

Design and Structural Assessment of a Special Boring Tool with an Inclined Clamping Mechanism

Karsakova N., Mussayev M.*, Tattimbek G., Dauletova F.

Abylkas Saginov Karaganda Technical University, Karagandy, Kazakhstan

*corresponding author

Abstract. The machining of large-diameter stepped holes requires high rigidity and positional stability of the cutting tool, particularly when boring bars with considerable overhang are employed. In addition to the structural characteristics of the boring bar, the cutting element clamping mechanism influences load transfer and displacement of the cutting edge during machining. This study presents the design and structural assessment of a special boring tool incorporating an inclined clamping mechanism. A three-dimensional model of the developed tool was created and subjected to finite element analysis to evaluate the deformation behavior of the cutting element during boring of a Ø295 mm hole. The structural response was assessed using total deformation and directional deformation components along the X, Y, and Z axes. The total deformation ranged from 0.17905 to 0.23775 mm, with a maximum value of 0.23775 mm. Directional analysis revealed maximum absolute displacements of 0.20932 mm, 0.094113 mm, and 0.088974 mm along the X, Y, and Z axes, respectively. The X-axis was identified as the dominant deformation direction, with displacement approximately 2.22 and 2.35 times greater than those along the Y- and Z-axes, respectively. The results demonstrate the importance of considering directional deformation when assessing the structural behavior of cutting assemblies and provide a quantitative basis for evaluating the rigidity and positional stability of the proposed inclined clamping mechanism.

Keywords: boring tool, boring bar, inclined clamping mechanism, stepped hole, finite element analysis, directional deformation, structural rigidity

Introduction

Large-diameter stepped holes are widely used in heavy machinery, mining equipment, power engineering, and transport systems for the installation of shafts, bearings, bushings, and other critical mechanical components. Unlike conventional cylindrical bores, stepped holes require machining of several coaxial diameters within a single workpiece while maintaining strict dimensional tolerances, positional accuracy, and high surface quality. Such requirements considerably increase the demands on tool rigidity, particularly during boring operations involving long overhangs. As the overhang-to-diameter ratio increases, the stiffness of the boring bar decreases significantly, making the machining process more susceptible to elastic deformation, self-excited vibration, and chatter, which ultimately reduce machining accuracy and accelerate tool wear [1–4].

The dynamic behaviour of boring bars has therefore been the subject of extensive investigations for several decades. Previous studies demonstrated that insufficient structural stiffness is one of the principal causes of vibration instability during deep-hole boring. Numerous analytical, numerical, and experimental studies have shown that chatter vibration not only deteriorates the surface finish and dimensional accuracy of machined holes but also reduces tool life and limits machining productivity [1, 5–7]. Consequently, improving the rigidity and dynamic stability of boring tools remains one of the major challenges in precision boring technology.

To overcome these problems, researchers have proposed various structural solutions aimed at suppressing vibration and improving machining stability. These include the application of passive and active damping systems, tuned mass dampers, particle damping, viscoelastic elements, piezoelectric actuators, optimized internal structures, and composite boring bars [2–4, 8–10]. Recent studies have also focused on variable-stiffness vibration absorbers and nonlinear dynamic optimization of boring bars, demonstrating considerable improvements in machining stability under severe cutting conditions [2, 3, 8].

Besides the rigidity of the boring bar itself, the cutting insert clamping mechanism plays a critical role in maintaining machining accuracy. The clamping assembly transfers cutting forces from the insert to the tool body while ensuring stable positioning of the cutting edge throughout the machining process. Local deformation of the clamping mechanism may cause micro-displacements of the cutting insert, resulting in increased vibration, reduced dimensional accuracy, and deterioration of surface quality. Despite the considerable attention devoted to vibration suppression of boring bars, comparatively fewer studies have investigated the structural behaviour of the cutting insert clamping assembly itself, particularly in special-purpose boring tools intended for machining large-diameter stepped holes.

Conventional industrial boring tools employ various insert clamping systems, including screw, pin, wedge, and cartridge mechanisms. These designs are primarily intended to simplify insert replacement and improve operational reliability. However, special boring tools designed for large-diameter stepped holes frequently require customized clamping arrangements dictated by geometric constraints and high cutting loads. The structural response of such

clamping systems under operational loading has received relatively limited attention in the literature, although deformation of the clamping assembly directly influences the positional stability of the cutting edge and, consequently, machining accuracy. Therefore, further investigations into the structural behaviour of specialized clamping mechanisms are required to support the development of more rigid and reliable boring tools.

