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COMPUTATIONAL AND ANALYTICAL MODELS OF THE MAJOR TYPES OF CUTTING TOOL FAILURE

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Abstract. *The paper presents analytical and numerical models for assessing the reliability of cutting tools used in the processing of critical parts for the defence and energy industries. The criteria of boundary wear on the back and front surfaces, possible fatigue failure and plastic deformation of the cutting edge are taken into account. Analytical dependencies have been constructed to calculate the number of parts that can be machined before tool failure, taking into account the physical and mechanical characteristics of the tool and processed materials, technological modes and thermal loading conditions. The results allow for the selection of tools and cutting parameters based on increased reliability and process optimisation. These mathematical dependencies make it possible to take into account the predominant type of cutting tool wear, which is especially important when working with large parts on heavy machine tools. The results of the study are of practical importance for industry, as they allow to increase the stability and productivity of technological processes.*

Keywords: *reliability; tool wear; fatigue; heavy engineering; cutting; adhesive wear; thermomechanical load; plastic deformation; cutting edge.*

1. Introduction

In heavy engineering, machining parts intended for use under high loads and temperatures, particularly in the defence and energy sectors, requires high precision and stability of the cutting tool. Tool reliability is one of the key parameters that determines the quality and efficiency of the technological process. The relevance of the topic is driven by the need to predict and extend the life of cutting tools by mathematically modelling the processes of wear and fracture. The aim of the study is to create reliable calculation models that allow determining the maximum number of parts that can be machined before tool failure.

2. Problem statement

The task is to build mathematical models for assessing the reliability of a cutting tool according to the criteria of limit wear, fatigue failure and plastic deformation. The input parameters are the physical and mechanical properties of the tool and processed materials, cutting modes (speed, depth, feed), and temperature conditions in the contact zone. The output parameter is the number of parts that can be machined without losing tool life. It is necessary to take into account various wear mechanisms, as well as random fluctuations in parameters that affect the accuracy of the forecast.

3. Literature review

The study of the problem of cutting tool reliability has become widespread in the scientific literature. A considerable number of papers [1–5] are devoted to the analysis of back surface wear as the main failure mechanism. Studies [6–8] examine the processes of adhesive and abrasive wear, as well as the influence of tool microgeometry. Some works [9–11] focus on thermomechanical loading in the cutting zone and modelling of temperature fields. However, insufficient attention is paid to a comprehensive assessment taking into account fatigue fracture and plastic deformation, which significantly affects reliability in heavy cutting conditions. This study aims to extend the existing models by using computational and analytical approaches and experimental observations.

4. Materials and Methods

The calculations are based on mathematical models that take into account adhesive wear on the back and front surfaces, fatigue, and plastic buckling. The modelling takes into account steels 40KhNMA (AISI 4340), X18H9T (AISI 321) and tool materials T14K8 (HS410), P6M5 (AISI M2). The dependences of contact pressures, cutting temperature, and wear parameters obtained by statistical processing of experimental data were used. The number of machined parts before failure was estimated based on the criteria of ultimate wear of the height, depth of the hole, ultimate plastic deformation, and fatigue failure.

The number of parts that can be machined before the maximum allowable height of the wear area on the rear surface is formed

$$N_{0.1} = \begin{cases} [h_{3n}] \cdot \sqrt{\dfrac{3{,}75 \cdot tg\alpha \cdot (1-\mu) \cdot (\sigma_s^2 + \sigma_{su}^2)}{q_{max} \cdot v \cdot \tau \cdot \delta \cdot \sigma_s}}, \text{ if } \dfrac{q_{max}}{7{,}5 \cdot \sigma_s \cdot (1-\mu)} < 1 \\ [h_{3n}] \cdot \sqrt{\dfrac{tg\alpha \cdot (\sigma_s^2 + \sigma_{su}^2)}{2v \cdot \tau \cdot \delta \cdot \sigma_s^2}}, \text{ if } \dfrac{q_{max}}{7{,}5 \cdot \sigma_s \cdot (1-\mu)} \geq 1 \end{cases}$$

where h – height of the wear area corresponding to the moment of time τ;

γ, α, ϕ – front angle, back angle and main angle in the tool plan respectively;

t – cutting depth;

q – limiting pressure necessary for complete buckling of surface microroughnesses of the machined material at the contact area;

δ - thickness of the layer from which adhesive bond breakage products are taken out;

σ_s, σ_{su}– yield strengths of the machined material and tool material at average temperature at the contact area respectively;

μ - friction constant.

