Modeling and study of the stress-strain state of the modular turning tools using numerical finite element method

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Abstract. The paper studies a comparative evaluation method for the modular cutting tools stress-strain state under the cutting forces loading with the help of the finite element numerical method. The method allows forecasting the modular cutting tool the position of the tip of the cutting edge with identification of the confidence bounds for its exploitation in compliance with its intended use and reference operating conditions. The conducted modeling describes the modular cutting tool structure as a ranked set of structural components, such as the frame, cutting insert, shim, etc., oriented towards a certain direction with some surfaces being contiguous and thus making contact interactions. The research examined different tool structural component layout options, including those equipped/not equipped with a shim, having a radial/tangential location type of cutting components. Regression models were obtained for calculating the total displacements of tips the cutting edges of the cutting inserts, as well as maximum equivalent stresses in the cutting inserts, depending on the attachment and cutting forces for various clamping patterns and positioning cutting plates in the form of linear polynomials. The authors developed recommendations for the most efficient application of the modular cutting tool structural component layout options under specific production conditions.

1. Introduction

The current state and development prospects for metal working is characterized by a broad use of modular cutting tools equipped with indexable cutting inserts which are mechanically clamped and made of hard alloys, ceramics and ultra-hard materials. A variety of machining situations alongside with underdeveloped calculation methods, unable to solve the problem of a rational tool structure choosing at the design stage, led to emergence of an extensive nomenclature of tools with the same intended uses [1, 2]. At the moment, several thousands of such cutting tool structures with mechanically clamped cutting components are designed and applied; they differ by their overall dimensions and structural design, the ways cutting components are located and clamped [3-6]. The existing design methods allow for identification of cutting tool geometric and structural parameters while being unable to evaluate a variety of cutting insert locations and clamping ways [1, 6, 11-17]. It is possible to provide the quality of design solutions using integrated design systems that allow automating the design of modular turning tools from a variety of spatial parametric geometric
prototypes of structural elements, such as the frame, cutting insert, shim, etc.; and assessing the stress-strain state of a tool [10, 18-20].

The goal of this paper is to develop the method for a comparative evaluation of modular turning tools stress-strain state to identify the best design solutions intended for specific operating conditions.

To reach the set out goal, the following objectives have been singled out:

- to form and provide an analytical description for the evaluation model of the modular turning tools stress-strain state with due regard to a variety of cutting insert locations and clamping ways;
- to conduct analytical research of the influence of the modular turning tool structural component design on the stress-strain state;
- to develop recommendations for application of the modular turning tool structures with various ways of cutting component location and clamping.

2. Key provisions of the method for a comparative evaluation of stress-strain state of the modular turning tool

The model of the stress-strain state of modular turning tools was developed assuming that the attachment and cutting forces act on a synthesized tool structure either simultaneously or in succession. Under the impact of these forces, the tool components are elastically strained which results in a change in their shape and dimensions [8, 22, 23].

At modeling the process of forming the stress-strain state in modular turning tools was divided into the following stages:

- placing a support element within a seat of the tool frame. At this stage elastic strains occur in the tool frame due to the shim mass;
- clamping a support element in the seat where the gap between seat support and the shim is adjusted by changing the attachment force. Elastic strains of the tool frame and the shim are caused by the attachment force;
- placing a cutter on the shim and in the frame seat. At this stage, there are elastic strains of the tool frame and the shim due to the cutter mass;
- clamping the cutter in the frame seat. At this stage, there is a redistribution of gaps between the pairs of supports and mounting surfaces, the seat and the shim, the shim and the cutter, as well as the emergence of a stress-strain state in the components of a modular cutting tool under the action of the attachment force after redistribution of the gaps (replaced by tension);
- placing a chipbreaker onto the cutter. Elastic strains occur in tool components due to the chipbreaker mass;
- clamping a chipbreaker onto the cutter, redistribution of gaps between the pairs of supports and mounting surfaces, the seat and the shim, the shim and the cutter, and the cutter and the chipbreaker;
- clamping the tool onto the machine. At this stage, the tool frame is strained due to its mass and the attachment force;
- application of the tool to the assembled structure with the determined gap scheme between the links of perturbing factors of the cutting process (cutting force). At the stage, further redistribution of gaps between the above-mentioned pairs of supports and mounting surfaces and the strain of components of the modular turning tool, which determine its stress-strain state, occurs.

The selection of the design model for estimating the stress-strain state of the modular turning tool was made on condition that the position of the tip of the cutting edge is fully determined by the contact conditions and the strain of the tool component layout.

The components of the cutter layout (design macro-components) are in contact with each other over certain surfaces (areas) the values of which are not specified in the initial conditions. The contours of the component surfaces are designed taking into account the deviations of the shape,
position, and the profile state. The system of perturbing factors is explicitly described. It consists of the main load vector and the main load moment acting on the tool.

The designed macro-components are divided into multiple bulk, surface, and core basic finite elements. The stress-strain state of the tool was estimated from the matrix expressions of the finite element method [1].