Accordingly, the objective of the present study is to develop a special boring tool incorporating an inclined clamping mechanism and to evaluate its structural behaviour using finite element analysis. A three-dimensional model of the proposed tool was developed and analysed under operational loading conditions to determine the total deformation and directional displacements of the cutting insert assembly. The obtained results provide a structural assessment of the proposed design and contribute to the further development of special boring tools intended for machining large-diameter stepped holes.

1. Design of the Special Boring Tool

1.1. Tool Design and Clamping Mechanism

A special boring tool was developed for machining large-diameter stepped holes in heavy-duty mechanical components. The design was intended to improve the rigidity of the cutting assembly while ensuring reliable positioning of the cutting insert under operational loading. Unlike conventional commercial boring tools, the proposed design incorporates an inclined clamping mechanism that provides stable fixation of the cutting insert and facilitates its replacement without altering the overall configuration of the tool.

The general configuration of the developed boring tool is presented in Figure 1. The tool consists of a cylindrical boring bar body, a tool holder, a replaceable carbide insert, an inclined clamping element, and fastening screws. The cutting insert is mounted in a specially machined seat located at the front end of the boring bar. The clamping mechanism secures the insert by transmitting the tightening force from the fastening screws through the inclined contact surfaces of the clamping element to the tool holder, thereby providing reliable fixation during machining.

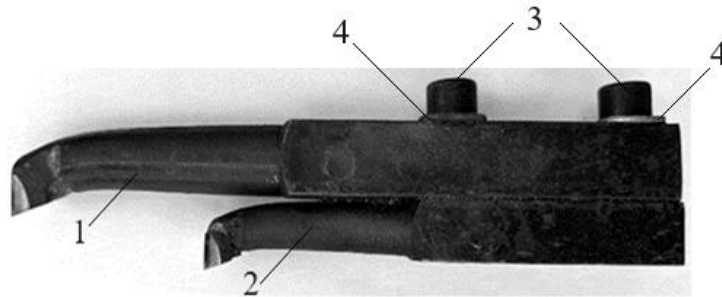


Fig. 1. - Developed special boring tool with an inclined clamping mechanism.

The inclined clamping mechanism was selected because it enables simultaneous generation of axial and radial clamping forces. Compared with conventional screw clamping systems, this configuration improves the contact between the mating surfaces and reduces the possibility of local displacement of the cutting insert during operation. As a result, the rigidity of the cutting assembly is expected to increase, contributing to improved positional stability of the cutting edge under machining loads. Similar design approaches have previously been adopted in the development of special boring tools intended to improve machining stability and reduce vibration [11, 12].

A detailed view of the clamping assembly is shown in Figure 2. The tool holder is positioned within the mounting groove of the boring bar and fixed by fastening screws. The inclined contact surfaces ensure uniform transmission of the clamping force while maintaining accurate positioning of the cutting insert. Owing to the modular design, the insert can be replaced without disassembling the entire boring tool, reducing maintenance time and simplifying tool servicing.

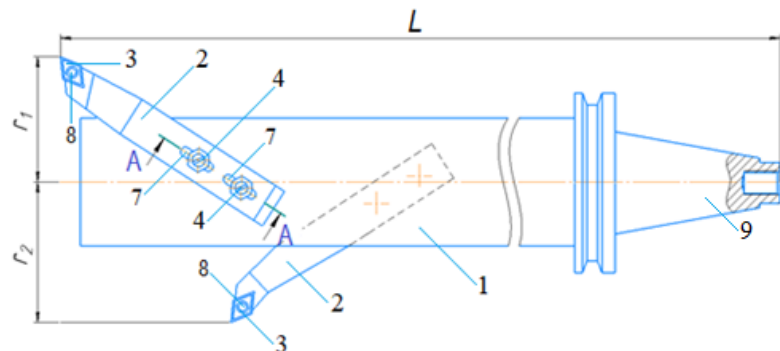


Fig. 2. - Detailed view of the inclined clamping mechanism.

