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PROBABILISTIC APPROACH TO CALCULATING THE RATIONAL THICKNESS OF THE TOOL'S CUTTING INSERT FOR HEAVY MACHINE TOOLS

Galyna Klymenko [\[0000-0002-1022-6324\]](#), Viktor Kovalov [\[0000-0001-5091-5856\]](#), Yana Vasylichenko [\[0000-0002-4566-8827\]](#), Dmytro Korchma [\[0009-0000-1875-6285\]](#), Roman Boroday [\[0009-0009-6730-9540\]](#)

Donbass State Engineering Academy (DSEA), bul. Mashinostroiteley, 39,
Kramatorsk, Ukraine
vasilchenko.ua@gmail.com

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Abstract. *The paper proves that the development of regulations for the operation of cutting tools on heavy machine tools, the formation of objective functions for optimising the parameters of machining parts should be carried out based on a given level of reliability of the cutting tool. In this case, a large number of indicators are used to determine the tool's reliability, durability and maintainability separately. Based on statistical and theoretical studies of the probabilistic nature of the properties of the cutting tool and the parameter of load distribution on it, quantitative dependencies between the parameters of the scattering of properties and the thickness of the tool plate of a prefabricated tool were obtained. The stochastic nature of the machining process on heavy machine tools causes a large dispersion of the properties of the machined and tool materials and other machining parameters. This leads to the need for a probabilistic approach to determining the design and technological parameters of the cutting tool. The reliability of a prefabricated cutter depends on both its load and the bearing capacity of the tool structure, which is the ultimate stress that characterises the strength of the structure. Using a probabilistic approach to calculating the thickness of the cutting plate of the cutters, a correction factor for the thickness was determined taking into account the level of reliability of the tool. The level of reliability was understood as the probability that the maximum stress arising under the action of the load will not exceed the bearing capacity. Typical structures that are most commonly used at modern heavy engineering enterprises were investigated. The law of distribution of cutting forces was determined on the basis of statistical data on the operation of carbide cutters. The thickness of the cutting element was calculated for the Rayleigh load distribution law, determined on the basis of statistical data on cutting forces during turning for different cutter designs. The distribution of the bearing capacity of the tool material of the tool inserts was determined on the basis of laboratory tests.*

Keywords: *cutting tool; reliability; failure probability; load-bearing capacity; cutting insert; cutting force.*

1. INTRODUCTION

Increasing the level of automation of existing metal-cutting equipment requires special attention to the stability of workpiece processing and the reduction of machine downtime, including that caused by cutting tool failures. This is especially important for heavy-duty CNC machines, the cost of which is very high

[1–2]. Therefore, the problem of increasing the reliability of cutting tools for heavy machine tools has become particularly relevant [3]. The process of cutting tool

operation is a complex technological system, and a number of indicators are used to assess its reliability [4–6]. The cutting tool is an integral part (the most vulnerable element) of the technological system of machining. The level of reliability of the technological system of turning cutters for heavy machine tools and its maintenance process is determined to a greater or lesser extent by all indicators of the reliability of the tool operation process.

Assessing the reliability of prefabricated turning cutters for heavy machine tools is essential not only at the stage of their operation but also at the stage of their design [7]. The development of regulations for the operation of cutting tools on heavy machine tools, the formation of objective functions for optimising the parameters of machining parts should be carried out based on a given level of reliability of the cutting tool. In this case, a large number of indicators are used to determine the reliability, durability and maintainability of the tool separately. The distribution of the tool life characterises the reliability of the cutting blade and does not allow solving the problem of ensuring reliable operation of the tool, including other structural elements of the prefabricated cutter. The availability factor can serve as a comprehensive indicator of the reliability of a prefabricated tool as a system [4].

The reliability of a prefabricated cutter depends on both its load and the bearing capacity of the tool structure, which is the ultimate stress that characterises the strength of the structure. If the reliability of a prefabricated tool is less than its rational level, it is necessary to change its structural elements, for example, the thickness of the cutting insert, which mainly determines the strength of the tool [8–10]. A design calculation method is often used, according to which the required reliability is incorporated into the designed structure in advance.

