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Investigation of the stress state of a carbide plate of a cutting tool

Abstract. Cutting tools with carbide inserts operate under harsh conditions that can cause cracking and failure, as their strength directly depends on the stress-strain state. The study was conducted to determine of the influence of the angle of installation in the holder of brazed carbide plates of cutting tools on their stress state was investigated. Experimental studies using the method of photoelasticity are characterised by high sensitivity, non-destructive effects, clarity, and speed of results. The study was carried out on the polarisation-projection unit PPU-7 using physical models of carbide plates made of optically sensitive material ED-6, which were attached to the holder with different installation angles. The resulting isochrome and isokline photographs made it possible to assess the actual visual picture of the existing stresses. During the experiment, the cutting tool models were loaded using a specially designed stand that simulated the cutting force. The principal stresses were calculated by the method of difference of tangential stresses for the selected insert installation angles. It was proved that the angle of attachment of the carbide insert to the holder undoubtedly affects the distribution of stresses in it during metalworking. A quantitative relationship has been established between the angle of attachment to the holder and the magnitude of internal stresses acting in the carbide plate. The highest stresses σ_{equ} occured in the cross-section of the cutting blade of a carbide insert regardless of the angle of attachment to the holder. The lowest level of acting stresses along the measurement points in three zones along the width of the carbide insert when attached to the holder at an angle of -30° was found. With connection angles of 15°, 0°, and -15°, critical stresses occur in all investigated areas across the width of the plate along the measurement points

Keywords: isocline; isochromes; anisotropy; photoelasticity; installation angle

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INTRODUCTION

The reliability and durability of turning tools play a crucial role in ensuring the stability of machining processes and the quality of manufactured components. During cutting, the tool is subjected to elevated temperatures, substantial mechanical loads and thermal fluctuations, all of which contribute to intensive wear or even brittle fracture of carbide inserts. The geometric parameters of the tool, particularly the installation angle of the carbide insert, significantly influence its ability to withstand these operational stresses. Consequently, investigating the stress-strain state of the insert and the effect of its orientation within the toolholder is essential for improving tool reliability and extending its service life.

As the authors M. Sobron *et al.* (2020) pointed out, before starting the machining process, it is necessary to know how long the cutting tool can operate before it breaks down or suffers critical wear. A. Adamu *et al.* (2021) provided a comprehensive review of approaches to optimising cutting parameters with the aim of reducing tool wear in turning operations. The authors highlighted that tool wear was governed by a complex interaction of cutting speed, feed rate, depth of cut and the material properties of both the tool and the workpiece. Their analysis demonstrated that the selection of appropriate machining parameters was essential for achieving stable cutting conditions, improving surface quality and extending tool life. That is, cutting tools, including turning cutters, must have high strength, heat resistance, wear resistance, and hardness. If wear occurs in the main area of chip impact, i.e., on the front surface, crater wear occurs, and if the main wear occurs on the back surface of the cutter, edge wear occurs (Roszkowski *et al.*, 2020). Thus, the main reason why turning inserts fail and need to be replaced is wear. The situation is different with cutting tools.

Unlike through-hole cutters, cut-off cutters operate under difficult conditions of non-orthogonal cutting, as the cutter is subjected to force and temperature loads on three sides. In such conditions, the lubricating coolant does not work effectively enough, which complicates the efficiency of the chip removal process. P. Zabrodskyi *et al.* (2021) noted that the main cause of failure of cutters is not wear, as in the case of passing cutters, but breakage of carbide inserts. At the same time, as the authors Y. Liu *et al.* (2025) pointed out, compared to wear, brittle fracture occurs more suddenly and less predictably. Experimental results by A. Rizzo *et al.* (2020) showed that breakage occurs due to the formation of surface cracks with their subsequent expansion. Cracks can appear as a result of untimely sharpening of the tool, incorrectly selected cutting modes, and for cutters with brazed inserts during the manufacturing process when the inserts are soldered.