The proposed structural configuration was developed using a computer-aided design (CAD) environment before numerical analysis. The three-dimensional model reproduced all principal structural elements of the boring tool, including the boring bar body, tool holder, cutting insert, inclined clamping mechanism, and fastening screws. This model served as the basis for subsequent finite element analysis aimed at evaluating the deformation characteristics of the developed design under operational loading conditions [13-15].

2. Finite Element Modeling

2.1 Three-Dimensional Model

A three-dimensional model of the developed special boring tool was created in KOMPAS-3D and subsequently used as the geometric basis for finite element analysis. The model reproduced the principal structural elements involved in the transmission of the machining load, including the boring bar body, the cutting element, and the inclined clamping assembly. The geometry of the model corresponded to the developed tool design presented in the previous section.

The three-dimensional representation of the boring tool is shown in Figure 3. Particular attention was paid to the cutting zone and the clamping assembly because displacement of the cutting element under external loading directly affects its positional stability relative to the machined surface. In this respect, the numerical model was intended primarily to evaluate the deformation response of the developed tool rather than to perform a strength assessment of its individual components.

The developed geometric model was imported into ANSYS for finite element analysis. The numerical assessment focused on the total deformation and the directional deformation components along the X, Y, and Z axes. This approach makes it possible to evaluate both the overall displacement of the cutting element and its displacement in individual coordinate directions, which is important for assessing the structural rigidity of the proposed clamping arrangement.

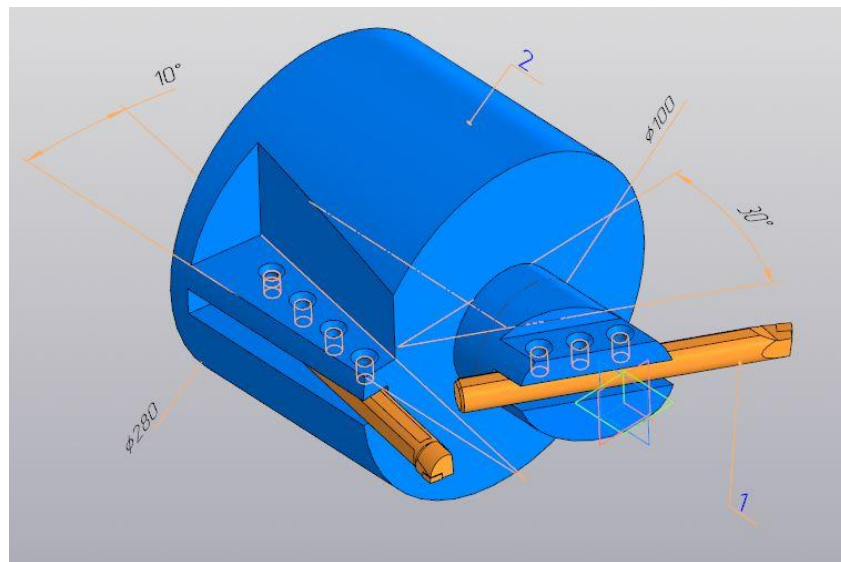


Fig. 3. - Three-dimensional CAD model of the developed special boring tool

2.2 Finite Element Model and Mesh

The finite element model of the developed boring tool was prepared in ANSYS using the three-dimensional geometry described in Section 3.1. The numerical model was constructed to evaluate the deformation response of the tool and, in particular, the displacement of the cutting element resulting from the applied machining load.

The geometry was discretized using a three-dimensional finite element mesh, as shown in Figure 4. The mesh covered the complete computational model and reproduced the geometry of the boring bar and the cutting region. Particular attention was given to the region near the cutting element, since this part of the structure directly receives the external machining load and its displacement is of primary interest for evaluating the positional stability of the cutting edge.

The finite element analysis was focused on deformation rather than on the strength or failure of the tool components. Accordingly, the numerical outputs considered in the present study were the total deformation and the directional deformation components along the X, Y, and Z coordinate axes. The total deformation characterizes the resultant displacement of the model, whereas the directional components make it possible to distinguish the contribution of displacement in each coordinate direction. Such separation is particularly important for a boring tool

because displacement of the cutting edge in different directions may affect the position of the tool relative to the machined surface differently.