2. APPLIED METHODS

Testing of cutting tools in both laboratory and production environments demonstrates the stochastic nature of the cutting forces that occur during workpiece processing, as well as the random variation of the cutting tool properties themselves. To take into account the probabilistic nature of tool operation, information on the distribution laws of both tool loads and tool bearing capacity is required.

For elastic systems, within which a prefabricated cutter is considered, the dependence of the maximum stresses S on the load q in general form is

$$S = K_C q,$$

where K_C – is a coefficient that depends on the dimensions of the tool's cross-sections.

The level of reliability is defined as the probability that the maximum stress arising from the load will not exceed the bearing capacity:

$$H = P(R > S),$$

where H – reliability level, P - event probability, R - load-bearing capacity, S - effective maximum voltage.

If the law of distribution of cutting forces is known, then using the rules for finding the law of distribution of functions of a random argument, it is possible to find the law of distribution of maximum stresses acting in the cutter structure

$$f_1(S). f_1(S) = \frac{1}{K} f_3\left(\frac{S}{K}\right)$$

The law of distribution of cutting forces is determined on the basis of statistical data on the operation of carbide cutters (Fig. 1), which does not negate Rayleigh's law.

The reliability or probability of failure-free operation can be determined:

$$H = \int_{-\infty}^{\infty} f_2(R) \left[\int_{-\infty}^{\infty} f_1(S) dS \right] dR \tag{1}$$

or

$$H = \int_{-\infty}^{\infty} f_1(S) \left[\int_S^{\infty} f_2(R) dR \right] dS \tag{2}$$

Substituting the known $f_1(S)$ and $f_2(R)$ in (1) or (2), integrating with the given level of reliability H_{giv} , we obtain the expression for determining the K_C :

$$K_C = \varphi(a_1, a_2, \dots, a_n, H_{giv}),$$

where a_1, a_2, \dots, a_n – parameters of the load distribution laws and load-bearing capacity are known in advance. Knowing the K_C , it is possible to find the cross-sectional dimensions of a toolholder or cutting insert.

When turning parts, a large number of random factors are observed to act on them, subject to different distribution laws. It was found that the load is distributed according to Rayleigh's law

$$f_3(q) = \frac{q}{a^2} e^{\left[-\frac{q^2}{2a^2} \right]}, \tag{3}$$

where a, q are the parameters of the Rayleigh distribution law, and the carrying capacity according to the normal law

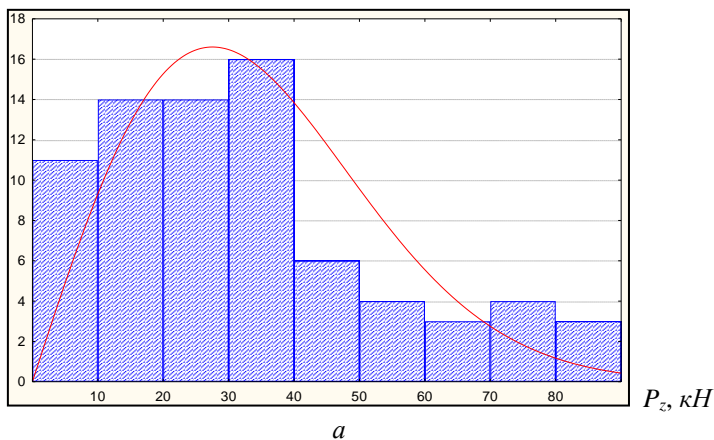
$$f(R) = \frac{1}{\sqrt{2\pi} \sigma_R} e^{-\left[\frac{(R-m_R)^2}{2\sigma_R^2}\right]}, \quad (4)$$

where m_R, σ_R – parameters of the law of normal distribution,

In accordance with (3) and (4), the level of reliability of the structure is determined:

$$H = \int_{-\infty}^{\infty} f_3(q) \left[\int_{-\infty}^R f_1(s) ds \right] dR = \int_{-\infty}^{\infty} f_2(R) F_1(R) dR. \quad (5)$$

N , шт.



