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Investigation of the Design of a Busbar Punching Tool Restored by Replacement of the Working Part with a Carbon Steel Insert

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Abstract. The aim of this study is to conduct a comprehensive comparative analysis of the stress-strain state of a restored busbar punching tool in order to improve its durability and performance. An overview of existing industrial methods for restoring punches and dies was carried out, including surfacing, welding, hard-facing, and thermal treatment approaches. The analysis showed that although these methods are widely used, each of them has inherent advantages and limitations related to cost, technological complexity, and the resulting service life of the tool. To overcome these challenges, a novel restoration technique is proposed, which involves replacing the worn working part of the busbar punching tool with a carbon steel insert. Numerical modeling of the stress-strain state of the restored tool was performed using the ANSYS software suite. The finite element simulations allowed for a detailed investigation of stress distribution, deformation patterns, and contact force distribution in the critical working zones of the tool under operational loads. The obtained results made it possible to identify the most heavily loaded regions of the structure, to compare them with the original tool design, and to assess the effectiveness of the proposed restoration method. The study demonstrated that the use of a carbon steel insert not only reduces localized stress concentrations but also contributes to extending the operational reliability and service life of the busbar punching tool. The findings of this research provide a practical contribution to the modernization and repair of punching tools, offering an economically viable and technically effective alternative to full tool replacement.

Keywords: busbar punching tool, mold, restoration, wear resistance, stress-strain state.

Introduction

In modern mechanical engineering, up to 70–80% of parts are manufactured using cutting operations, which ensures high productivity at relatively low production costs. In the design of technological processes and die tooling, the durability of the working tool becomes particularly important, especially in the case of busbar punching tools that are subjected to high contact loads and impact forces [1].

The main factors limiting the service life of cutting dies include abrasive and adhesive wear, chipping of cutting edges, tempering of the surface layer, and local thermal damage. These types of wear directly affect the accuracy, quality, and dimensional stability of the manufactured parts. Wear of the working elements can increase the labor intensity of the cutting process by up to 40% and the cutting resistance by up to 20%, compared to tools with sharp edges. In addition to improving the wear resistance of new tools, an important direction is the restoration of worn working elements, including busbar punching tools. These measures help extend the service life of expensive tooling, reduce the cost of purchasing new equipment, and minimize production downtime.

Research aimed at determining the applicability of punching operations, the extent and nature of wear, and tool consumption was carried out at several industrial enterprises in Kazakhstan. In particular, practical analysis and data collection were conducted at the following production facilities: Karaganda Zharyk LLP, Astana Electromechanical Plant LLP, Almaty Electromechanical Plant LLP, Asia Trafo LLP, and Kentau Transformer Plant JSC [1, 2].

The results of the research conducted under industrial conditions confirm the high degree of wear experienced by busbar punching tools during operation. It was found that the punches and dies comprising these tools are subject to intensive abrasive wear, edge chipping, and fragmentation of the working surfaces. Due to the nature of their operation, punching tools are classified as heavily loaded, since they come into direct contact with the pressed metal under conditions of high temperature, significant specific pressure, and intense friction. One of the most critical factors contributing to reduced tool life is overheating, which leads to a decrease in the strength properties of the tool material. This results in reduced hardness, plastic deformation, and in some cases, failure of the working elements. Exceeding the tempering temperature of the die material during pressing is especially critical, as it can cause deformation, loss of shape, and tool failure.

Operating conditions are also characterized by sudden dynamic loads caused by uneven distribution of pressing forces. These impact loads require a combination of high hardness and sufficient impact toughness in the tool, which is difficult to achieve with conventional tool steels and alloys. In most cases, the contradiction between hardness and toughness becomes the decisive factor in tool failure under sudden load changes. Moreover, uncontrolled release of pressure at the end of the operation can lead to microcracks and subsequent tool breakage.

Figure 1 shows photographs of broken or worn-out busbar punching tools.

a) b) c)

Fig. 1. - Broken or worn-out busbar punching tools

Given the high wear rate, busbar punching tools are most often designed as replaceable components. This design choice necessitates their regular replacement or restoration. In this regard, the task of improving the design and manufacturing technologies of such tools becomes highly relevant, aiming to enhance their operational durability, reduce maintenance and replacement costs, and increase the overall efficiency of pressing operations. Key directions in ensuring the reliability and longevity of busbar punching tools include the development of new design solutions, the application of modern wear-resistant materials and coatings, and the optimization of equipment operating modes.

