Estimation of Stress-Deformed State of the Cutting Insert of a Disk Mill Using Computer-Aided Engineering

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Abstract. The efficiency of the assembly tool is largely determined by the cutting tool insert installation scheme, as well as by the accuracy of manufacturing mating surfaces and loading conditions. When milling the normal types of destruction of the cutting blade are chipping and micro-dyeing. In this regard, in order to improve the reliability of a tool, it is desirable to provide the most uniform distribution of stresses at the initial time. In the article, the stressed-deformed condition of a cutting blade of a disk mill is considered taking into account the schemes of the cutting tool insert basing, the clamping force and the external cutting force. The stages of solving the problem of determining the stressed-deformed condition design of a disk mill are shown. The ratios of the force of clamping of the cutting tool insert and external force are determined. The joint effect on the stress state of the cutting tool insert of the clamping force and external force is analyzed.

1. Introduction
Cutters are a universal widespread tool that provides high performance machining. Depending on the position of the axis relative to the machined surface, milling cutters are disc, end and finger, and in construction - integral and prefabricated. When using the cutting part of a hard alloy as a material, only small-sized tools are manufactured. Most of the carbide milling structures are prefabricated, that increase durability and reduce tooling costs. A wide range of inserts causes a variety of both the conceptual diagrams of their installation in the housing, and the variants of realizations in concrete structures.

The main reasons for the deterioration of cutting insert are: high power and temperature loads, low strength and wear resistance of hard alloy, non-optimal structural and geometric parameters. This makes it necessary to determine the stress-strain state and strength, i.e. in the study of the distribution of dangerous stresses, leading to destruction. Many works have been devoted to the study of the stress-deformed state of the cutting edge, but they practically do not consider the design of the tool as a whole, which leads to a lack of understanding of the behavior of its various components. Therefore, it will be useful from a scientific and practical point of view, the study and coordination of stress-deformed state on the surfaces of the components of the mill design.

Designing a new design requires considerable time and money. Simulation is used to reduce them. Modeling is an effective and now universally applicable method of creating any objects, processes and phenomena. The main purpose of the model is to make it possible to predict the behavior of the
projected object with permissible changes in its structure and parameters (comparative analysis of alternative design options) and environmental conditions (research of the object in various situations). The purpose of modeling the stressed-deformed state of the milling design is to synthesize the amount of tightening of the insert when a cutting force is applied to the cutting element.

2. Methodology

The efficiency of the assembly tool is largely determined by the cutting insert installation scheme, the accuracy of manufacturing the mating surfaces and loading conditions. Production experience has shown that, when milling, the destruction of the insert is fragile, and the widespread types of destruction of the cutting blade are chipped and micro-dyeing. In this regard, in order to increase the reliability of the tool, it is desirable to provide the most uniform distribution of stresses in the cutting blade at the initial time. In addition, practical experience shows that the operability of cutters with indexable inserts essentially depends on the adopted scheme of basing, the binding force and the joint influence of the binding force and external force.

The finite element method (FEM) is widely used in the study of cutting processes. The most common case is orthogonal cutting. The paper [1] presents 2D thermo-mechanical FEM model of orthogonal cutting. The stresses in the primary and secondary deformation zone are simulated. Concluded that the variation of friction coefficient affects thrust force component and temperatures more than it affects cutting force.

The greatest amount of research is devoted to turning [2-10]. The authors are explored stress, strain, temperature, chip formation mechanisms and other characteristics of turning process. Several studies show the modeling of the broaching process [11, 12]. The FEM was applied [13] for understanding and predicting the residual stress values during ball-burnishing, allowing to determine the optimal process parameters. Modeling and simulation of the laser cutting process [14] using the analysis of heat transfer and general energy balance analysis made it possible to determine of temperature and stress distribution along with heat-affected zone. In the research of the deep twist drilling process, the authors [15] simulated the light drilled structure and the conventional welded structure and analyzed their behavior under compression loads. The von Mises stresses and the displacement of the models are determined. A lot of research has been also devoted to modeling the milling process. With the help of finite element analysis, the effect of the cutting speed on the cutting force, the temperature, width and curl radius of chip, and the wearing depth of tool are investigated over the milling process [1, 16-20].