Scientists have conducted extensive research to determine the causes of cracks and breakage in carbide plates. Thus, F. Wu *et al.* (2021) and J. Östby *et al.* (2022), the method of analytical research is used to study the proposed theory of sliding lamellae formation in carbide inserts at the WC/WC grain boundary based on shear stresses. Finite element modeling of the cutting process by C. Xiao *et al.* (2024) provided information on the deformations along each point of the cutting line, the stresses occurring at each node/point, and the temperature distribution in the tool and workpiece during the machining process. The study was conducted using Deform 2D computer-aided design software. The authors V. Gutakovskis *et al.* (2022) used the Third Wave Advant Edge software to model turning and study stresses using the finite element method. W. Cai *et al.* (2025) used the Johnson-Cook constitutive model to determine the shear stress on the primary shear plane. It takes into account the strain, strain rate, and temperature effect to describe the stress. This model is widely used in cutting modelling and simulation studies.

Among the experimental methods used to study the stress-strain state, it is necessary to note, for example, the holographic method. M. Kumar *et al.* (2025) used a holographic interferometry unit to determine the deformations of turning cutters, which made it possible to combine the results of experimental and numerical studies. In the work by S. Lubis *et al.* (2020), a non-destructive X-ray diffraction method was used to measure surface stress. The authors B. Bergmann *et al.* (2025) used a method for calculating internal stresses based on measured external stresses. In this case, the internal stresses of worn cutting tools are calculated at different states of wear.

Therefore, the solution of the problem of optimising the geometric parameters of cut-off turning tools with brazed carbide inserts by determining the influence of the angle of installation in the holder on their stress-strain state is of scientific interest. The insufficient study of this issue requires additional research to identify ways to increase the durability and reliability of cutting tools. The aim of this study was to investigate the effect of the installation angle of brazed carbide inserts in the toolholder on their stress-strain state and to optimise tool design for improved durability during metalworking.

MATERIALS AND METHODS

It is difficult to ensure machining accuracy in prefabricated cutters due to the presence of additional gaps at the joints of the carbide inserts, so they were used in single or small batch production. Tools with brazed inserts (Fig. 1) offered significantly better precision than prefabricated cutters and were therefore preferred for use in Computer Numerical Control (CNC) machines.

Figure 1. Cutting-off tool with brazed carbide insert
Source: prepared on the basis of research data by P. Zabrodskyi (2021)

In the study, analytical and experimental methods were used to determine the stress state of carbide inserts in cut-off tools. One of the key methods involves calculating the shear stress in the material. For this, the formula proposed by J. Östby *et al.* (2022) was used to compute the shear stress (τ), which took into account the material's mechanical and thermal properties:

$$\tau = \frac{1}{\sqrt{3}}\left[A + B\left(\frac{\gamma}{\sqrt{3}}\right)^n\right]\left[1 + Cln\left(\frac{\dot{\gamma}}{\dot{\gamma}_0}\right)\right]\left[1 - \left(\frac{T-T_r}{T_m-T_r}\right)^m\right], \quad (1)$$

where A is the yield strength; B is the strain hardening coefficient; C is the sensitive strain rate coefficient; n is the strain hardening degree index; m is the thermal softening index; T_r is the reference temperature (ambient temperature); T_m is the melting point; γ is the strain; $\dot{\gamma}$ is the strain rate; $\dot{\gamma}_0$ is the reference strain rate.

To evaluate the stress-strain state of carbide inserts of cut-off cutters, the polarisation-optical method, or photoelasticity method, was used. In the present work, the polarisation-optical method, or photoelasticity method, was used to assess the stress-strain state of carbide plates of cutting tools. This method was based on the properties of certain transparent materials, which become optically anisotropic when deformed under mechanical stress. They developed optical anisotropy and the associated double birefringence. This was the so-called piezoelectric effect. In this case, the main values of the dielectric constant were linearly related to the main stresses within the elastic range. The main advantage of the polarisation-optical method was its ability to determine residual stresses. For the manufacture of models studied by the polarisation-optical method, materials were used that must have high transparency, stable optical and mechanical characteristics, sufficient strength, and optical and mechanical isotropy.

