CONTRIBUTION TO IMPROVING OF MACHINE PARTS MECHANICAL PROPERTIES BY THERMOMECHANICAL HARDENING

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Current industrial production is characterized by requirements for improving the physical and mechanical properties of the used material. This causes a workload creating a rather complex load on all types of machines and mechanisms during operation. The design of such objects is currently based on a wide range of computational and experimental methods that allow modelling their state and behaviour even in the case of complicated non-stationary loading conditions. In this paper, the authors focus on the statistical evaluation of selected manufacturing operations related to mechanical and thermomechanical processing of products [Kuric 2011]. For example, in the case of long pipe billets with a thickness coefficient of 2-4, practically the only way of their production in the metallurgical cycle is cross-roll piercing followed by reduction. This process has high productivity but at the same time certain disadvantages. These disadvantages limit the efficiency and the range of use of the pipe blanks obtained by piercing, which leads to a consequent shortening of the machine production cycle. The presented approaches allow changing the structure of technological processes of production of axisymmetric metal products, by modifying the thermomechanical processing at the beginning of the production cycle.

KEYWORDS

thermomechanical processing, thermomechanical hardening, heating process, cooling process, deformation

1 INTRODUCTION

The entire contemporary civilization depends on the technical development and, consequently, is improved with the use of numerous different machines and mechanisms. Currently, they are indispensable to any area of human activity, whether it be in mining and processing industries, transport, agriculture, military affairs and other sectors of the economy. In almost all branches of industry, there is a definite tendency towards intensifying the exploitation of the objects in the realm of technology: the carrying capacity and travel speed of transport are increasing, and the efficiency of technical equipment is enhanced.

Accordingly, the operational requirements for the production produced become stricter, and the operating conditions themselves toughen up [Aleksandrova 2018]. State-of-the-art technologies, and especially advanced machines and equipment, are designed largely for extreme climatic conditions, ensuring resistance to aggressive environments and operating at high altitudes and at great depths [Kuznetsov 2023]. They are becoming structurally more and more complex and have been transformed, to a large extent, into mechatronic systems [Lysenko 2011].

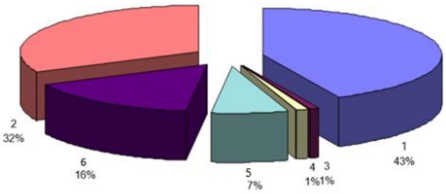
Therefore, the design of machine parts, which includes a wide range of elementary surfaces of various configurations with strict requirements for dimensional fidelity, shape errors, and surface conditions, is also becoming more complex.

2 STATISTICAL ANALYSIS

The requirements for the physical and mechanical properties of the material in terms of strength, ductility, toughness, and hardness are constantly increasing. All this is due to the fact that workloads create a rather complex pattern of stresses of various types of machines and mechanisms during operation, including supercritical ones [Saga 2018].

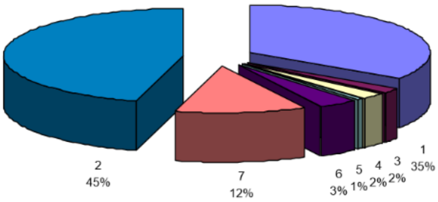
The design and construction of such objects are currently based on a wide range of calculation methods, software products that enable their state and behaviour under non-stationary loading conditions to be modelled [Saga 2014]. However, the most modern and advanced methods do not completely dispense assumptions and limitation. Any boundary value problem has initial and boundary conditions; any key assumptions concerning constant or linearized parameters can be defined, which makes an approximate estimate to be obtained. However, in reality, that simulation may not correspond to the actual object. On the technological process implementing, the actual state of the production facility is formed, which is determined by the increasing role of technological methods and solutions used for the production of parts of modern machines and equipment used under severe conditions.