Thus, the comprehensive development of methods for enhancing the wear resistance and restoration of stamping tools is a crucial step toward improving the reliability of technological tooling, increasing product quality, and reducing production costs. The conducted studies have shown that various methods and approaches are used to restore tools and technological equipment. One of the most effective restoration approaches is surfacing the working surface with wear-resistant material.

Work [3] describes the plasma surfacing method as an effective means of restoring and improving the wear resistance of stamping tool surfaces that frequently fail. The process uses a high-temperature plasma jet (up to 15,000°C, formed using argon and helium) to melt the filler material and apply it to the surface of the part. Special attention is given to the selection of material, application technology, and optimization of surfacing parameters (current strength, torch distance, powder feed rate) to ensure high-quality coating. Recommended parameters include a current of 55–60 A, a distance of 10–12 mm, 3–4 passes with intermediate cooling, and the necessity of powder drying and sieving. The main drawback of the method is its high sensitivity to process parameters and the need for careful preparation of powder materials, as failure to comply with the technology may result in coating defects and damage to the part.

The study in work [4] focuses on restoration methods for bending dies that wear out during the production of parts such as brackets. Based on analysis of material properties and wear characteristics, the authors proposed and tested three methods: brazing of hard alloy plates, surfacing with welding electrodes, and laser surfacing with powder materials. Testing on samples made of U10A and Kh12M steels-including microstructural analysis and hardness measurements-demonstrated that the most effective methods for restoring strong and wear-resistant surfaces are welding with OZh-3 electrodes and laser powder surfacing. The application of these methods, as well as the potential replacement of die material with Kh12M steel, can significantly increase the service life of the dies and improve production performance.

In conclusion, the analysis of existing restoration methods shows that each method has its own advantages and limitations, and effectiveness largely depends on the type of damage, accuracy requirements, and available resources. Modern technologies offer high precision and minimal thermal deformation but are associated with high costs for equipment and personnel training. Traditional methods remain relevant for restoring large surface areas, although they require careful control and subsequent processing. The most rational approach appears to be the integration of different methods based on the specific task, which allows for optimizing the repair process, extending tool life, and reducing production costs.

As part of these efforts, the Department of Technological Equipment, Mechanical Engineering, and Standardization is carrying out a scientific project. The project focuses on the restoration and enhancement of the wear resistance of busbar punching tools. Particular attention is given to identifying design and technological solutions capable of addressing the shortcomings identified in the literature. As a result of the conducted research, a new tool design has been proposed, offering improved strength characteristics, maintainability, and operational durability. The aim of this study is therefore to conduct a comprehensive comparative analysis of the stress-strain state of a restored busbar punching tool in order to improve its durability and performance.

1. Methods and materials

As a result of the scientific research, a new tool design has been proposed, featuring improved strength, maintainability, and operational durability. This design is based on a composite concept that allows for the replacement of the most wear-prone working element without the need to discard the entire tool body. Such an approach not only enhances service life but also provides significant economic benefits by reducing repair costs and downtime in production. Figure 2a presents a sketch of the working part of the composite tool, illustrating its key design features.

The present research, carried out in the laboratories of the Department of Technological Equipment, Mechanical Engineering and Standardization and the Welding Institute of Abylkas Saginov Karaganda Technical University, continues earlier work aimed at increasing the durability and wear resistance of tooling equipment. Within the framework of this study, both worn-out tools retrieved from production lines and newly manufactured components intended for the assembly of composite tools were investigated. This made it possible to combine practical observations with controlled experimental analysis.

At the initial stage, a thorough examination of the actual condition of the worn working part of the tool was performed (Fig. 1). According to earlier studies and experimental data, this component is subjected to severe operational loads, including high contact pressures, cyclic thermal stresses, and abrasive wear. As a result, it often exhibits surface damage such as intensive wear, chipping, and the formation of micro- and macro-cracks. These defects critically affect the accuracy of busbar punching operations and can ultimately lead to premature tool failure. The detailed assessment carried out at this stage provided a basis for evaluating the extent of material degradation and determining the necessity and scope of restorative measures.