N , шт.

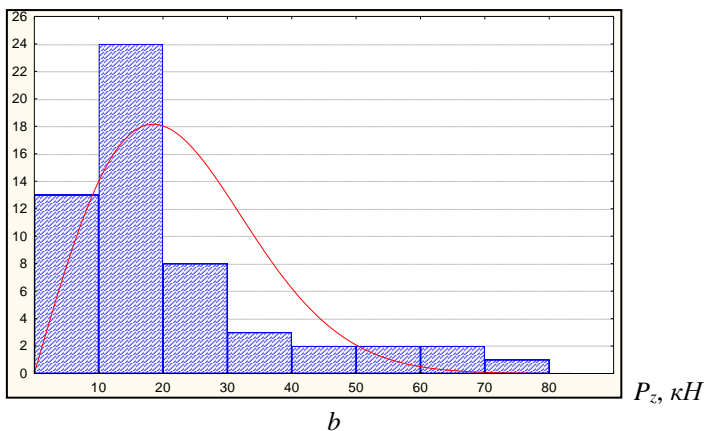


Figure 1 Distribution of the cutting force component P_z during turning on heavy-duty lathes: a - with $D_{max} = 2500$ mm, b - with $D_{max} = 1250$ mm.

$$f(R) = \frac{1}{\sqrt{2\pi} \sigma_R} e^{-\left[\frac{(R-m_R)^2}{2\sigma_R^2} \right]}, \quad (6)$$

where m_R, σ_R – parameters of the normal distribution law,

In accordance with (1) and (2), the level of reliability of the structure is determined:

$$H = \int_{-\infty}^{\infty} f_3(q) \left[\int_{-\infty}^R f_1(S) dS \right] dR = \int_{-\infty}^{\infty} f_2(R) F_1(R) dR. \quad (7)$$

Substituting (5) and (6) into (7), we obtain :

$$H = 1 - \frac{1}{\sqrt{1 + \frac{\pi\sigma_R^2}{2K^2m_q^2}}} e^{-\left(\frac{\frac{1}{\frac{4K^2m_q^2}{\pi m_R^2} + \frac{\sigma_R}{m_R}}}{\frac{\pi m_R^2}{m_R}} \right)}. \quad (8)$$

After transformations, this expression becomes the following:

$$(1-H)^2 \left(1 + \frac{\pi m_R^2 \left(\frac{\sigma_R}{m_R} \right)^2}{2K^2 m_q^2} \right) = e^{-\left(\frac{\frac{1}{\frac{4K^2m_q^2}{\pi m_R^2} + \frac{\sigma_R}{m_R}}}{\frac{\pi m_R^2}{m_R}} \right)}. \quad (9)$$

With a small variability of σ_R/m_R , we obtain the approximate dependence for determining K_h

$$K_h = \frac{m_R}{2m_q} \sqrt{-\frac{\pi}{\ln(1-H)}}. \quad (10)$$

To determine the thickness of the plate for the average values of the parameters (reliability level 0.5), three-dimensional models of turning cutters were developed in SolidWorks. We studied the typical schemes of plate fastening, which are most often used at modern machine-building enterprises (Fig. 2).

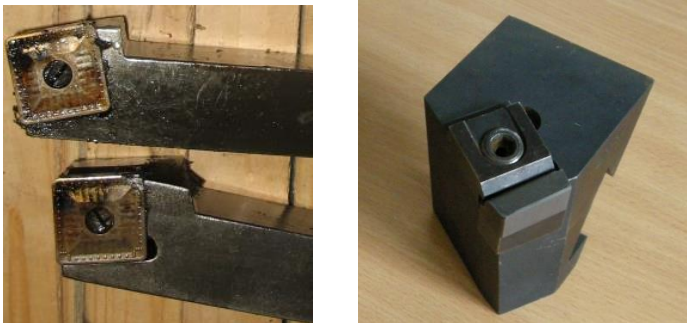


Figure 2 Designs of turning cutters for turning parts on heavy machine tools

The insert thicknesses for the carbide cutters for a reliability level of 0.5 were calculated using the finite element method with the ANSYS software package. The cutting forces were taken from a range of the most frequent ones encountered when machining parts on heavy-duty lathes.

