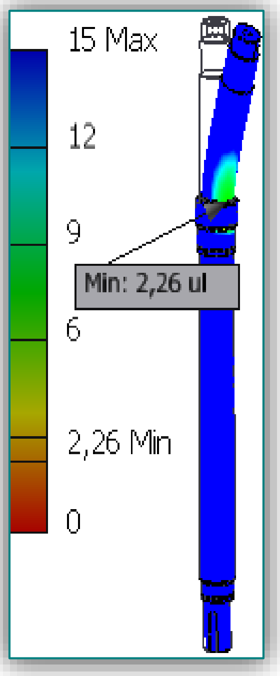

Figure 6. Distribution of factor of safety

The maximal equivalent strain 0,000698 (Figure 5) is higher than the allowable strain for shafts:

$$[f]\ /l \leq (0{,}0002 \div 0{,}0003).$$

A strength control for spindle failure was carried out. The program calculates the factor of safety as the ratio of the maximum allowable stress to the maximum von-Misses stress when using Yield Strength as a Yield Limit:

$$\text{Factor of safety (FOS)} = \sigma_{\text{limit}} / \sigma_{\text{vonMises}}$$

The distribution of safety factor (FOS) is shown on Figure 6. A minimal safety factor of 2.26 is received localized to the bearing support "A". The factor of safety is very close to 1, i.e. there is a potential danger of spindle failure.

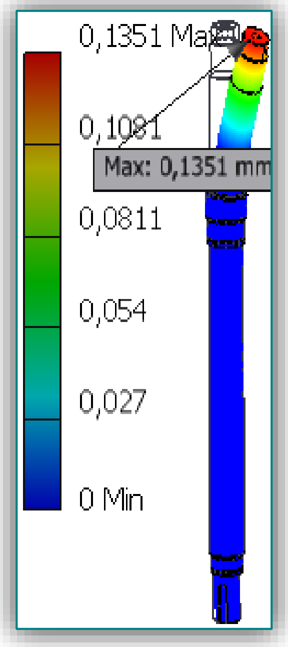

Figure 7. Distribution of resultant displacement

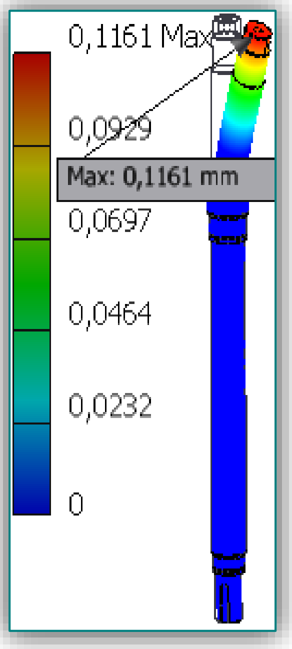

Figure 8. Distribution of *Z*-displacement

Table 1. Values of the maximal stresses, strains and displacements

Parameter	Max. values (for FOS – minimal) I var.	II var.
Von Mises stress, $\cdot 10^{-6}$ N·m^{-2}	68.42	154.50
Ist principal stress, $\cdot 10^{-6}$ N·m^{-2}	67.42	136.90
3rd principal stress, $\cdot 10^{-6}$ N·m^{-2}	9.769	21.50
Equivalent strain, $.10^{-4}$	3.14	6.98
Factor of safety (FOS)	5.12	2.26
Resultant displacement, mm	0.05869	0.135
Z – displacement, mm	0.05816	0.116

Obviously, comparing the results of two variants of spindle loading, the doubled cutting force causes an increase of the stresses, strain and displacements values and reduction of the safety factor – as a result the spindle is threatened by a failure. The maximal values of the stresses, strain and displacements are localized in the same places as in the Ist loading variant.

With the help of modulus "Shaft Generator" of the program Autodesk Inventor® the distribution of "ideal diameter" along the spindle length was received setting the same material and loads – Figure 9. It is evident that in the place of cutter fixing (the most loaded section) a maximal spindle diameter of 30,4195 mm was calculated and offered by the program, that means the real spindle diameter of 30 mm in this location is lower and must be increased to avoid spindle failure in given loading conditions.

CONCLUSIONS

Received results from the static analysis by FEM of 3D model of cutting spindle loading with real-acting cutting force 2 times greater than theoretically calculated one causes increasing of the stresses, strains and displacements values and reduction of the safety factor. Having in mind that the dynamic loading was not involved in calculations shows that the spindle is at the limit of rupture. This must be taken into account in designing of new milling machines with lower spindle position and in the operation of existing ones. The received displacements at such loading of the spindle show that the roughness of the treated surfaces of parts will increase.

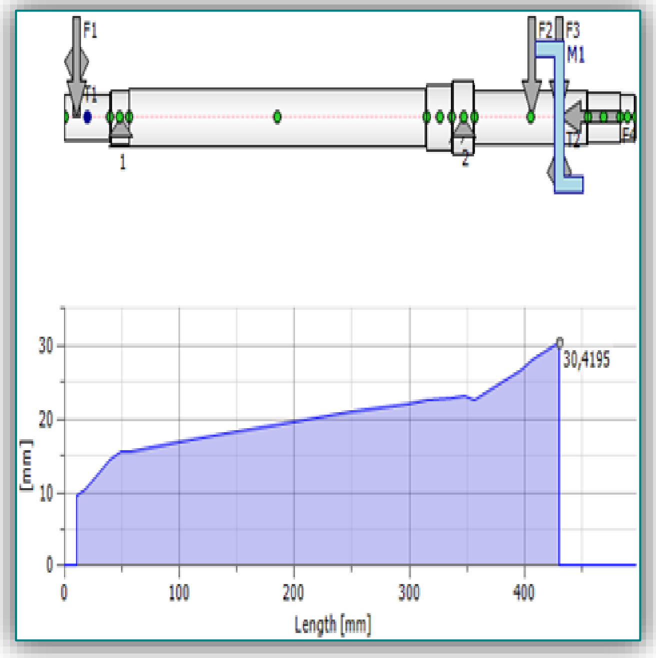

Figure 9. Distribution of "ideal diameter"

It is recommended for new woodworking milling machines with lower spindle position:

- To increase spindle diameter in the place of cutter fixing from 30 mm to 32 mm;
- The cutters to be fixed lower, near to the support and technological height can be adjusted by the lifting mechanism of the slide.

For existing woodworking milling machines is recommended not to load maximum to avoid any dangerous consequences.

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