In the preparation stage, the worn working part of the tool was carefully removed by mechanical processing (Fig. 2b). This ensured that the remaining body of the tool could be preserved and reused without compromising its structural integrity. At the same time, new working inserts of different diameters were manufactured in order to carry out comparative testing and validation of the proposed composite design (Fig. 2c). The inserts were produced from carbon tool steel U10A, a material widely recognized for its favorable balance of hardness, wear resistance, and machinability. Its selection was substantiated in earlier phases of the research [5], where U10A demonstrated stable performance under cyclic mechanical loads and suitability for subsequent heat treatment aimed at enhancing strength and toughness.

By integrating these preparatory steps, the foundation was laid for a systematic evaluation of the composite tool's stress–strain state, enabling the subsequent modeling and experimental verification phases of the study.

a) b) c)

Fig. 2. - Sketch of the composite tool design (a), the prepared guiding part of the tool (b), and new working parts of various diameters (c)

The working parts made of U10A steel underwent heat treatment in an SNOL 3/1100 laboratory muffle furnace at the International Materials Science Center of Abylkas Saginov Karaganda Technical University (Fig.3a). This operation is critically important for forming the required microstructure and achieving the necessary physical and mechanical properties, which are essential for the tool's durability.

For carbon steels, typical heat treatment regimes include: normalization – heating to temperatures above the critical points (approximately 800-850°C), followed by holding and air cooling; quenching – heating above the critical temperatures with holding and rapid cooling in water, oil, or salt solutions; tempering – heating the quenched steel to a temperature below the critical point, holding it, and then cooling to achieve the desired toughness.

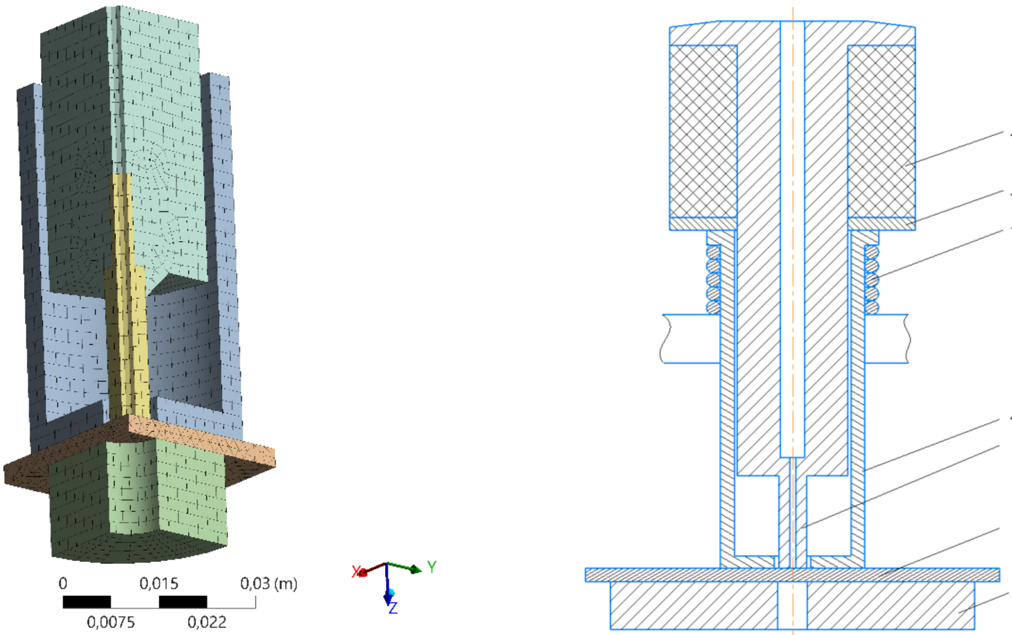
After heat treatment, the assembly of the composite tool was carried out. The working part was inserted into the guiding part for subsequent permanent joining (Fig.3b).

a) b)

Fig. 3. - Heat treatment in the SNOL 3/1100 muffle furnace (a) and the tool assembly process (b)

The wear of the working surface of the busbar punching tool is largely determined by its stress–strain state in the deformation zone. Given the multi-stage nature of the punching processes, it is advisable to use mathematical modeling, which enables an unlimited number of virtual experiments with minimal labor costs [6].

