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Evaluation of the Structural Strength of a Prefabricated Milling Cutter with Replaceable inserts During Machining

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Abstract: Simulation modeling of the stress state of a prefabricated milling cutter with replaceable inserts during machining was carried out in the ABAQUS 2020 program using the finite element method. It has been established that the structural strength of a cutting tool depends on the geometry, material and cutting conditions. Based on the simulation, stress concentrators in a milling cutter with replaceable inserts were identified. The safety factor of the structure has also been determined, which meets the standard requirement. It has been established that a prefabricated milling cutter with replaceable plates during machining under extreme conditions ensures its performance with a margin of 20%. Thus, a prefabricated cutter with replaceable inserts is applicable for machining newly created and restored surfaces after hardfacing.

Key words: FEM-analysis, stress, safety factor, fatigue strength.

Inrtroduction.

The trends in the modern cutting tool market are such that in order to maintain competitiveness, cutting tool manufacturers are forced to constantly look for new solutions to ensure the efficiency of machining. Experiments are constantly being carried out with the shape of the cutting edge in order to ensure cutting at higher speeds and at the same time obtain better quality milled surfaces [1].

Currently, cutting tools equipped with carbide replaceable polyhedral inserts in the shape of polyhedra (triangles, squares, rhombuses, etc.), each side of which is a cutting edge, are increasingly used. The plates are attached to the tool bodies using special devices that allow them to be rotated around their axes, introducing a new cutting edge into the working position instead of a dull one [2].

It is also important to develop tools for mechanical processing of surfaces after restoration by surfacing. The deposited layer is quite hard and the tool experiences a lot of wear during machining. For this purpose, you can also use a cutting tool with replaceable polyhedral inserts.

When creating a new cutting tool, the strength of the structure is assessed using the finite element method.

The finite element method is the main method of modern computational mechanics, which underlies the vast majority of modern software systems designed to perform calculations of engineering structures on a computer [3].

The finite element method makes it possible to almost completely automate the calculation of mechanical systems, although, as a rule, it requires a significantly larger number of computational operations compared to classical methods of mechanics of a deformable solid [4].

The finite element method allows you to construct a convenient scheme for forming a system of algebraic equations with respect to the nodal values of the desired function. Approximate approximation of the solution using simple polynomial functions and all necessary operations are performed on a separate standard element [5]. Then the elements are combined, which leads to the required system of algebraic equations. This algorithm for transition from a single element to their complete set is especially convenient for geometrically and physically complex systems. Each individual algebraic equation obtained on the basis of the finite element method contains an insignificant part of the nodal unknowns from their total number. In other words, many coefficients in the equations of an algebraic system are equal to zero, which greatly facilitates its solution [6].

For strength calculations, the finite element method is often used in various software.

One such program is ABAQUS, a universal general-purpose system designed both for multi-purpose engineering multidisciplinary analysis and for research and educational purposes in a wide variety of fields. This package can be used at all stages of the design and creation of modern products [7].

ABAQUS meets the ISO 9001 quality standard and the quality standard established by the American Nuclear Review Board for quality assurance of nuclear power plant design (ANSI/ASME NQA-1, 1983). Also, the results obtained using the ABAQUS software package show the validity of the results, reaching 98% [8].

The task of choosing a rational design of cutting tools is complex and time-consuming, requiring the synthesis and evaluation of a large number of combinations of structural options for assembly structural elements, the values of their parameters and the materials from which they are made. The rationality of the form and the correctness of the chosen material determine the strength of the cutting tool design.

Therefore, the purpose of this article is to develop a methodology for assessing the strength of a new design of a prefabricated cutter with replaceable inserts for processing restored spline surfaces using surfacing methods.