To study the stress-strain state of a carbide plate at different installation angles, models of cut-off cutters were made with front angles of -30, -15, 0, 15, and 30 degrees. The models of carbide insert of the cutting tools were made of optically sensitive material based on ED-6 epoxy resin, the hardening of which was provided by methyl tetrahydrophthalic anhydride with an optical constant =1.88 MPa. The geometric dimensions of the carbide insert models at different angles of installation in the holder are shown in Figure 2.

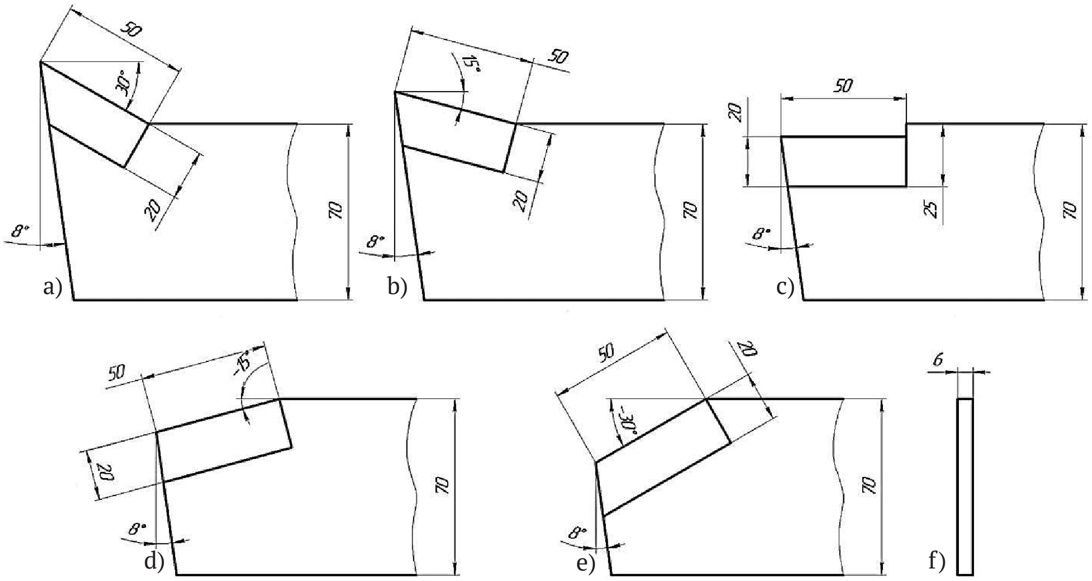


Figure 2. Geometric dimensions of models of cutting tools with the angle of installation of a carbide insert
Note: a) γ = 30°; b) γ = 15°; c) γ = 0°; d) γ = 15°; e) γ = 30°; f) thickness of the carbide insert
Source: compiled by the authors

The geometric scale of modelling for the geometric parameters of the model is selected based on:

$$\alpha = \frac{l_n}{l_m} = const, \quad (2)$$

where l_n, l_m are the lengths of any corresponding segments in reality and the model.

The force scale can be chosen arbitrarily:

$$\beta = \frac{P_n}{P_m} = const. \quad (3)$$

The relationship between the stress similarity scale δ and the force scale β is expressed through the geometric scale α:

$$\delta = \frac{\sigma_n}{\sigma_m} = \frac{\beta}{\alpha^2} = const. \quad (4)$$

The elastic modulus of the model, which has a stress dimension, should be modeled on the same scale as the stress б, according to the general principles of similarity theory:

$$\frac{E_n}{E_m} = \delta = const\,, \tag{5}$$

where E_n, E_m are the elastic moduli at the corresponding points in nature and the model.