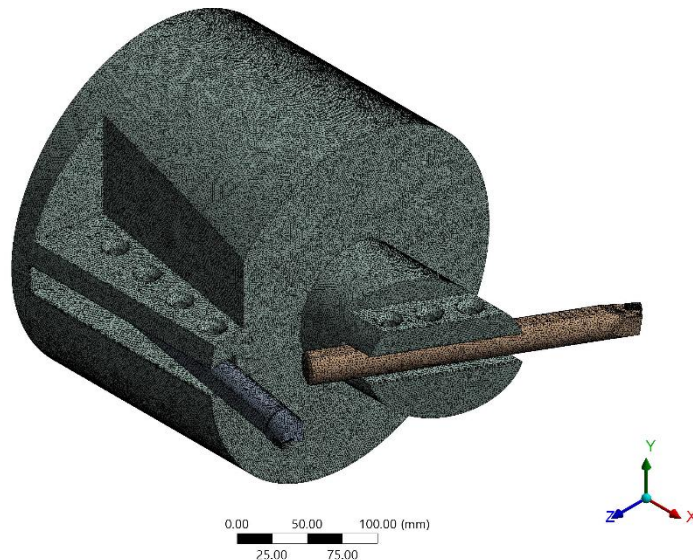


Fig. 4. - Finite element mesh of the developed special boring tool.

2.3 Boundary Conditions and Loading

The boundary conditions of the finite element model were defined to represent the loading scheme of the boring tool during machining of $\varnothing 295$ mm hole. The mounting region of the boring bar was constrained to reproduce its fixation in the machine-tool holder. For the static structural analysis, a resultant cutting force of 1500 N was adopted as the simulated machining load and applied to the cutting insert in the cutting region of the tool.

The applied load was transmitted from the cutting element through the clamping assembly to the boring bar body. This loading scheme was used to evaluate the deformation response of the developed tool and the positional stability of the cutting region. Since the primary objective of the numerical analysis was to assess the deformation behavior of the tool rather than its strength or failure resistance, the resulting displacement was considered as the main response parameter.

The applied load was transmitted from the cutting element through the clamping assembly to the boring bar body. This loading scheme was used to evaluate the deformation response of the developed tool and the positional stability of the cutting region. Since the primary objective of the numerical analysis was to assess the deformation behavior of the tool rather than its strength or failure resistance, the resulting displacement was considered as the main response parameter.

The numerical results were evaluated in terms of total deformation and directional deformation along the X, Y, and Z coordinate axes. The total deformation represents the resultant displacement of the analyzed structure, whereas the directional components provide information on the displacement of the cutting region in individual spatial directions.

3. Results and Discussion

The finite element analysis was used to evaluate the deformation behavior of the cutting element of the developed boring tool during machining of a $\varnothing 295$ mm hole. The numerical results were analyzed in terms of total deformation and directional deformation along the X, Y, and Z axes. The corresponding deformation fields are presented in Figures 5–8, while the characteristic values obtained from the numerical analysis are summarized in Table 1.

Table 1. Deformation characteristics of the cutting element obtained from finite element analysis

Deformation component	Maximum value (mm)	Minimum value (mm)	Maximum absolute value (mm)
Total deformation	0.23775	0.17905	0.23775
X-axis	-0.14805	-0.20932	0.20932
Y-axis	-0.068643	-0.094113	0.094113
Z-axis	-0.047977	-0.088974	0.088974

The distribution of total deformation is shown in Figure 5. The calculated values vary from 0.17905 to 0.23775 mm, with a maximum resultant deformation of 0.23775 mm. The deformation field is non-uniform across the cutting

element, indicating that its different regions respond differently to the applied loading. The gradual variation of displacement over the analyzed geometry indicates a continuous deformation response rather than a highly localized displacement at a single point.