In all these works, the finite element method is used to model the interaction of the tool with the workpiece. The integrated model proposed by the authors [21] takes into account the clamping preloads, machining forces, locator–workpiece contact interaction, fixture compliances, machine table stiffness, and forced vibrations. The FEM in study [22] creates spindle, holder and tool models and is used to simulate the contact conditions of tool and workpiece as well as spindle and tool holder and contact of tool-workpiece. In the paper [23], the authors illustrate the analysis of tooltip positioning error along the three coordinate axis in a CNC machine. This study takes into account only static loads, neglects the dynamic effect during milling, and assumes that the tool and the workpiece deform to their static equilibrium positions at any milling instant.

At the same time, in open access there is no information on modeling and optimization of the design of mills with the finite element modelling.

In the designs of prefabricated milling cutters, a circular form is often used. The round insert has the advantage associated with the lack of corner areas, which are stress concentrators. Besides, when turning the insert with worn cutting edge around axis, it is possible to use practically the entire perimeter of the cutting edge, thus increasing tool life and reducing costs. However, the circular cutting edge determines the various deformations of the cutting layer associated with the direction of the outgoing chip removal, causing a different amount of cutting force. Therefore, modeling the design of cutters with round inserts requires consideration of specific features.
For the analysis of stressed-deformed state, a 3D model of a disk milling cutter (Figure 1) consisting of a housing 1, a cassette 2 with a pressed pin 4, a cutter insert 3, a ring 5, a washer 6 and a screw 7 is created. When the screw 7 is screwed, the cassette 2 moves radially, thanks to which the insert 3 is pressed against the base surface of the housing 1. This design corresponds to the fastening system of the plate, designated according to the ISO 518 standard by the letter P: the basing of the insert in the tool body along the support and side surfaces with a pin clamped through the central hole. The method provides a guaranteed pressure against the surface of the body, high accuracy of positioning of the main cutting edge, good chip removal, coincidence in the direction of cutting forces and fastening.

The cutter can cut through the grooves with a depth greater than the radius of the insert, which imposes a limit on the thickness of the shell. In this paper, we consider a round insert with a clearance angle. At the base of the conical lateral surface of the insert, two circuits are possible in the cutter body (Figure 2): in the first scheme (Figure 2a), the contact of the conical surface of the insert with the body is carried out by a smaller cone diameter, and in the second scheme (Figure 2b) - larger. Evaluation of stressed-deformed state in both cases requires modeling of two versions of the housing, the remaining elements of the design remain unchanged.

The developed design scheme (Figure 2c) takes into account the application scheme of the components of the cutting force and subsequent modeling (clearances Δ1 and Δ2). Due to the symmetry of the cutting edge, the axial component of the cutting force (in the X-axis direction) is not taken into account, but only the radial Py and the tangential Pz components are taken into account. Also, an assumption has been made that the component cutting forces are distributed evenly along the entire cutting edge (in a half circle). The clamping force of the Pc is directed parallel to the cassette's reference plane. Pressing the pin into the holder allows, when performing calculations, to accept them as a single component (cassette).

The methodology for calculating the stressed-deformed state includes three successive steps that correspond to the actual construction of the mill.
Figure 2. Basing schemes of insert: (a) first scheme; (b) second scheme; (c) schematic view of a simplified model of a disk mill.

Step 1 - ensuring the specified relative arrangement of the structural elements. The housing is rigidly fixed, i.e. there is no movement along the coordinate axes. At this point, there are gaps between the assembly components: $\Delta 1$ - between the pin and the insert and $\Delta 2$ - between the insert and the housing. When performing calculations at this step, the absence of interference (interference) between the components whose criterion is the magnitude of the stresses is checked (theoretically it should be zero).

Before performing the calculations, it is necessary to spatially sample the calculated area, i.e. replacement of the solid model by a net of finite elements (FE). This requires a reasonable choice of the type and size of the FE. The type of FE is due to the studied properties of the object, its shape and dimensions. Among the volume elements, the FE in the form of a cube and a regular tetrahedron provides the best convergence conditions for the solution. We take as the FE the type SOLID185, used for three-dimensional modeling of volumetric constructions. It is determined by 8 nodes (cube) in 3 degrees of freedom in each. The element has the properties of plasticity, hyperelasticity, hardening, creep, deformations and displacements. It can take the form of a 6 (prism), 5 (pyramid) or 4 (tetrahedron) node element, if it is necessary to coordinate the mesh with the partition. The size of the FE is chosen on the basis of a trade-off between sampling errors and the required computing power resources. When choosing the size of FE for prefabricated structures, it is desirable to observe the proportionality of different components. Therefore, the size of the FE for the housing is taken equal to 1 mm, and for cassette and insert - 0.5 mm.