The Poisson's ratios of the real materials μ_n and the model materials μ_m as dimensionless quantities must be equal to each other:

$$\mu_n = \mu_m. \tag{6}$$

When these conditions of similarity are met, it is sufficient that the internal (studied) stresses in the model have a scale of δ, the displacement has a scale of α, and the deformations of the model and the nature coincide. A special stand was used to perform the study, where models of incisors were installed and loaded with a force that simulated the cutting force (Fig. 3). A universal dynamometer was used to measure the applied force.

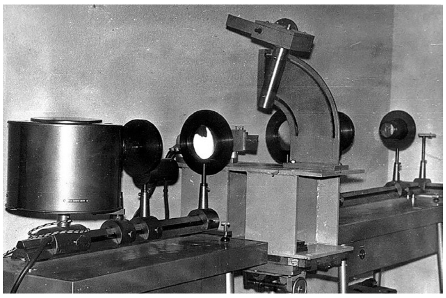


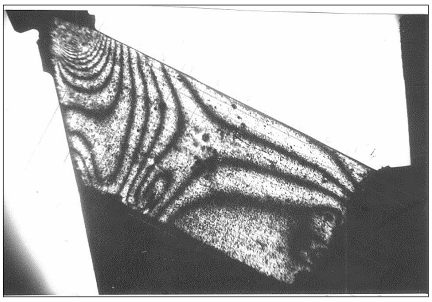
Figure 3. Polarisation and projection unit (PPU-7) with a load stand

Source: compiled by the authors

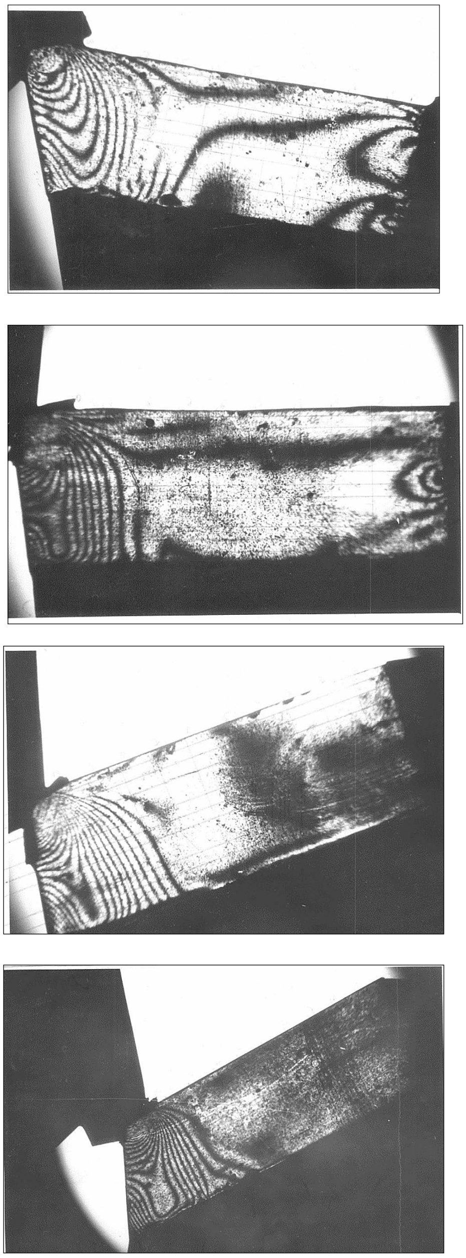
To determine the stresses, it was necessary to obtain pictures of isochromes (stripes of the same colour connecting points with the same difference in principal stresses) and pictures of isoclines (dark-coloured lines connecting points with the same direction of principal stresses).