1. Research methodology

Modeling of the stress state of a prefabricated cutter with replaceable inserts was carried out in the ABAQUS 2020 program. When modeling the stress state of a prefabricated cutter with replaceable inserts, it is important to correctly generate the correct finite element mesh (FEM). The meshing process used three-dimensional second-order HEXA FEMs (hex elements) to accurately represent the distribution of internal stresses in the samples under the influence of external forces [9]. Figure 1 shows the mesh applied to an assembly cutter with replaceable inserts. The prefabricated cutter was divided into 67,872 nodes and 62,000 elements.

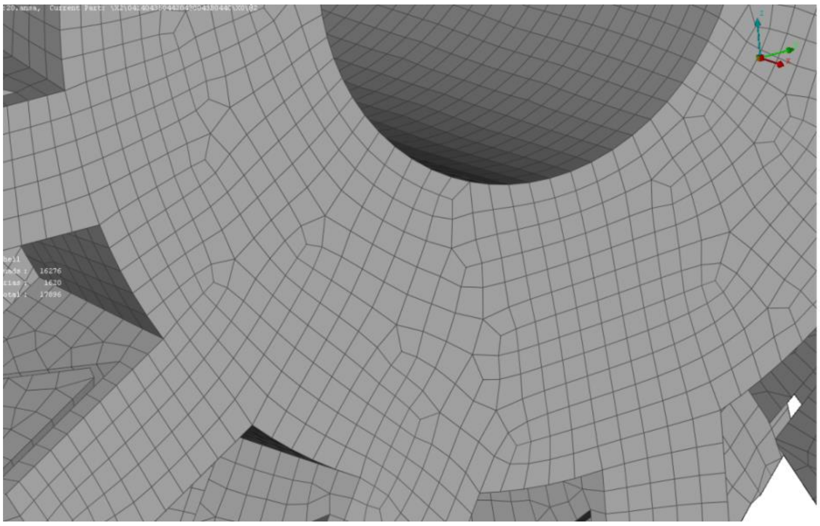

Fig. 1. – Finite element mesh

Presenting the simulation modeling methodology in the form of a certain sequence, we can distinguish 7 main steps.

At step 1 (Step 1 - material properties) are specified by the input data for the designed design of a prefabricated cutter for dimensional processing of splines. In order to obtain a stress state of the cutter close to real milling conditions, a dynamic load mode was used, taking into account the data indicated in Table 1.

Table 1. Loads during operation of a milling cutter with replaceable inserts

Parameter name	Meaning
Axial feed of milling cutter	52.3 mm/rev
Feed per tooth	0.06 mm
Cutting speed	638 m/min
Rotation frequency	82 rpm

Also, to simulate the stress state, the properties of materials were determined - this is the material of the cutter body, replaceable carbide inserts (Table 4.2).

Table 2. Physical properties of materials involved in the process of milling the machined surface

Physical parameter of the material	Milling cutter body material - steel 30KhGSA (GOST 4543)	Plate material – T5K10 (GOST 3882)
Density	7.85 g/cm^3	12.5-13.1 g/cm^3
Poisson's ratio	0.280	0.21
Tensile strength	820 MPa	1421 MPa
Yield strength	>835 MPa	-
Elongation at break	>10%	-
Volume modulus of elasticity	215 GPa	160 GPa
Shear modulus	84000 MPa	245× 10^9 Pa

To determine point stress amplitudes, the following scheme was used (Figure 2).

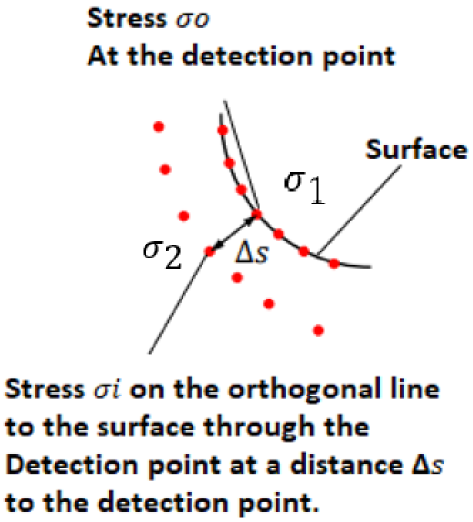

Fig. 2. – Diagram of point stress amplitudes

At the second stage (2 Step (Temperature factor)), the working temperature was selected, T = 1200°C. The choice of such a high value is explained by the fact that the mechanical processing of materials of increased hardness and strength requires significantly more energy, which leads to an increase in temperature in the cutting zone, which can reach 1100 °C. Accelerating the processing process, including increasing the tool feed, also leads to a significant increase in the amount of heat in the processing zone [10].