A statistical analysis showed (Fig. 1) that most of the operations in the manufacture of products and parts in engineering production relate to mechanical and thermomechanical processing [Yakimovich 2007].



a)

1. Mechanical processing, 2. Bench-work and assembly, 3. Stamping and forging, 4. Welding and soldering work, 5. Application of coating, 6. Heat treatment and other works



b)

1. Mechanical processing, 2. Bench-work and assembly, 3. Stamping and forging, 4. Welding and soldering work, 5. Electrophysical chemical processing, 6. Heat treatment, 7. Application of coating and other work

Figure 1. The proportion of the applied technological stages in the total labor intensity of product manufacturing of a) low and medium complexity, b) high complexity

In the modern nomenclature of machine and equipment parts, the share of axisymmetric product of types of rotating bodies is about 30 % or even more. These, in particular, include disks $L/D \leq 1$, sleeves $L/D \approx 1$ and shafts $L/D > 1$, where L is the length, and D, respectively, the diameter of the part. In machine designs and as a processing tool, they can be implemented in the form of solid-cored and hollow bored shafts, axles, guide pins, punch stamps, rolling mill rolls, sleeves and shell cases, circular cutters for cutting tapes and foil in rolling production, barrels of sporting and hunting weapons and a whole range other position. As can be seen, the range of such units is very wide. Parts and units usually operate under conditions of static and dynamic loads, bending moments and torques, pressure and temperature pulses, and under contact stress loading [Saga 2012, Jakubovicova 2014 & 2016].

3 PROBLEM ANALYSIS

Despite the fact that non-metallic and composite materials are currently widespread [Hu 2022], experience has shown that for parts of a similar range, structural and instrumental carbon and alloy steels are widely used and, apparently, will be a vital part of engineering solutions for a long time [Majko 2022]. In connection with the widespread practice of their use in the designs of machines and mechanisms, the problem of improving the technology for manufacturing parts and their usage is still urgent. This is also due to the need to increase production efficiency in general from the standpoint of comprehensively ensuring high performance standards associated with increasing reliability and in-use life under hard operating conditions [Suslov 2022, Klarak 2024]. The solution to this problem is directly related to the currently observed development trends in the machine-building sector, including the following:

- considerable variability in production range and focus on mass production;
- an increase in the use of metal to over 0.6, while the relative share of the plastic forming operations in the total labour intensity of the manufacture is getting over 30 %;
- the combination of shaping and hardening with additional exposures of different physical natures;
- the elimination of environmentally adverse production factors and aggressive environments from technological processes.

The classical technology for the manufacture of parts and units such as bodies of revolution, in particular, solid-core and hollow bored shafts, axles, pins, rods and a number of others, involves (depending on the mass production) the use of hot-rolled cylindrical steels and semi-continuous casting, open forgings, forgings produced by horizontal forging machines or spun casting, and others. At this point, it is necessary to determine a large allowance for mechanical processing due to the significant thickness of the defective layer and scale on the surface of the stock materials.

In addition, the formation of mechanical characteristics of the part material should be provided with heat-treat operations performed separately, such as quenching and following tempering (low, medium or high, depending on the steel grade). Hardening heat treatment is traditionally done through mechanical processing, which causes a number of organizational difficulties associated with the need to transport stock materials to hardening shops or heat-treatment shop areas with their subsequent return to mechanical processing to remove the remaining part of the allowance and bring the parts and units in accordance with the requirements of the drawing.

Mechanical processing in the general case involves operations to remove crude, semi-finished, and finished parts of the allowance using both edged tools and abrasive tools [Bratan 2023]. In this case, a rather wide range of measurement cutting tools is applied, especially for hole-making operations where tool sets are indispensable, in particular reamers, broaches, etc. Until recently, the formation of mechanical characteristics at the early stages of the technological process was extremely limited due to the lack of tools and equipment for processing in a heat-hardened state of stock materials.

By now, advanced cutting tools had appeared made from perspective materials, including ceramics and hard alloys with wear-resistant coatings, which enabled hardening to be carried out at the beginning of the technological route [Zajac 2020]. This initiated a new direction in the development of technologies for manufacturing this type of unit with thermomechanical processing and, in general, became the basis for a new class of thermomechanical technologies.