RESULTS AND DISCUSSION

Patterns of isochromes (Fig. 4) and isoclines were obtained at the same load P_z=1,000 N. To evaluate the existing stresses, along arbitrary lines, two parallel auxiliary sections were drawn on opposite sides of these lines at a sufficiently close distance from the main ones. Along these sections, the values of the tangential stresses and were determined, as well as the difference of these stresses between the auxiliary sections.



a)



b)

c)

d)

e)

Figure 4. Photocopies of isochromes of samples with different angles of carbide plate fixation

Note: a) γ = 30°; b) γ = 15°; c) γ = 0°; d) γ = -15°; e) γ = -30°

Source: compiled by the authors

The values of the normal stresses σ_x and σ_y were determined using the following formulas:

$$\sigma_{xn} = \sigma_{x0} - \sum_{i=1}^{n} \left(\Delta\tau_{xy}\right)_i \frac{\Delta x_i}{\Delta y}; \tag{7}$$

$$\sigma_{yk} = \sigma_{y0} - \sum_{r=1}^{k} \left(\Delta\tau_{xy}\right)_r \frac{\Delta y_r}{\Delta x} + \gamma \sum_{r=1}^{k} \Delta y_r, \tag{8}$$

where n, k are the number of measured points along the x and y axes, respectively; σ_{x0}, σ_{y0} are the known values σ_x i σ_y at the starting point of integration; Δx_i, Δy_r are the intervals along the x and y axes through which measurements were made; Δx, Δy – are the distances between parallel auxiliary sections along the x and y axes, respectively; $\gamma\sum_{r=1}^{k}\Delta y_r$ is the product of the volume weight and the length of the integration segment (taken into account if the model works under its own weight).

The dangerous cross-section of the carbide insert was determined according to the second theory of strength. To do this, first, knowing the values of σ_x, σ_y, and τ_{max}, the values of the principal stresses σ_1 and σ_2 were calculated. Next, the value of the equivalent stress σ_{equ} was calculated for the case of a plane stress state:

$$\sigma_{equ} = \sigma_1 - \mu\sigma_2. \tag{9}$$

In each of the three longitudinal sections of the plate: near the surface, in the middle, and at the base for all angles of the plate installation, the calculation was performed for ten points (Fig. 5).

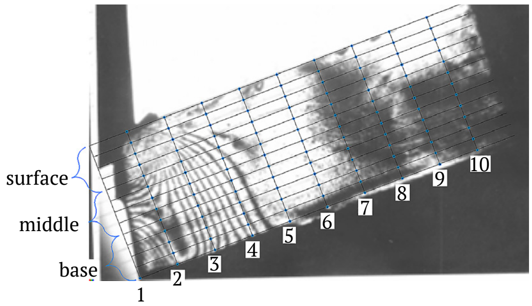


Figure 5. Scheme of the study on the example of a sample with a plate hard-metal insertion angle of $\gamma = -15°$

Note: the numbers show the division of the field into zones

Source: compiled by the authors

Based on the values of σ_{equ}, the dependences of the location of dangerous sections in them and the value of σ_{equ} at different angles of the carbide plate installation were obtained. The tensions distribution graphs σ_{equ} (in values are presented strips) are shown in Figures 6-8. The analysis of the results of the surface zone study (Fig. 6) showed that the largest number of stress bands occurred in the plate with the installation angle of $\gamma = 15°$ and $\gamma = 30°$, i.e., the samples shown in Figure 4a and Figure 4b. The plates with attachment angles of $\gamma = -15°$ and $\gamma = -30°$ (Fig. 4d and Fig. 4e) show the same result, i.e., no load tensions strips. For the specimen with an insertion angle of $\gamma = 0°$ (Fig. 4c), the smallest number of tensions strips occurred at the end connection to the holder. An increase in the load at the end connection indicates dangerous sections and areas of possible insert cracking, which will lead to further loss of the integrity of the cutting tool. The study of the middle zone (Fig. 7) along the length of the hard metal insert showed the largest number of stress bands for the sample with an insertion angle of $\gamma = 0°$ in the front part of the insert and for the sample with an insertion angle of $\gamma = 15°$ at the point of attachment of the end part to the holder. Almost the same number of stress bands along the length of the middle zone was observed for the specimen with an insertion angle of $\gamma = 30°$, which may indicate a possible reason for the low durability of this type of cutting tool. Along the base of the carbide insert (Fig. 8), the highest tensions occur in the specimens with an installation angle of $\gamma = 30°$ and $\gamma = 15°$. The lowest tensions are observed in the method of installing carbide inserts with an angle of attachment to the holder of $\gamma = -30°$ and $\gamma = -15°$. Under the condition of direct attachment, i.e., the angle of installation is $\gamma = 0°$, almost the same level of load is observed along the measurement points, which poses a hidden threat of destruction of the soldering point of the insert to the holder.