At the third stage (3 Step (Construction characteristics), to analyze the fatigue strength and the nature of the distribution of internal stresses of the samples, a calculation technique was used [11], according to which readings of the internal stress characteristics are taken from two points, taking into account the distance between them, and the gradient was also calculated stress.

When modeling, amplitude (alternating) loads were chosen as loads on the cutter, since they are the worst for any model.

The fatigue strength of materials under repeated variable loading largely depends on the nature of the change in stress over time.

The place where the loads are applied is the area surrounding the cutting edge of the cutter, simulating roughing with a cutting depth of 2 mm.

At the fourth stage (4 Step (amplitude initialization)), the program automatically determined the loads for the designed cutter structure based on the entered input parameters.

Periodic load is a variable load with a pattern of change established over time, the values of which are repeated after a certain period of time. The determination of voltage values is graphically presented in Figure 3.

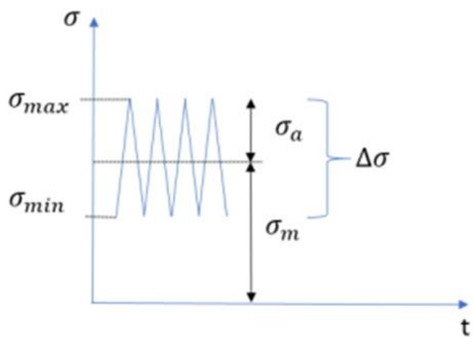

Fig. 3. - Stress cycle

Stress cycle is the totality of all alternating stress values during one period of load change.

Typically, the stress cycle is characterized by two main cycle parameters:

– σ_{max} - maximum cycle stress;

– σ_{min} - minimum cycle stress;

– σ_m - average cycle stress [11].

The amplitude cycle stress is determined by the formula [11]:

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2} \quad (1)$$

The average cycle stress is determined by the formula [11]:

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} \quad (2)$$

where σ_{max}, σ_{min} – maximum and minimum values of equivalent stresses.

The stress cycle asymmetry coefficient is determined by the formula [11]:

$$R = \frac{\sigma_{max}}{\sigma_{min}} \quad (3)$$

In cyclic loading, during alternation, the average stresses are equal to 0, and during pulsations, the average stresses are equal to the amplitude stresses (Figure 4).

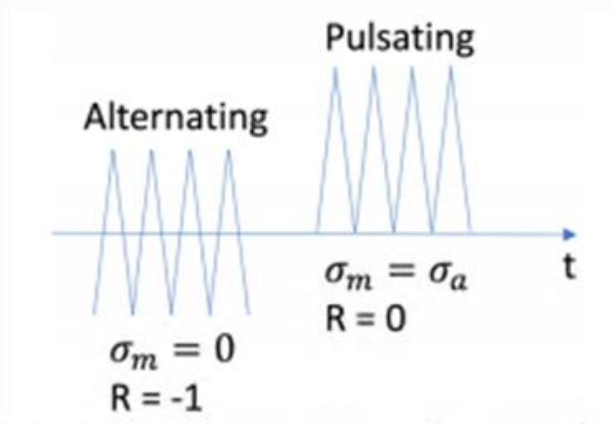

Fig. 4. - Stress coefficients for alternations and pulsations

The overall safety factor is determined by the formula [11]:

$$\alpha_{BK,\sigma} = \frac{\sigma_{\alpha 1}}{\sigma_{BK}} \cdot j_D \quad (5)$$

where $\sigma_{a,1}$ – maximum stress amplitude depending on the type of stress, MPa;

σ_{BK} - fatigue strength of components, MPa;

j_D - overall fatigue strength coefficient.