Research on thermomechanical processing (TMP) has been actively carried out since the late 1950s of the 20th century. In the context of physical metallurgy, the mechanisms for the formation of a unique set of properties during TMP, including the combination of high-lasting quality and toughness at a certain hardness, have been well studied by such famous scientists as V. Sadovsky, M. Bernstein, O. Romaniv and others. That made it possible to develop a number of basic technological TMP schemes, including high-temperature TMP (HT TMP), low-temperature TMP (LT TMP), high-temperature isothermal TMP (HTI TMP) and a number of other schemes. Quite close analogues of TMP are controlled rolling and ausforming, which serve the same function, providing a set of enhanced properties, usually in the flow of a rolling mill in the metallurgical production cycle [Bernshtein 1968]. At the same time, ensuring dimensional accuracy, shape errors and surface quality during shaping was nearly beyond the scope of professional attention.

In the development of TMP, it has been discovered that this approach could be adapted to the cycle of production engineering for processing parts of a specific range. For axisymmetric parts, modifications of the basic TMP scheme were developed without violating the basic principles of continuously sequential heating to the austenitisation temperature, plastic deformation and quenching cooling of hot-wrought austenite. For parts such as shafts, pins, and rods, HTMP with screw compression deformation (SCD) in an idle stand was developed and for parts such as discs, a high-temperature thermomechanical surface treatment scheme (HT TMST) was introduced.

3.1 *Recommendations and Proposed Solution*

In particular, for long pipe billets with a thickness coefficient of 2–4, practically the only way to produce them in the metallurgical cycle is cross-roll piercing followed by reduction. This process has high productivity, but at the same time, it has certain disadvantages, including the following:

- the screw trace in the channel of the pipe blank with a crest height of up to 0.5 mm and a step of 25–30 mm from the piercing mandrel;
- wall thickness deviation up to 0.6–0.8 mm;
- misalignment of the channel axis up to 0.9 mm;
- a layer of scales on the outer and inner surfaces up to 0.3 mm thick;
- low surface quality,
- high anisotropy of mechanical properties along the length and cross-section of the workpiece.

These defects limit the efficiency and range of application of pipe blanks obtained by piercing, resulting in a subsequent reduction in the machine-building cycle.

For metallurgical pipe blanks of this range to be used effectively in the machine-building cycle and for a unified pipe blank to be

produced for an expanded range of products, it is proposed to calibrate the pipe stocky in order to specify the quality requirements by using the HT TMP at the first stage of the manufacturing process with deformation of the metallurgical tubular blank by screw compression deformation (SCD) in a three-high idle stand on a short retained cooled mandrel [Dementyev 2015]. As preliminary research has shown, this technology allows for dimensional accuracy at the level of 9–11 accuracy grades, wall thickness variation at the level of 0.2 mm, non-straightness of the channel axis in the range of 0.2-0.25 mm, surface quality at the level of 1.25 MIC, as well as a combination of high strength (1500 MPA) and toughness of the metal (0.6 MJ/m2 or more). This turned out to be possible due to the creation of a controlled three-dimensional deformed state during HP due to varying technological modes - the degree of deformation, the relative angle of rotation of the deforming rollers, the ratio of the diameter of the rollers to the effective diameter, the arm length of the mandrel in the deformation zone, the strain aging time before cooling, and the ratio of coolant flow rates in the outer and indoor sprayers. For vibroimpulsive deformation, the basic variable modes for complex formation of quality to be ensured are following:
- the degree of deformation;
- the energy of a blow;
- the impact frequency;
- the force of static compression of the roller of the vibroimpulsive mechanism on the workpiece.