To assess the durability of a cutting tool according to the criterion of maximum permissible wear on the front surface, the number of parts that can be machined until the criterion of maximum permissible adhesive wear on the front surface is calculated.

$$N_{0.2} = \begin{cases} \dfrac{[Q] \cdot (\sigma_s^2 + \sigma_{su}^2) \cdot \xi \cdot 7{,}5 \cdot sin\varphi \cdot (1-\mu)}{\sigma_s \cdot v \cdot \delta \cdot q_{max} \cdot t \cdot \tau}, \text{ if } \dfrac{q_{max}}{7{,}5 \cdot \sigma_s \cdot (1-\mu)} < 1 \\ \dfrac{[Q] \cdot (\sigma_s^2 + \sigma_{su}^2) \cdot \xi \cdot sin\varphi}{\sigma_s^2 \cdot v \cdot \delta \cdot t \cdot \tau}, \text{ if } \dfrac{q_{max}}{7{,}5 \cdot \sigma_s (1-\mu)} \geq 1 \end{cases}$$

ξ - chip shrinkage factor;

The average number of parts that can be machined before fatigue failure of the cutting insert is determined by the expression:

$$N_{0.3} = \frac{N_b}{f\tau}\left(\frac{\sigma_0}{\sigma_{max}}\right)^m,$$

σ_0 – endurance limit of the tool material under asymmetric loading cycle;

f – frequency of cutting force oscillations;

N_b – baseline number of loading cycles of the material used to determine the value of σ_0; $N_b = 10^6$ – loading cycles;

τ – processing time of a single workpiece;

m – constant characteristic of the tool material.

Estimation of the average number of parts $N_{O.4}$. whose machining is possible before reaching the criterion of maximum permissible plastic buckling of the cutting edge is carried out according to the formula:

$$N_{0.4} = \frac{[e]}{\left\{\tau \dot{e}_0 e_0 sh\left[\dfrac{\sigma_{equ}}{\sigma_T \cdot 1{,}1}\left(\dfrac{\theta}{\theta_p}\right)^s\right]\right\}^{0{,}5}}$$

5. Experiments

A series of computational experiments were carried out using the models described in the previous section for various combinations of tool and material to be machined. Feed rate, cutting speed and depth of cut were selected as variable parameters. The results were verified by comparing them with the data of physical experiments reported in [13].

6. Results

The dependences between the cutting speed and the number of machined parts before the tool failure were obtained. Graphs of tool life were constructed according to various criteria: wear on the back surface (Fig. 1), front surface (Fig. 2), fatigue fracture (Fig. 3), and plastic fracture (Fig. 4). For the P6M5 (AISI M2) tool, when machining steel 40, it was found that the critical wear is on the back surface at speeds above 150 m/min, while plastic deformation dominates at high feeds.

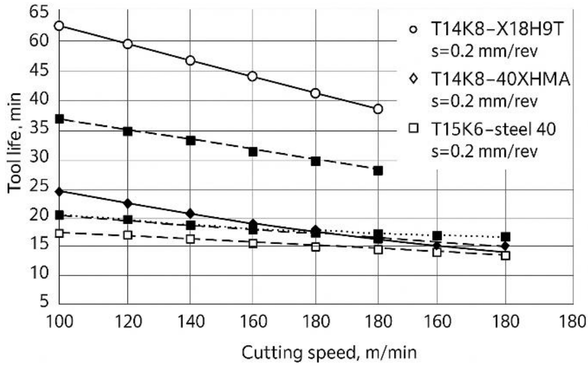

Figure 1 - Resistance of cutting tools according to the criterion of maximum permissible wear on the rear surface

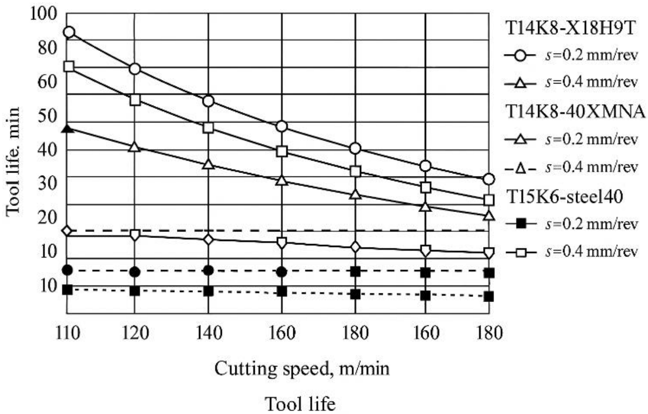

Figure 2 - Cost of cutting tools according to the criterion of maximum permissible wear on the front surface