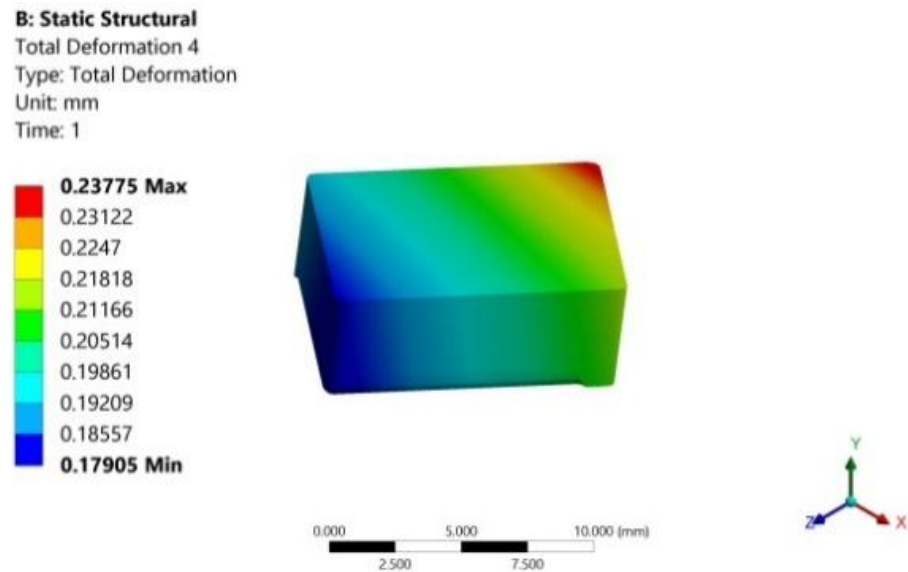


Fig. 5. - Total deformation of the cutting element during boring of a $\varnothing 295$ mm hole.

Analysis of the directional components provides additional information on the spatial displacement of the cutting element. As shown in Figure 6, the deformation along the X-axis varies from -0.14805 to -0.20932 mm. The negative sign indicates that displacement occurs in the direction opposite to the positive X-axis of the global coordinate system. In terms of absolute magnitude, the maximum X-directional displacement reaches 0.20932 mm, making the X component the dominant directional deformation observed in the numerical analysis.

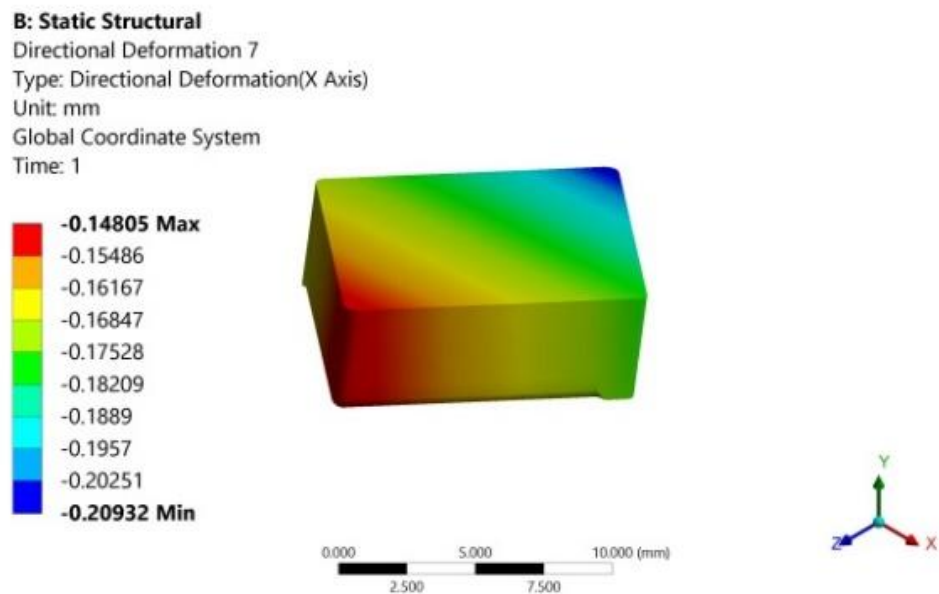


Fig. 6. - Directional deformation of the cutting element along the X-axis during boring of a $\varnothing 295$ mm hole.

The deformation along the Y-axis is considerably smaller (Figure 7). The calculated values range from -0.068643 to -0.094113 mm, corresponding to a maximum absolute displacement of 0.094113 mm. This value is approximately 55% lower than the maximum absolute displacement obtained along the X-axis. The results therefore indicate that the response of the cutting element is strongly direction-dependent, with the displacement along the X-axis being substantially greater than that along the Y-axis.