The interaction between macro-components was modeled by the introduction between the contacting nodes of rods (connections) with low stiffness:

\[
[K]^K [U] = \{P\} - [K]^K \{\Delta\}
\]

where

\[
[K]^K = \frac{AE}{L} \begin{bmatrix} [T] & 0 \end{bmatrix}^{-1} [G] \begin{bmatrix} [T] \ 0 \end{bmatrix}
\]

\[(1)\]

\[
[K]_k \text{ is the contact rod rigidity matrix; } [T] \text{ is the matrix of transition from the macro-component local coordinate system to the tool global coordinate system; } \{P\} \text{ is the global load vector; } AE/L \text{ is rod rigidity; } \Delta \text{ is the gap between abutting surfaces of macro-components measured surface-wise; } \{U\} \text{ is the displacement vector.}
\]

Contact stiffness of the cutter layout consisting of the macro-components with known amount of contact links was calculated according to the following formula:

\[
\sum_{c=1}^{N_c} [K]^c + \sum_{K=1}^{N_K} [K]^K = \{P\} + \{P_0\}
\]

where

\[
\{P_0\} = \sum_{K=1}^{N_K} [K]^K \{\Delta\}
\]

\[(3)\]

There \([K]^c\) is the finite element stiffness matrix.

Modeling of the interaction of real surfaces of macro-components was carried out based on the kinematic contact condition for two contiguous points. The area of contact between the nodes of surface finite elements was specified using the iteration method.

The strains and stresses of bulk finite elements and macro-components based on Hooke’s law [39] were calculated using the following equations:

\[
\{\varepsilon\} = [B] \{U\}
\]

\[
\{\sigma\} = [D] \{\varepsilon\}
\]

\[(5),(6)\]

where \{\varepsilon\}, \{\sigma\} are column vectors and strains and stresses of bulk finite elements; \([B], [D]\) are gradient matrices and elastic solid finite elements.

The stress state of the cutter macro-components was estimated by the principal and equivalent stresses calculated using the maximum-distortion-energy theory:

\[
\sigma_1^3 - J_1 \sigma_1^2 + J_2 \sigma - J_3 = 0,
\]

where

\[
J_1 = \sigma_x + \sigma_y + \sigma_z
\]

\[
J_2 = \sigma_x \sigma_y + \sigma_y \sigma_z + \sigma_z \sigma_x - \tau_{xy}^2 - \tau_{yz}^2 - \tau_{zx}^2
\]

\[
J_3 = \sigma_x \sigma_y \sigma_z - \sigma_y \tau_{xy}^2 - \sigma_z \tau_{yx}^2 - \sigma_x \tau_{zx}^2 + 2 \tau_{xy} \tau_{yx} \tau_{zx}
\]

\[(7),(8)\]
where \( \sigma_1, \sigma_2, \sigma_3 \) are principal stresses; \( \sigma_x, \sigma_y, \sigma_z \) are normal stresses; \( \tau_{xy}, \tau_{yz}, \tau_{zx} \) are tangential stresses; are equivalent stresses.

\[
\sigma_{eq} = \frac{1}{\sqrt{2}} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2} \leq \sigma
\]  

(9)

This method was implemented by the numerical finite element method using C++.

3. Implementation of the method for a comparative evaluation of stress-strain state of modular turning tools

The developed method was implemented by the example of the design rationale of the modular turning tools. The authors considered four typical clamping and supporting options for a cutting insert: C, M, P, S at radial and tangential insert positioning.

Analytical research were conducted to check the capacity and to assess the validity of the developed models by the example of calculation of the structures for modular turning tools used for machining of medium-carbon steel work pieces 40X (\( E = 2 \times 10^5 \) MPa, \( \mu = 0.3 \)). The taken cutting inserts material was the steel grade T15K6 (\( E = 5.2 \times 10^5 \) MPa, \( \mu = 0.3 \)). The clamping and cutting forces varied in the ranges of 500,...,2000 N and 1,...,10 kN respectively.

According to the results of calculations, the overall distribution of strains, displacements, and stresses in the entire tool has been established.

It has been determined that the greatest strains, displacements, and stresses in the tool frame occur at the stage of its penetration into the workpiece. The radial forces from the workpiece arising during cutting unload the cutting blade. Radial strains that occur under the impact of cutting force in the tool frame cause radial displacements of its tip, affecting the accuracy of the surface to be machined.

The attachment force of the cutting inserts has an effect on the displacements of the insert assemblies, both in the joints with the frame seat and in the insert frame for all methods of positioning and clamping.

Introduction of the shim into the cutter helps to reduce the stiffness of the tool by an average of 10% for all the considered clamping methods due to the formation of additional joints between the shim and the cutting insert, as well as the shim and the tool frame.

Based on numerical experiments to assess the stress-strain state of modular turning tools, it has been established that: attaching the cutting insert according to the “C” pattern should preferably be used only for radial positioning of the cutting inserts with cutting forces of up to 6 kN; using a tool at high cutting forces may result in the rotation of the cutting insert relative to the side surfaces of the frame seat and the emergence of additional tensile stresses along the front surface of the cutting insert due to torque. This may both damage the cutting insert and chipping of side surfaces of the seat.