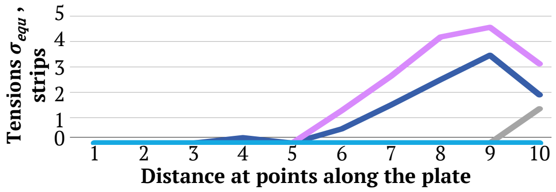


Figure 6. Stress distribution σ_{equ} along the front surface of a hard metal insert at different installation angles

Note: ■ – $\gamma = 30°$; ■ – $\gamma = 15°$; ■ – $\gamma = 0°$; ■ – $\gamma = -15°$; ■ – $\gamma = -30°$

Source: compiled by the authors

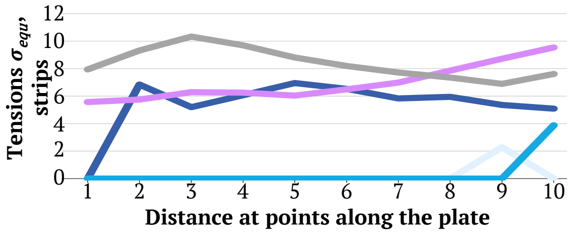


Figure 7. Stress distribution pattern σ_{equ} along the middle section of a hard metal insert at different installation angles

Note: ■ – $\gamma = 30°$; ■ – $\gamma = 15°$; ■ – $\gamma = 0°$; ■ – $\gamma = -15°$; ■ – $\gamma = -30°$

Source: compiled by the authors

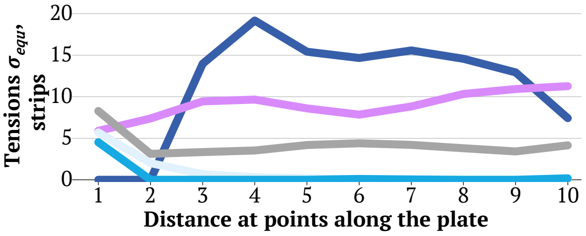


Figure 8. Stress distribution σ_{equ} along the base of the hard metal insert at different installation angles

Note: ■ – $\gamma = 30°$; ■ – $\gamma = 15°$; ■ – $\gamma = 0°$; ■ – $\gamma = -15°$; ■ – $\gamma = -30°$

Source: compiled by the authors

A significant amount of research into factors affecting the durability of cutting tools has focused on through-type turning tools. This is understandable, since this type of tool performs the main work in turning. The insufficiently studied factors affecting the durability of cut-off turning tools prompted the search for a scientific solution to the problem. According to M. Zheng *et al.* (2012) cut-off tools operate under very harsh conditions, and the main cause of failure is the breakage of their carbide inserts. In accordance with the findings of M. Zheng *et al.* the primary cause of failure in cut-off turning tools has been identified as carbide insert breakage. The proposed methods by A. Kurt *et al.* (2015) for studying the stress-strain state do not allow for a full assessment of all the factors involved, in particular the geometry of the cutter, on the destructive loads acting on it. The gap in these studies has been addressed by the current study, which emphasises the influence of geometric parameters – specifically, the installation angle of the carbide inserts – on stress distribution and overall tool durability Thus, studying the influence of geometric parameters on the stress state of carbide inserts of cut-off turning tools using the photoelasticity method makes it possible to optimise the design of tools, which will increase their strength and service life. While earlier studies by A. Pandey *et al.* (2024) focused on wear and temperature-induced failure, the current study provides a more precise understanding of the mechanical stress factors. The current study offers new insights into the relationship between tool geometry and stress concentration, which can help optimise tool design and extend service life.