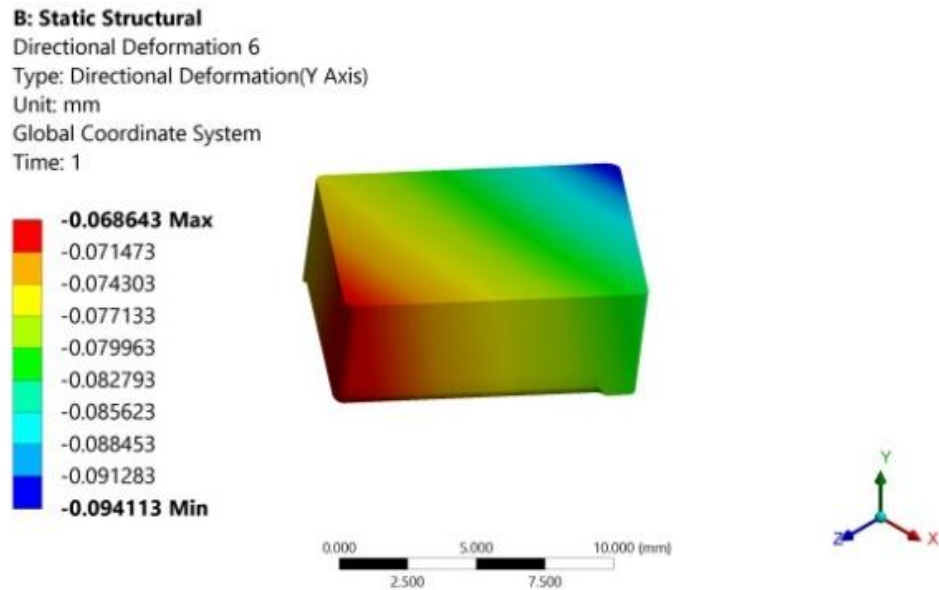


Fig. 7. - Directional deformation of the cutting element along the Y-axis during boring of a Ø295 mm hole.

A similar tendency is observed for the Z-axis component presented in Figure 8. The calculated deformation ranges from -0.047977 to -0.088974 mm, giving a maximum absolute displacement of 0.088974 mm. This represents the smallest maximum directional displacement among the three coordinate components and is approximately 57% lower than the corresponding value along the X-axis. The Y- and Z-directional displacement magnitudes are relatively close, whereas the X-axis response is clearly dominant.

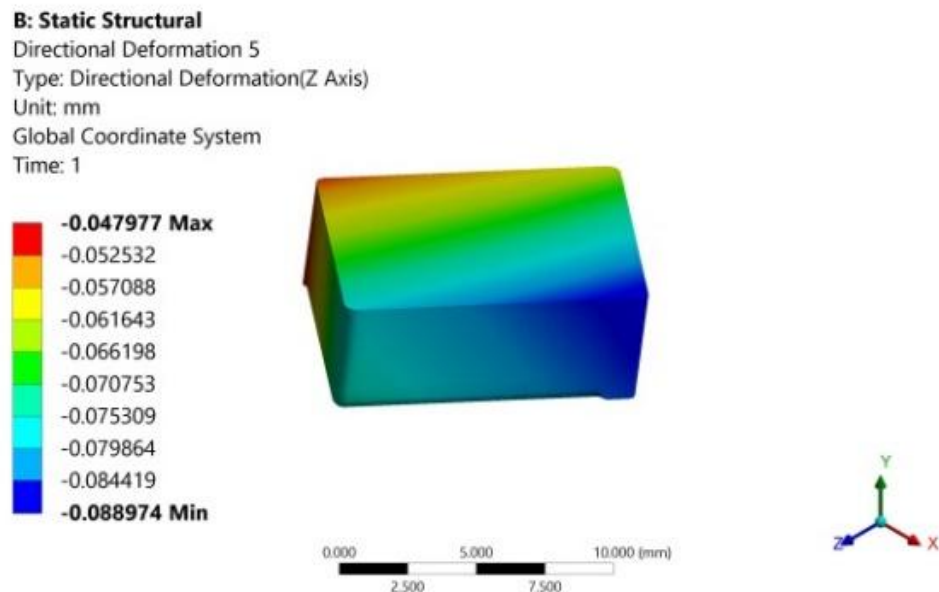


Fig. 8. - Directional deformation of the cutting element along the Z-axis during boring of a Ø295 mm hole.

The comparison of the three directional components demonstrates that the deformation behavior of the cutting element is anisotropic with respect to the adopted global coordinate system. The maximum absolute displacement along the X-axis is approximately 2.22 times that along the Y-axis and 2.35 times that along the Z-axis. Consequently, the X direction represents the principal direction of displacement under the adopted loading conditions. This result is important from the standpoint of tool design because displacement of the cutting element changes the spatial position of the cutting edge relative to the machined surface.