When mounting the cutting insert according to the “C” pattern tangentially, the detachment of the insert’s support from the frame seat’s support is possible due to the opening of the joint.

Attaching the cutting insert according to the “M” pattern is more preferable for tangential positioning than the radial one. However, the use of this scheme for tangential positioning of the cutting insert is difficult because of the bulkiness and the need to introduce additional clamping components into the tool design.

Positioning the cutting insert according to the “S” pattern is preferable among all the considered options since it most accurately provides positioning and clamping of the cutting insert in the frame seat due to uniform distribution of the attachment forces along the axes of coordinates and the selection of gaps in the joints between the cutting insert and the frame seat during the attachment stage.

Positioning the cutting insert according to the "P" pattern is preferable at large values of cutting force for radial positioning. The use of this scheme for tangential positioning and at large values of cutting force can cause separation of the cutting insert from the support of the frame seat.
The areas of maximum tensile stresses at the tip of the cutting edge of the tool, located along the front surface of the cutting insert, and compression, located along the posterior surface of the cutting insert at the tip of the cutting edge, have been identified. Along the front surface of the cutting insert from the top of the cutting edge to the hole, there is an area of possible breakage in the form of tensile stresses.

According to the results of calculations using the experimental design theory, regression models were obtained for calculating the total displacements of tips the cutting edges of the cutting inserts, as well as maximum equivalent stresses in the cutting inserts, depending on the attachment and cutting forces for various clamping patterns and positioning cutting plates in the form of linear polynomials.

\[
U_x = b_0 + b_1 \cdot x_1 + b_2 \cdot x_2 \quad (10)
\]

\[
\sigma_{equ} = b_3 + b_4 \cdot x_1 + b_5 \cdot x_2 \quad (11)
\]

where \( x_1 \) is the cutting force, \( H \); \( x_2 \) is the attachment force, \( H \); \( b_0, b_1, b_2 \) and \( b_3, b_4, b_5 \) polynomial factors (see Table 1).

### Table 1. Polynomial factors (10)-(11).

| Location type of cutting components and their clamping | Tool equipped/ not equipped with a shim | \( b_0 \) | \( b_1 \) | \( b_2 \) | \( b_3 \) | \( b_4 \) | \( b_5 \) |
|------------------------------------------------------|------------------------------------------|--------|--------|--------|--------|--------|--------|
| Radial positioning of the cutting insert              | C no                                      | 1.04E+1 | 1.37E-5 | 5.82E-6 | 13.46  | 0.37   | -0.006 |
|                                                     | M no                                      | 5.70E-6 | 1.25E-5 | 4.20E-5 | 5.86   | 0.14   | 0.086  |
|                                                     | P no                                      | 1.85E-4 | 2.11E-5 | 1.87E-5 | -12.27 | 0.71   | -0.078 |
|                                                     | S no                                      | 3.63E-4 | 2.07E-5 | 1.60E-6 | 9.26   | 0.57   | 0.024  |
|                                                     | C yes                                     | 5.78E-5 | 3.16E-5 | 1.81E-5 | -     | -      | -      |
|                                                     | M yes                                     | 1.20E-3 | 1.97E-5 | -3.86E-5 | -     | -      | -      |
|                                                     | P yes                                     | 9.53E-3 | 3.76E-5 | -4.17E-6 | -     | -      | -      |
|                                                     | S yes                                     | 2.83E-4 | 3.71E-5 | -2.32E-6 | -     | -      | -      |
| Tangential positioning of the cutting insert          | C no                                      | 1.17E-4 | 8.28E-6 | 3.81E-6 | -8.26  | 0.31   | -0.006 |
|                                                     | M no                                      | -1.41E-6 | 9.91E-6 | 1.52E-5 | 14.47  | 0.25   | -0.073 |
|                                                     | P no                                      | 1.41E-4 | 1.83E-5 | 8.92E-6 | 23.91  | 0.27   | 0.243  |
|                                                     | S no                                      | 1.22E-4 | 1.82E-5 | 1.36E-5 | 0.38   | 0.27   | 0.697  |

The use of linear polynomials is based on the linearity of interconnections in the considered range of forces.

The comparison of obtained results with other theoretical and experimental studies [6-7, 13-14] showed that the distribution of displacements and stresses in cutting inserts was similar. This made it possible to use (10) and (11) for comparing various designs of modular turning tools.

### 4. Conclusion

The research formal results allow forecasting of stress-strain state of modular turning tools, revelation of interrelation between the structural component layout factors and the machining accuracy output parameters at the technical production preparation stage.

This provides the basis for identification of the best solutions for various engineering requirements and limitations as well as for recommendations of the most efficient application of one or another structural component layout under specific operating conditions.
The developed method helps to significantly reduce the scope of conducted modelled and real experiments as it has the purpose of identification and prevention of the wrong cutting tool structure choice at the technical production preparation stage.

The proposed method will be developed as the evaluation of stress-strain state of modular mills.

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