The overall fatigue strength coefficient is determined by the formula [11]:

$$j_D = \frac{j_F \cdot}{k_{td}} \cdot j_s, \quad (6)$$

where j_F – material safety factor;

j_s – safety factor (j_s = 1 with an average probability of maintaining the safety margin 97,5%);

k_{TD} – temperature coefficient (K_{TD} = 1 for alloy steel).

2. Results and discussion

Based on the results obtained, the sensitivity of the model to amplitude loads, as well as the fatigue strength of the components, were calculated. The results of calculating the distribution of internal stresses are presented in Table 3.

Table 3. Propagation of internal stresses as a result of milling cutter simulation

Input data	
Maximum stress, $\boldsymbol{\sigma}_{max}$, MPa	326
Minimum stress, $\boldsymbol{\sigma}_{min}$, MPa	32
Intermediate results	
Amplitude cycle stress, σ_a, MPa	147
Stress cycle asymmetry coefficient, R	0.0981595
Stress sensitivity, M_σ	0.417
Medium stress factor, $K_{AK,\sigma}$	0.68745351
Average cycle stress, σ_m, MPa	179

Maximum stress ($\boldsymbol{\sigma}_{max}$ = 326 MPa) is the stress that occurs in the cutter body, where the replaceable carbide insert meets, which occurs when the cutter tooth enters the workpiece. This leads to a sharp change in the cross-sectional area of the cut, and, consequently, in the forces acting during the cutting process.

Minimum stress ($\boldsymbol{\sigma}_{min}$ = 32 MPa) this is the stress considered in the same place, which remains in the cutter body from the moment the cutter tooth leaves the machined surface and makes a circle until the next entry into the workpiece, the so-called residual stress.

The amplitude cycle stress ($\boldsymbol{\sigma_a} = 147$ MPa) was obtained using formula (1).

At the fifth stage (5 Step (Work cycles)), the strength of the cutter was investigated. To simulate the operation of the cutter during the cutting process, the "dynamic mode" was used. Dynamic loads include periodic, repetitive (cyclic) loads. When modeling the cutter, the average value of the load cycles of the cutter structure 4×10^6 acting on the structural elements was specified. with given conditions. As practice shows, loads that change cyclically over time in magnitude or in magnitude and sign can lead to the destruction of a structure at stresses significantly lower than the yield strength (or tensile strength). This kind of failure is usually called "fatigue". The results are presented in Table 4.

Table 4. Influence of the number of working cycles on the strength of the cutter structure

Input data	
Number of cycles (default number of work cycles 4×10^6)	
N	4000000
Intermediate results	
Fatigue coefficient, K_{BK}	1
Fatigue Strength of Components, σ_{BK}, MPa	234.705358

With a given endurance limit for steel 30XGSA = 490 MPa, the proposed cutter design is able to resist fatigue failure, since $\boldsymbol{\sigma}_{BK}$ = 234.705358 MPa.

According to the ISO 15641 standard, safety requirements are established for high-speed processing (mechanical removal of chips at high peripheral speeds) on metal-cutting machines as a result of the use of cutters. ISO 15641 establishes design methods, centrifugal force test procedures, operational limitations and provides information to minimize or eliminate these hazards. Therefore, at the sixth stage (6 Step (safety factor)), the worst-case operating conditions of the cutter with the imposition of large amplitude loads and a high degree of wear were investigated (Table 5).

Table 5. Results of operating the cutter with high amplitude loads

Input data	
Material safety factor, j_f	1.2
Final results	
Overall fatigue strength factor, j_D	1.26758151
Overall safety factor, $\alpha_{BK,\sigma}$	0.79390809

According to Table 5, we can conclude that the safety factor of the material is 1.2. It is the lower limit of the standard safety factor of the material (1.2÷1.5) [12]. It was also found that under the action of amplitude loads during 4×106 loading cycles, the overall safety factor is equal to 0.79390809 MPa. This means that the assembled milling cutter in question with replaceable inserts has a damage resistance reserve level of about 20% and remains operational.