The resultant deformation of 0.23775 mm should therefore be considered together with its directional components rather than as an isolated parameter. The directional analysis demonstrates that most of the displacement is associated with the X component, while substantially smaller contributions are observed along the Y and Z axes. Such decomposition provides a more informative assessment of the structural response of the cutting element and makes it possible to identify the direction in which the developed assembly is most susceptible to displacement.

From a structural perspective, the obtained results demonstrate that the inclined clamping mechanism maintains the cutting element as an integrated part of the tool assembly while transferring the applied load through the contact region. At the same time, the calculated directional deformation indicates that the structural response is governed predominantly by displacement along one coordinate direction. This observation is relevant to the further development of the clamping assembly, since increasing rigidity in the dominant deformation direction may be particularly important for improving the positional stability of the cutting edge.

It should be emphasized that the present analysis evaluates the static deformation behavior of the developed tool. Therefore, the obtained results should not be interpreted as direct evidence of chatter suppression or vibration reduction. Nevertheless, static rigidity and displacement of the cutting element are important structural factors affecting the dynamic behavior of boring tools. The present results consequently provide a structural basis for assessing the proposed inclined clamping mechanism without extending the conclusions beyond the scope of the performed finite element analysis.

Conclusions

This study presented the design and structural assessment of a special boring tool incorporating an inclined clamping mechanism. The proposed design was developed for machining large-diameter stepped holes, with particular attention paid to the deformation behavior and positional stability of the cutting element. Based on the finite element analysis, the following conclusions can be drawn:

The developed boring tool employs an inclined clamping mechanism intended to provide stable positioning of the cutting element and transfer the machining load from the cutting region to the boring bar body. The proposed configuration provides a compact structural arrangement suitable for special boring operations involving large-diameter stepped holes.

Finite element analysis showed a non-uniform deformation distribution within the cutting element. The total deformation ranged from 0.17905 to 0.23775 mm, with the maximum resultant deformation reaching 0.23775 mm under the adopted loading conditions.

The directional deformation analysis revealed a pronounced dependence of the structural response on the coordinate direction. The maximum absolute displacement along the X-axis was 0.20932 mm, compared with 0.094113 mm along the Y-axis and 0.088974 mm along the Z-axis.

The X-axis was identified as the dominant deformation direction. The maximum absolute X-directional displacement was approximately 2.22 times greater than that along the Y-axis and 2.35 times greater than that along the Z-axis. This indicates that the rigidity of the cutting assembly in the X direction is particularly important for maintaining the positional stability of the cutting edge.

The decomposition of the resultant deformation into directional components provided a more detailed assessment of the structural behavior of the developed tool than consideration of total deformation alone. Such an approach allows the principal displacement direction to be identified and provides useful information for evaluating the structural performance of the clamping assembly.

The present results provide a structural assessment of the proposed inclined clamping mechanism based on static deformation analysis. Since dynamic, modal, and experimental investigations were outside the scope of the present study, the obtained results should not be interpreted as direct evidence of vibration or chatter suppression. Nevertheless, the identified deformation characteristics provide a basis for evaluating the rigidity and positional stability of the developed cutting assembly. Future work should include experimental modal testing and cutting trials under actual boring conditions to validate the static finite element analysis results and to assess the dynamic behavior of the developed boring tool.

Funding. This research was funded by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan, Grant No. AP27511047.

References

- [1] Sun J., Sun C., Yan Z. State-of-art, challenges, and outlook on deep hole boring: Chatter suppression, tool wear monitoring, and error measurement // *International Journal of Advanced Manufacturing Technology*. – 2025, Vol. 136, pp. 2075–2105. DOI: 10.1007/s00170-025-15007-x.
- [2] Guan Y., Yu G., Hu Q., Xu D., Xu J., Lushchik P. Vibration Characteristics Analysis of Boring Bar with Tunable Dynamic Vibration Absorber // *Materials*. – 2025, Vol. 18, Issue 6, Article 1324.
- [3] Wang B. et al. Research Progress and Application of Vibration Suppression Technologies for Damped Boring Tools // *Machines*. – 2025.
- [4] Oezkaya E. et al. Design and Performance Study of a Bionic Damping Boring Bar Based on the Woodpecker // *CIRP Journal of Manufacturing Science and Technology*. – 2025.
- [5] Li H., Xia Y., Su B., et al. Ultrasonic Vibration-Assisted Chatter Suppression for Deep Hole Boring of Stainless Steel // *International Journal of Advanced Manufacturing Technology*. – 2024, Vol. 131, pp. 1691–1703. DOI: 10.1007/s00170-024-13016-w.