3. RESULTS AND DISCUSSION

Examples of the stresses that arise for calculating the geometric parameters of the cutting element of a turning cutter at the design stage for given loading conditions are shown in Figs. 3, 4.

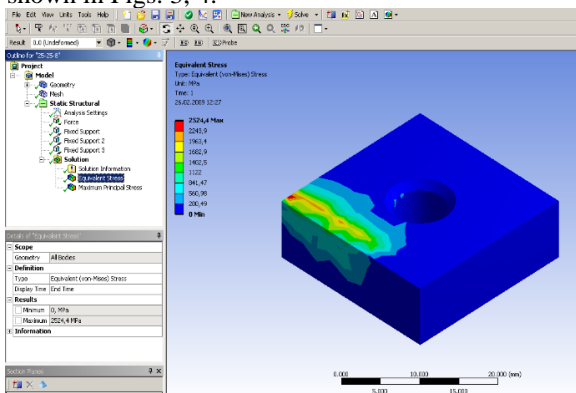


Figure 3 Distribution of equivalent stresses occurring in a square-shaped cutting insert

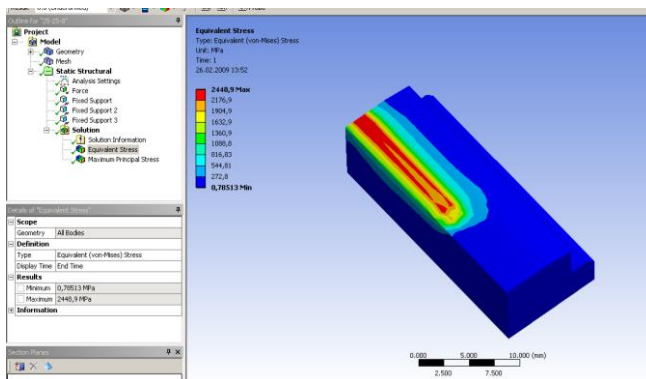


Figure 3 Distribution of the equivalent stresses that occur in the insert

For the Rayleigh load distribution law, we calculated the thickness of the cutting insert (Fig. 4) under different types of stresses arising during preliminary turning of parts on heavy machine tools.

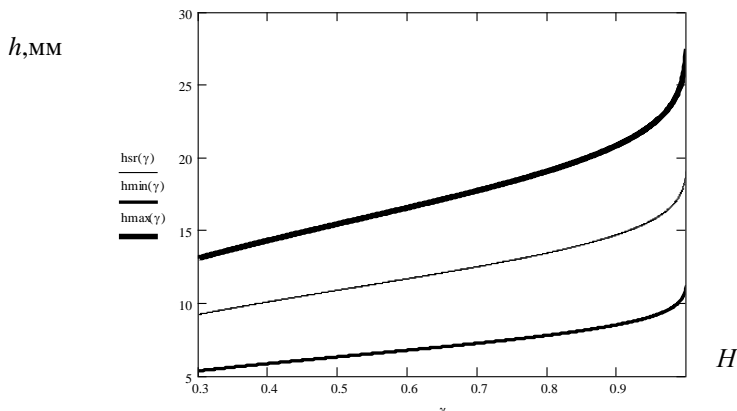


Figure 4. Dependence of the cutting element thickness on the reliability level H

The probabilistic approach to calculating the thickness of a prefabricated cutter insert made it possible to determine correction factors for the thickness of the insert depending on the level of reliability, which take into account the distribution parameters of both the properties of the cutting tool and its load.