Although the photoelasticity method is not as commonly used in modern analytical research due to the development of alternative techniques, it still offers significant advantages, as highlighted by Q. He *et al.* (2025). Specifically, this method is known for its high sensitivity, non-destructive nature, and ability to provide detailed insights into stress distribution. These advantages make the photoelasticity method particularly valuable for studying the stress-strain state of cutting tools under operational conditions. Geometric parameters of the tools themselves are among the critical factors affecting the reliability and durability of cutting tools. S. Shvets & V. Astakhov (2020) emphasised that the required geometry of the cutting system is achieved by adjusting the tilt of the carbide insert in both radial and axial directions. This observation aligns with the current study, which also investigates the impact of carbide insert installation angles on stress distribution and tool durability, further supporting the importance of geometric optimisation for enhancing tool performance. The durability of turning tools has a significant impact on machine tool productivity. According to research by S. Ghosh *et al.* (2018), cutting tool failure causes almost 20% of machine downtime. It is very important to know the remaining service life of the cutting tool in order to replace it in a timely manner that meets the goals of sustainable development - responsible use. However, it is difficult to predict the service life of a cutting tool because each cutting tool has different characteristics when cutting metal.

Cutting conditions such as feed rate, cutting speed, depth of cut, as well as workpiece material and tool material, have a significant impact on tool durability. These factors directly influence the wear rate and lifespan of the cutting tool, making it essential to optimise machining parameters to extend tool life. A.A. Yontar & Y. Kartal (2017) explored the effects of various cutting parameters on tool wear and machinability, emphasising the complexity of predicting tool lifespan due to the dynamic nature of these factors. Similarly, L. Bouzidab *et al.* (2018) highlighted the importance of optimising cutting conditions, particularly when finishing AISI 304 stainless steel, to minimise flank wear and maximise tool life. Both studies underscore the need for a comprehensive understanding of cutting parameters to improve tool performance and minimise downtime.

Tool geometry, such as positive/negative frontal angle or honed/beveled edge, also has a significant impact. A study of the causes of cutting tool failures by A. Rizzo *et al.* (2020) has shown that during the metal cutting process, cutting tools must withstand high heat, high pressure, abrasion, thermal and mechanical shocks. This finding aligns with the current study, which also underscores the critical role of cutting forces in determining the stress state within the carbide insert. Control and analysis of stress conditions are crucial for the reliability of elements. Ignoring stress concentrations can lead to structural failure, as demonstrated in the analysis of the silo tower collapse by Ye. Bakulin *et al*. (2022). Therefore, the data obtained in the current study on the distribution of stresses in a carbide plate allow reasonably selecting the optimal method of fastening it and prevent premature tool failure. The decisive parameter affecting the strength of a carbide turning tool insert is the cutting forces that arise during metal machining and, accordingly, cause a certain stress state in the insert body. Therefore, when designing a tool, it is very important to know the relationships between the parameters of the insert geometry in the tool coordinate system.

The influence of destructive factors was studied using a non-destructive photoelasticity method with a polarisation-projection device. Based on the obtained photos, isochromes and isoclines were used to determine the maximum permissible stresses in a carbide plate depending on its geometric shape and the angle of installation in the holder. The most acceptable from the point of view of the minimum tensions can be considered samples with carbide insertion angles of $\gamma = -15°$ and $\gamma = -30°$. This installation method will ensure the highest durability of the carbide insert and the cutting tool as a whole. The intermediate position is occupied by a sample with a mounting angle of $\gamma = 0°$, but the significant load on the front of the insert in the middle zone and the connecting end part can cause cracks and contribute to further destruction of the tool integrity. Regardless of the angle of insert insertion, the maximum loads occur in the cutting zone, which may be a determinant of tool life and requires further research.