- [6] Zhao W., Zhang Q., Li Y., Jing S. Lateral Random Vibration of Boring Bar for BTA Deep-Hole Process // Journal of Vibration and Shock. – 2024, Vol. 43, Issue 3, pp. 46–57.
- [7] Li L., Yang D., Cui Y. Optimization of Machining Performance in Deep Hole Boring: A Study on Cutting Tool Vibration and Dynamic Vibration Absorber Design // Advances in Production Engineering & Management. – 2023, Vol. 18, Issue 3, pp. 371–380.
- [8] Nonlinear System Optimization of Cutting Tools with Dynamic Vibration Absorbers in Deep Hole Boring: A Stability Analysis // Alexandria Engineering Journal. – 2025, Vol. 112, pp. 246–253.
- [9] Matsubara A., Maeda M., Yamaji I. Vibration Suppression of Boring Bar by Piezoelectric Actuators and LR Circuit // CIRP Annals. – 2014, Vol. 63, Issue 1, pp. 373–376.
- [10] Suyama D., Diniz A.E., Pederiva R. The Use of Carbide and Particle-Damped Bars to Increase Tool Overhang in the Internal Turning of Hardened Steel // International Journal of Advanced Manufacturing Technology. – 2016, Vol. 86, pp. 2083–2092.
- [11] Song Q., Shi J., Liu Z. et al. Boring Bar with Constrained Layer Damper for Improving Process Stability // International Journal of Advanced Manufacturing Technology. – 2016, Vol. 83, pp. 1951–1966. DOI: 10.1007/s00170-015-7670-5.
- [12] Takahashi W., Suzuki N., Shamoto E. Development of a Novel Boring Tool with Anisotropic Dynamic Stiffness to Avoid Chatter Vibration in Cutting: Part 1: Design of Anisotropic Structure to Attain Infinite Dynamic Stiffness // Precision Engineering. – 2021, Vol. 68, pp. 57–71. DOI: 10.1016/j.precisioneng.2020.11.007.
- [13] Kępczak N., Bechciński G., Rosik R. Operating Properties of Deep Hole Boring Tools with Modified Design // Materials. – 2024, Vol. 17, Issue 7, Article 1551. DOI: 10.3390/ma17071551.
- [14] Mussayev M., Kassymbabina D., Sherov K. Investigation of the Design of a Busbar Punching Tool Restored by Replacement of the Working Part with a Carbon Steel Insert // Material and Mechanical Engineering Technology. – 2025, No. 3, p. 16. DOI: 10.52209/2706-977X_2025_3_16.
- [15] Akulovich L.M., Mendaliyeva S.I., Sherov K.T., Toshov J.B., Mussayev M.M. Study of the Influence of the Angle of Inclination of the Axis of Ferroabrasive Grains on the Productivity and Surface Roughness of the Processed Part // Material and Mechanical Engineering Technology. – 2025, No. 4, p. 86. DOI: 10.52209/2706-977X_2025_4_86
- [16] Nurzhanova O., Zharkevich O., Berg A., Zhukova A., Mussayev M., Buzauova T., Abdugaliyeva G., Shakhmatova A. Evaluation of the Structural Strength of a Prefabricated Milling Cutter with Replaceable inserts During Machining // Material and Mechanical Engineering Technology, №4, 2023, 10-17

Information of the authors

Nurgul Karsakova, PhD, Abylkas Saginov Karaganda Technical University
e-mail: n.karsakova@ktu.edu.kz

Medgat Mussayev, PhD, Abylkas Saginov Karaganda Technical University
e-mail: m.mussayev@ktu.edu.kz

Gulerke Tattimbek, teacher, Abylkas Saginov Karaganda Technical University
e-mail: g.tattimbek@ktu.edu.kz

Fariza Dauletova, master student, Abylkas Saginov Karaganda Technical University
e-mail: f.dauletova@ktu.edu.kz