In addition to fatigue strength, the study identified stress concentrators of a milling cutter with replaceable inserts during the cutting process (Figure 5).

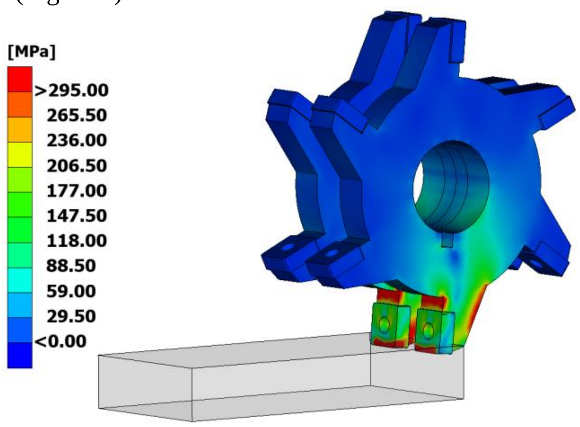

Fig. 5. - Stresses in a milling cutter with replaceable inserts during the cutting process

According to the data obtained, the highly loaded surfaces of the assembled cutter with replaceable plates are the step transition of the cutter teeth, the stresses on which are 296 - 298 MPa (Figure 6), and the rear part of the teeth, the stresses on which are 295 - 296 MPa.

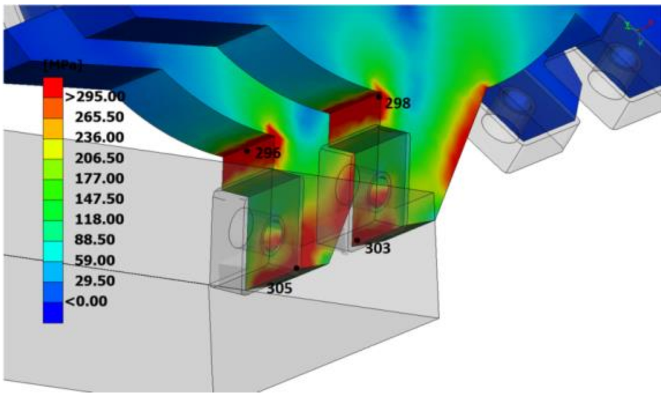

Fig. 6. – Stresses in stepped transitions of cutter teeth

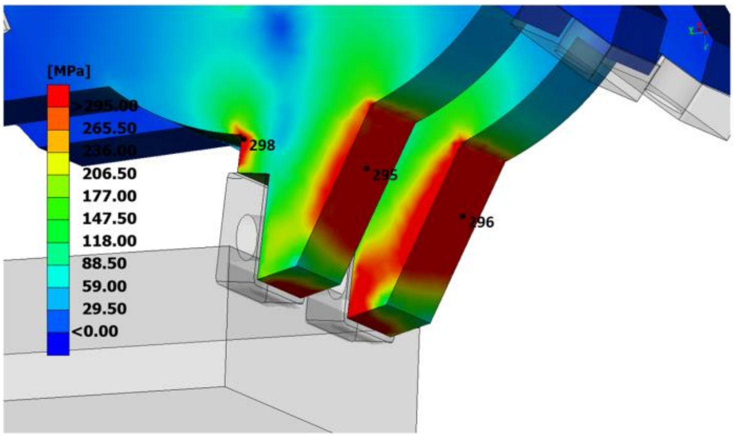

Fig. 7. – Stresses on the back of the cutter teeth

The highest stresses (345 – 365 MPa) in the cutter design occur at the edges of the replaceable inserts, since they have direct contact with the material being processed during machining (Figure 8).