The model should include the minimum necessary part of the design, allowing to obtain an adequate solution at the minimum cost of the calculation time. Since the design is axisymmetric, to create a finite element mesh and accelerate the calculation in the computer-aided engineering system, it is sufficient to have one sector of the enclosure containing one cassette with the insert (Figure 3).

The initial data include the properties of materials: the Young’s modulus $E$ and the Poisson’s ratio $\mu$. As the material of the housing and the cassette, structural steel is adopted, and the insert is a hard alloy.

The boundary conditions are as follows: rigid fixation of the housing in all coordinates; limit the movement of the cassette along the X and Z axes; no gaps between the cassette and the housing.

We accept contact interactions with a friction coefficient of 0.25: between the flat surfaces of the housing of mill and the cassette; between the conical surface of the insert and the housing; between the
lower surface of the insert and the plane of cassette; between the hole in the insert and the cylindrical surface of the pin.

![Figure 3](image)

**Figure 3.** (a) the mill sector; (b) its representation by a finite element mesh.

Step 2 - insert holder tightening. It occurs when assembling the mill before work or changing of worn insert. To do this, the $P_c$ clamping force is applied to the end face of the cassette in the direction of the $Y$ axis. As a result, the screw presses the insert to the base surface in the housing, creating a certain interference. The corresponding stresses appear on the components of the structure.

Step 3 – modeling the cutting process. A uniformly distributed cutting force is applied to the cutting edge of the insert. The value of the tangential component of the cutting force is assumed equal to 500; 1000; 1500; 2000; 2500 N, and radial - equal to half of the tangential component. There is a redistribution of stresses resulting from the clamping of the cassette.

The resulting tension in the cassette is concentrated on the cylindrical surface of the pin (Figure 4a). As a result of the application of the components of the cutting force, the insert is clamped to the support plane of the cassette, which causes the appearance of stresses on it (Figure 4b). After the application of the cutting force, the redistribution of stresses between the pin and the reference plane occurs: a decrease on the pin and an increase in the plane (Figure 4c).

![Figure 4](image)

**Figure 4.** Stress change with increasing cutting force: (a) without cutting force; (b) with minimum cutting force; (c) with maximum cutting force.

In general, the magnitude of the stresses on the surface of the pin and the support surface of the cassette are different. However, with a certain clamping force, it is possible to determine such a cutting force at which the stresses on the pin 2 and the support plane 1 are aligned (Figure 5a). This condition can be reflected graphically: the interrelation of the clumping force and the cutting force (Figure 5b). Therefore, for a given cutting force, it is possible to determine the clamping force, which ensures equal stresses on the holder and the pin. If necessary, it is possible to ensure the equal strength of these elements, taking into account their geometrical parameters and the type of loading. It can be noted that with insufficient clumping force, the calculation fails. The excessive clamping force leads to stress in the structural elements of the cutter above the conventional yield strength of structural steel.
(Figure 6a), which leads to plastic deformation and violation of proper functioning. Also, with an increase the clumping force the stress at the point of contact of the insert, they become higher than the stresses at the cutting edge (Figure 6b), which can cause brittle fracture of the insert not in the cutting zone.

An analysis of the graphs of the relationship of cutting and clumping forces shows that the basing scheme affects the magnitude of the required clumping force. With small cutting forces (up to 3000N) basing according to the first scheme requires the application of a smaller clamping force. In addition, this scheme provides a closer to the linear relationship of forces.

3. Conclusions
In the article, the stressed-deformed state of a cutting blade of a disk mill is considered taking into account the insert scheme of basing, clamping force and cutting force.

If the clamping force of the cassette is insufficient after loading, even with the minimum cutting force, infinitely large displacements of the insert occur, leading to a failure in the calculation. In practice, this means dropping the insert from the housing of mill.

The excess clamping force causes the occurrence of stresses above the conditional yield strength of the structural materials of the components. In practice, this will cause plastic deformation of proper functioning. The brittle destruction of insert may not occur in the cutting zone.
The clamping force can be assigned depending on the expected cutting force, which will ensure in the process of work the equality of the stresses on the holder and the pin. The basing of the first scheme with low cutting forces is preferable from the point of view of lower stresses in the holder and pin.

Continuation of the research can be done by comparing the stressed-deformed state with other types of disk milling constructions, examining various insert materials, changing the insert geometry and the direction of cutting force, taking into account temperature deformations.

Acknowledgments
South Ural State University is grateful for financial support of the Ministry of Education and Science of the Russian Federation (grant No 9.5589.2017/8.9).