The durability of cutting tools is influenced by a complex interplay of factors, including cutting conditions, tool geometry, and material properties. Research has shown that factors such as feed rate, cutting speed, and depth of cut, along with tool and workpiece materials, significantly affect tool wear and lifespan. Additionally, the geometry of the tool, such as insert angles and edge design, plays a crucial role in determining stress distribution and tool performance. Cutting tools, particularly those with carbide inserts, must withstand high heat, pressure, and mechanical stresses, making it essential to understand the relationship between cutting forces and tool geometry. As demonstrated in the current study, optimising these parameters is key to improving tool durability and minimising failures. These insights pave the way for further advancements in tool design, with a focus on optimising geometry and cutting conditions to enhance tool life and operational efficiency. The findings underscore the importance of comprehensive approaches to tool design and machining process optimisation for the future of sustainable and efficient manufacturing.

CONCLUSIONS

Hidden fracture of the inner part of carbide inserts is difficult to detect visually, compared to the possible appearance of cracks on their surface. This study provided a clear understanding of the distribution of loads along the carbide insert along its width. In an applied sense, it is important to know the geometric features of the cutting tools to establish the required angles of attachment of carbide inserts to the holder, depending on the specified production conditions. This will increase the service life of the cutting tools and the productivity of metal cutting operations.

According to the results of the studies, it was found that the angle of attachment of the carbide insert to the toolholder significantly affects the stress distribution in it during tool operation. It is the current level of stress in the defined zone of the carbide insert that determines its resistance to cracking and subsequent fracture. In terms of insert strength, the most optimal setting angle is $\gamma = -30°$, since the minimum value of dangerous stresses σ_{equ} is observed along the measurement points in all three zones along the width of the insert.

The results have shown that the most dangerous option for installing a carbide insert in a holder is an angle of $\gamma = 30°$. The maximum stresses occur in all studied zones along the width of the insert along the measurement points, compared to the attachment angles of 15°, 0°, -15°, and -30°. The sample with an attachment angle of $\gamma = 30°$ can be considered to have the best surface finish quality indicators. However, even minor deviations from the machining process technology cause significant wear and frequent tool breakage. Further research should focus on a deeper investigation of the impact of various geometric parameters of carbide inserts on their stress resistance under different machining conditions.

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CONFLICT OF INTEREST

None.

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Дослідження напруженого стану твердосплавної пластини відрізного різця

Анотація. Різальні інструменти з твердосплавними пластинами працюють у жорстких умовах, які можуть спричинити розтріскування та руйнування, оскільки їхня міцність безпосередньо залежить від напружено-деформованого стану. Дослідження було проведено з метою визначення впливу кута встановлення в державку напаяних твердосплавних пластин відрізних різців на їх напружений стан. Експериментальні дослідження за методом фотопружності відзначаються високою чутливістю, неруйнівним впливом, наочністю, швидкістю отримання результатів. Виконували дослідження на поляризаційно-проекційній установці ППУ-7 з використанням фізичних моделей твердосплавних пластин з оптично-чутливого матеріалу ЕД-6, які приєднувались у державку з різними кутами встановлення. Отримані фотокартки ізохром та ізоклин дозволили оцінити реальну візуальну картинку діючих напружень. Під час експерименту моделі відрізних різців навантажувалися за допомогою спеціально розробленого стенду, що моделював силу різання. Розрахунок головних напружень виконувався методом різниці дотичних напружень для обраних кутів встановлення пластин. Доведено, що кут приєднання твердосплавної пластини до державка безперечно впливає на розподіл в ній напружень під час металообробки. Встановлено кількісний зв'язок між величиною кута приєднання до державки та величиною діючих внутрішніх напружень у твердосплавної пластинки. Найбільші напруження σ_{equ} діють в перерізі ріжучого леза твердосплавної пластини незалежно від кута приєднання до державка. Встановлено найменший рівень діючих напружень вздовж точок вимірювання у трьох зонах за шириною твердосплавної пластини при приєднані до державка під кутом -30°. За умови кутів приєднання 15°, 0° та -15° виникають критичні напруження у всіх досліджених зонах за шириною пластини вздовж точок вимірювання

Ключові слова: ізоклин; ізохром; анізотропія; фотопружність; кут встановлення