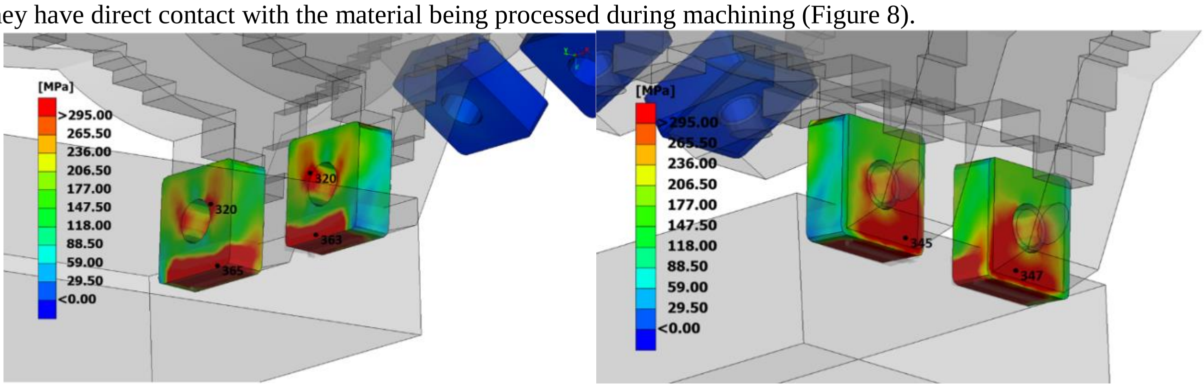

Fig. 8. - Stresses on the replaceable inserts of a prefabricated cutter

In this area, scratches and chipping of the cutting edge of the insert will form on the rake surface, reducing the strength of the cutting edge. Accordingly, the greatest wear on the rake surface will occur precisely in this zone, since it is in this area that the greatest cutting constraint is observed.

Also, the vulnerable point of the plate is the circular cross-section for mechanical fastening, the stress in which is 320 MPa.

To evaluate the structural strength of a prefabricated milling cutter with replaceable inserts, the stress concentration coefficient and the strength coefficient were used.

The safety factor is determined by formula (6):

$$n = \frac{\sigma_t}{\sigma_{max}} \quad (6)$$

where σ_t – yield strength of the material, MPa;

σ_{max} - maximum stress in the milling cutter, MPa.

The results of the study of the stress state of a cutter assembly with replaceable inserts are presented in Table 4.6.

Table 6. Parameters of the stress state of a cutter assembly with replaceable inserts

Parameter name	Parameter value in stepped tooth transitions	Parameter value for the back side of the teeth	Parameter value for replaceable inserts
Maximum stress, MPa	298	296	365
Safety factor	1.5	1.5	4.9

The standard safety factor for cutting tools in mechanical engineering is n ≥ (1.5÷2.5) [13]. The safety margin is maintained for all components of the cutter design, with a stress spread of 60 MPa, provided that extra loads were specified that exceeded the actual loads by 4 times. However, for replaceable plates the safety margin is higher since they are made of high-alloy T5K10 glory, consisting of chromium, tungsten and vanadium.

Thus, as a result of assessing the strength of the design of a cutter assembly with replaceable plates during machining, it was established that the design has a 20% margin of fatigue strength and can be used when processing spline surfaces of parts such as rotating bodies.

Conclusions

1. The developed strength assessment method determines the amplitude cycle stress, cycle asymmetry coefficient, sensitivity, average stress factor, average cycle stress, fatigue strength and fatigue strength coefficient, as well as the safety factor of the structure.

2. The safety factor of replaceable polyhedral inserts is 3 times higher than the safety factor of the cutter body.

3. Dangerous stress concentrators of a cutter assembly with replaceable inserts are the stepped transitions and the back side of the teeth, the circular section for mechanical fastening, as well as the cutting edge of replaceable multifaceted inserts.

4. The design of the prefabricated cutter with replaceable inserts satisfies the standard safety factor, which allows its use when processing deposited surfaces.

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