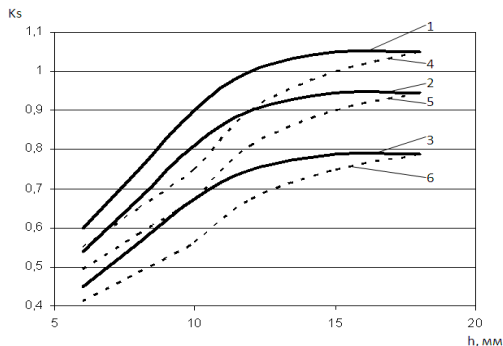


Figure 5 Fragment of a map for selecting a feed correction factor depending on the thickness of the insert l - height of the toolholder $H = 40$ mm, reliability level 0.65; 2 - height of the toolholder $H = 40$ mm, reliability level 0.8; 3 - height of the toolholder $H = 40$ mm, reliability level 0.9; 4 - height of the toolholder $H = 63$ mm, reliability level 0.65; 5 - height of the toolholder $H = 63$ mm, reliability level 0.8; 6 - height of the toolholder $H = 63$ mm, reliability level 0.9

Software and comprehensive standardisation maps for heavy machine tools were developed and implemented to select tool operation regulations based on the level of reliability of the operation process, which for the first time take into account the design of the machine and tool, the level of tool reliability and tool consumption.

4. CONCLUSIONS

For the first time, on the basis of statistical and theoretical studies of the probabilistic nature of the properties of a cutting tool and the parameter of load distribution on it, quantitative dependencies between the parameters of scattering properties and the thickness of the cutting plate of a prefabricated cutter were obtained. It is proved that ensuring the reliability of a cutting insert of the level 0.8 requires an increase in its thickness by 30% compared to the calculated values for the average load.

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Галина Клименко, Віктор Ковальов, Яна Васильченко, Дмитро Корчма,
Роман Бородай, Краматорськ, Україна

ІМОВІРНІСНИЙ ПІДХІД ДО РОЗРАХУНКУ РАЦІОНАЛЬНОЇ ТОВЩИНИ РІЗУЧОЇ ПЛАСТИНИ ІНСТРУМЕНТУ ДЛЯ ВАЖКИХ ВЕРСТАТІВ

Анотація. У статті доведено, що розробка регламентів експлуатації різальних інструментів на важких верстатах, формування цільових функцій оптимізації параметрів обробки деталей повинні здійснюватися виходячи із заданого рівня надійності різального інструменту. При цьому використовується велика кількість показників, що визначають окремо безвідмовність, довговічність та ремонтпридатність інструменту. На основі статистичних і теоретичних досліджень імовірного характеру властивостей різального інструменту і параметра розподілу навантаження на нього отримані кількісні залежності між параметрами розсіювання властивостей і товщиною інструментальної пластини збірного інструменту. Стохастичний характер процесу обробки на важких верстатах зумовлює великий розкид властивостей оброблюваних і інструментальних матеріалів та інших параметрів обробки. Це призводить до необхідності імовірного підходу до визначення конструктивно-технологічних параметрів різального інструменту. Надійність роботи збірного різця залежить як від його навантаження, так і від несучої здатності конструкції інструменту, яка є граничним напруженням, що характеризує міцність конструкції. Використовуючи імовірнісний підхід до розрахунку товщини різучої пластини різця, було визначено поправочний коефіцієнт на товщину з урахуванням рівня надійності інструменту. Під рівнем надійності розуміли імовірність того, що максимальне напруження, яке виникає під дією навантаження, не перевищить тримальної здатності. Досліджувалися типові конструкції, які найчастіше використовуються на сучасних підприємствах важкого машинобудування. Закон розподілу сил різання визначався на основі статистичних даних про роботу твердосплавних різців. Товщина різучого елемента розраховувалася для релейського закону розподілу навантаження, визначеного на основі статистичних даних про сили різання при токарній обробці для різних конструкцій різців. Розподіл тримальної здатності інструментального матеріалу пластин визначено на основі лабораторних випробувань.

Ключові слова: різальний інструмент; надійність; імовірність відмови; тримальна здатність; різальна пластинка; сила різання.