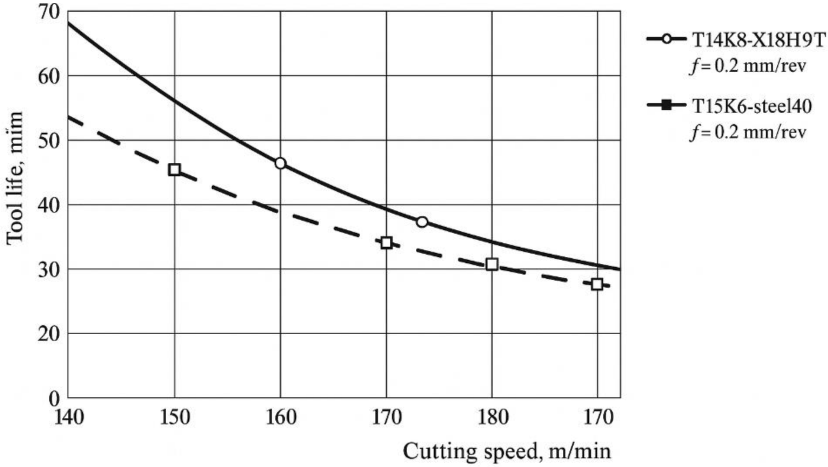

Figure 3 - Resistance of cutting tools by fatigue failure criterion

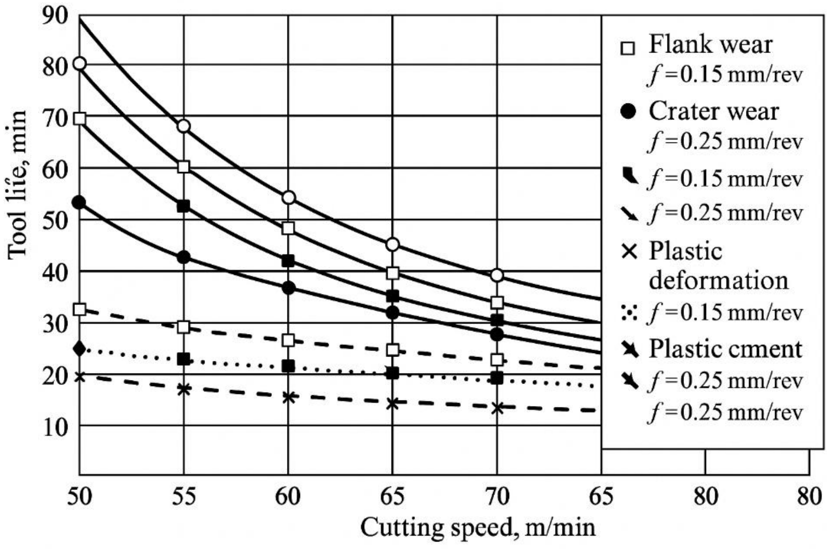

Figure 4 - Resistance of cutting tools according to the criteria of maximum permissible wear on the rear surface, front surface, maximum permissible plastic buckling of the cutting edge. Tool material P6M5 (AISI M2). Material to be machined is steel 40 (AISI 1040)

7. Discussion

The results confirm the relevance of the used models for predicting tool reliability under heavy cutting conditions. The most consistent results were obtained for the wear criteria. A nonlinear relationship between machining parameters and resistance is observed. It is important to note that fatigue failure models are more sensitive to fluctuations in input parameters. In the future, it is advisable to take into account the effects of thermal diffusion and structural changes in the tool's near-surface layer.

8. Conclusions

1. A set of mathematical models for assessing the reliability of a cutting tool according to the four main criteria of wear and fracture has been developed.
2. The dependence of the number of machined parts on the physical and mechanical parameters of the tool-workpiece system was determined.
3. The P6M5 (AISI M2) tool showed the lowest stability when machining steel 40 at high feeds, which is due to plastic edge distortion.
4. The application of the proposed models makes it possible to justify the choice of cutting modes to increase tool life.
5. In the future, it is necessary to take into account stochastic fluctuations in external factors to improve the accuracy of forecasts.

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РОЗРАХУНКОВО-АНАЛІТИЧНІ МОДЕЛІ ВИНИКНЕННЯ ПЕРЕВАЖНИХ ВИДІВ ВІДМОВ РІЗАЛЬНОГО ІНСТРУМЕНТУ

Анотація *У статті представлено комплексні розрахунково-аналітичні моделі оцінки надійності різального інструменту, що застосовується під час обробки відповідальних і великогабаритних деталей, характерних для важкого машинобудування при виробництві приладів оборонного та енергетичного призначення. В умовах сучасних викликів, пов'язаних із посиленням вимог до точності, стабільності та довговічності обробки, розроблена методика дозволяє об'єктивно враховувати складні фізико-механічні та експлуатаційні фактори, що впливають на працездатність різального інструменту. Моделі охоплюють механізми зносу задньої та передньої поверхонь, накопичення втомних пошкоджень, мікротріщиноутворення, а також пластичне деформування різальної крайки в умовах термомеханічного навантаження. Кількісна оцінка ресурсу проводиться на основі аналітичних залежностей, які дозволяють прогнозувати кількість оброблюваних деталей до критичного стану інструменту за кожним із критеріїв відмови. Введено показники ймовірності відмови з урахуванням типового механізму зносу, що дозволяє приймати зважені рішення щодо планування інтервалів обслуговування й заміни. Значну увагу приділено варіативності умов обробки, флуктуаціям навантаження та впливу температурного поля, що суттєво підвищує точність оцінки надійності в реальних умовах експлуатації. Практичне значення дослідження проявляється в підвищенні загальної технологічної надійності процесів, скороченні простоїв обладнання, зниженні витрат на нераціональне використання інструменту та підвищенні продуктивності виробництва. Запропонований підхід може ефективно використовуватися інженерами-технологами, конструкторами, спеціалістами з технічного обслуговування та діагностики в галузі важкого машинобудування, зокрема для підприємств, що працюють на замовлення оборонного комплексу або енергетики.*

Ключові слова*: надійність; знос інструменту; втома; важке машинобудування; обробка різанням; адгезійний знос; термомеханічне навантаження; пластична деформація; різальна крайка.*