References
[1] Yuan Y, Jing X, Ehmann K F et al 2018 Modeling of cutting forces in micro end-milling J. of Manufacturing Processes 31 844–858
[2] Markopoulos A P, Vaxevanidis N M and Manolakos D E 2015 Friction modeling in finite element simulation of orthogonal cutting Tribology in Industry 37 440–448
[3] Yan H, Hua J and Shivpuri R 2005 Numerical simulation of finish hard turning for AISI H13 die steel Science and Technology of Adv. Materials 6 540–547
[4] Bassett E 2014 Belastungsspezifische Auslegung und Herstellung von Schneidkanten für Drehwerkzeuge (Hannover)
[5] Ma Y, Zhang J, Peng P et al 2018 Study on the evolution of residual stress in successive machining process Int. J. Adv. Manuf. Technol. 96 1025-34
[6] Ortiz-de-Zarate G, Madariaga A, Garay A et al 2018 Experimental and FEM analysis of surface integrity when broaching Ti64 Procedia CIPR vol 71 (Elsevier) pp 466-471
[7] Peirovi S, Pourasghar M, Nejad A F et al 2017 A study on the different finite element approaches for laser cutting of aluminum alloy sheet Int. J. Adv. Manuf. Technol. 1 1-15
[8] Lopez de Lacalle L N, Fernandez A, Olvera D. et al 2011 Monitoring deep twist drilling for a rapid manufacturing of light high-strength parts Mechanical systems and signal processing 25 2745–52
[9] Rai J K and Xirouchakis P 2008 Finite element method based machining simulation environment for analyzing part errors induced during milling of thin-walled components Int. J. of Machine Tools and Manufacture 48 629–643
[10] Pour M and Ghorbani H 2017 Improving FEM model of low immersion milling process using multi-objective optimization of tool elastic support dynamic properties Int. J. Adv. Manuf. Technol. 92 2279–97
[11] Rodriguez A, Lopez de Lacalle L N, Celaya A et al 2012 Surface improvement of shafts by the deep ball-burnishing technique Surface and Coatings Technology 206 2817-24
[12] Zhang P and Wang Y 2018 A study on chip and microstructure of 7055 aluminum alloy's 3D HSC based on FEM and experiment Vacuum 152 205-213
[13] Bermudo C, Sevilla L, Martin F et al 2016 Study of the Tool Geometry Influence in Indentation for the Analysis and Validation of the New Modular Upper Bound Technique Applied Sciences 6 1-16
[14] Xiong Y, Wang W, Jiang R et al 2018 Mechanisms and FEM Simulation of Chip Formation in Orthogonal Cutting In-Situ TiB2/7050Al MMC Materials 4 1-19
[15] Biermann D, Menzel A, Bartel T et al 2011 Experimental and computational investigation of machining processes for functionally graded materials Procedia Engineering 19 22–27
[16] Xie L-J, Schmidt C, Biesinger F et al 2009 Wear progress prediction of carbide tool in turning of AISI1045 by using FEM Proc. of CIST2008 & ITS-IFTOMM2008 (Beijing: Elsevier) pp 372-375
[17] Krajinović I, Daves W, Tkadletz M et al 2016 Finite element study of the influence of hard coatings on hard metal tool loading during milling Surface and Coatings Technology 304 134-141
[18] Liao Y G and Hu S J 2001 An Integrated Model of a Fixture–Workpiece System for Surface Quality Prediction Int. J. Adv. Manuf. Technol. 17 810–818
[19] Zhang Q, Zhang S and Li J 2017 Three dimensional finite element simulation of cutting forces and cutting temperature in hard milling of AISI H13 steel Procedia Manufacturing 10 37–47
[20] Yanda H, Ghani J A, Rizal M et al 2015 Performance of uncoated and coated carbide tools in turning FCD700 using FEM simulation Int. J. Simul. Model. 14 416-425
[21] Klocke F, Lung D and Buchkremer S 2013 Inverse identification of the constitutive equation of Inconel 718 and AISI 1045 from FE machining simulations Procedia CIRP 8 212–217
[22] Pour M and Ghorbani H 2017 Improving FEM model of low immersion milling process using multi-objective optimization of tool elastic support dynamic properties Int. J. Adv. Manuf. Technol. 92 2279–97
[23] Afkhamifar A, Antonelli D and Chiabert P 2016 Variational analysis for CNC milling process Procedia CIRP 43 118-123