To study the stress–strain state of the busbar punching tool, a numerical simulation method was employed using the ANSYS software package. In particular, the Explicit Dynamics module was utilized for effectively tracking the propagation of shock waves, analyzing large deformations, and predicting material failure.



a) b)

Fig. 4. - Finite element model of the tool (a) and punching scheme (b): 1 – punch; 2 – punch holder; 3 – buffer; 4 – spring; 5 – washer; 6 – workpiece; 7 – die

2. Results and discussion

A finite element model of the studied object was developed within the simulation environment. To improve computational efficiency and reduce calculation time, a symmetric quarter-section of the full model was used for simulation (Fig.4a).

At each stage of the modeling process, the stresses, deformations, and distribution of contact forces in the working zones of the tool were determined. The obtained results made it possible to identify the critically loaded areas of the structure and assess the effectiveness of the proposed restoration and modernization methods.

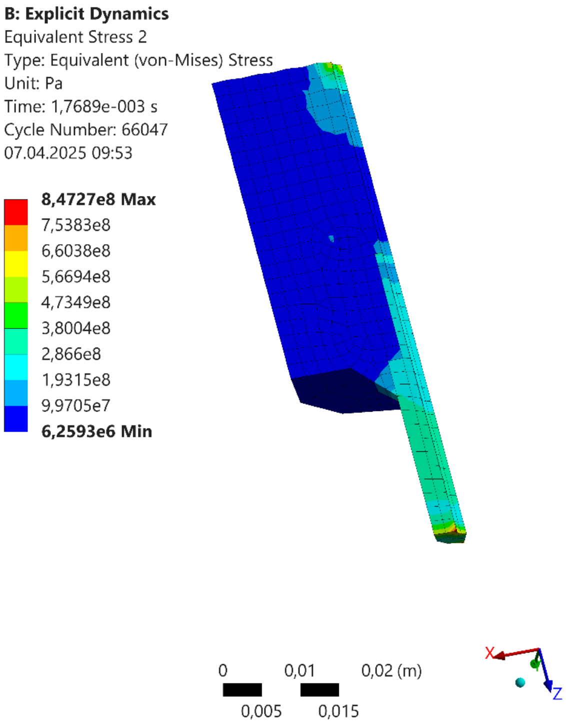


Fig. 5. – Stress-strain state of the composite tool

The highest stresses, indicated in red on the color scale, are concentrated exclusively at the cutting edge of the tool. As the distance from the cutting edge increases into the body of the tool, the stress values drop sharply, transitioning from maximum to significantly lower levels.

For the working part of the tool made from carbon tool steel, the value of 847.27 MPa is considered significant. Carbon tool steels (e.g., grades U8, U10, U12), after proper heat treatment (quenching and tempering), typically exhibit a yield strength in the range of 600-1000 MPa and an ultimate tensile strength of 1000-1200 MPa or higher. Therefore, the obtained maximum stress may fall within the acceptable strength limits of high-strength carbon tool steel.

This indicates that, under the given loading conditions, the cutting edge of the tool is unlikely to experience immediate failure and is capable of withstanding such stresses without significant plastic deformation or brittle fracture.

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Conclusions

The conducted research revealed the issue of premature wear of busbar punching tools, as well as difficulties in their restoration due to the lack of an established technological process for repair and recovery. To address this problem, a restoration method was proposed involving the replacement of the tool's working part with a carbon steel insert.

An experimental prototype of the restored tool was manufactured in the department’s laboratory facilities.

Using numerical simulation with the ANSYS software package, the stress-strain state of the busbar punching tools was analyzed. The simulation focused on determining the stresses occurring in the tool’s working zones, deformations, and the distribution of contact forces.

In the simulation of the busbar punching tool restored by replacing the working part with a carbon steel insert, it was found that the maximum stress in the working area reaches 847.27 MPa, which falls within the acceptable strength limits for high-strength carbon tool steel.

The results of the computer simulation confirmed the applicability of the proposed restoration method for busbar punching tools. Further research should include experimental testing of tools restored by surfacing and by replacement of the working part with a carbon steel insert, both under laboratory and industrial conditions.

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