Equipping production with specialized equipment is indispensable to the implementation of technological schemes for thermomechanical processing of heavily loaded axisymmetric parts (pins, axes, shafts, rolls, etc.), which have proven themselves in terms of comprehensive formation of increased quality requirements and service properties. Technical solutions incorporated into the design of such equipment, or more precisely, into the structure, operating relations and design of process systems for thermomechanical processing (TC TMP, STK HTMP SCD) must first ensure the fundamental technological scheme of TMP to be implemented. It consists of scanning the heating, deformation and cooling of the product (workpiece) in accordance with certain ranges of time, power, thermal parameters and TMP modes, as well as the range of overall dimensions of the processed item and the specified process productivity. Due to this, a directed effect on the structure, morphology of phases and components of the volumetric stress-strain state of the material is achieved, which, in fact, form the characteristics of structural strength, accuracy and surface quality of products [Domanski 2017].

In connection with the above, the composition of such a STK HTMP SCD (for example, for processing long axisymmetric parts of solid and hollow cross-section according to the HTMP SCD scheme in a non-drive stand) must necessarily include the following components, united by an integrated control system:
- heating system (it is most effective to use induction heating);
- deforming equipment,
- coolant system with, preferably, a closed-loop cycle for cooling means that require preparation.

3.2 Statement of the Modeling Problem

Currently, there are no proven methods for formalizing thermomechanical hardening (TMH) processes due to the complexity of their description and the lack of a strict functional relationship between parameters, modes and quality indicators; one of the approaches to solving this problem is the fuzzy logic method.

During modelling, the object must acquire a set of qualities or input variables (accuracy, surface properties, material properties, etc.) at minimal cost as a constriction, and the output is some fuzzy variable of dimension, $V \cdot L$ where L L is the length of the selected route, and V is the number of parameters on a given route component. An elementary component of the process is fuzzy variables or parameters of the components.

Description of stages and definitions

$$M = \{M_i\}_{i=1,m} \tag{1}$$

is a set of routes.

$$M = \begin{pmatrix} k_{11}, k_{12}, \dots, k_{111};\ k_{21}, k_{22}, \dots, k_{212}; \dots; \\ k_{m1}, k_{m2}, \dots, k_{m1m} \end{pmatrix}, \tag{2}$$

$k_{ij}(\tilde{t}_{ij})$ is the j-th component on i-th route, where $\tilde{t}_{ij} = (t_{i1}, \dots, t_{inj})$ is a vector of route parameters.

For a particular situation, the vector of root parameters can be defined as following:

$$t_{ij} = (x, T\ (x), U, G, M), \tag{3}$$

where x is name of the parameter $\mathrm{T}(\mathrm{x})$ are terms for the parameters, U are interpretations of terms, G are rules for a generation x, M are rules for the linguistic interpretation of each meaning.

For example: x is the temperature, $\mathrm{T}(\mathrm{x})$ = {"very high", "high", "medium",...}, $U = [-250,250]$: about zero is "medium", about 100 is "high", etc.

Input: $K_i, \vartheta \in [a,b], p_1 \leq\ |M_i| \leq p_2$.

Output: a fuzzy variable consisting of all parameters and their degrees of preference (technological process).

The basic object of the model description is the interconnection between product quality indicators, route and modes.

The result of the calculations performed on each route can be presented in the form:

$$y_i(\tilde{t}) = (F_{mi}{}^{\circ} \dots {}^{\circ}F_{m1}), \tag{4}$$

where (f_i) is the vector of input parameters, F_i is the vector of the operators acting at the *i*-th stage of material processing (describe the operation of each element of the route):

$$F_i: \tilde{t}\ \rightarrow\ \tilde{t}^*. \tag{5}$$

The entire task can be described by a tuple:

$$\langle A, X, \{G_a\}, K, F, P_s \rangle, \tag{6}$$

where A are alternatives (routes), X are outcomes of alternatives (costs, modes of route components), G_a is the distribution of outcome probabilities $G_a: X_a\ \rightarrow \boldsymbol{P}$ (empirically or analytically, thanks to preliminary calculation in accordance with physical laws), $\boldsymbol{F}$ is the mapping of the set of outcomes into the set of linguistic vector estimates $\boldsymbol{X} =\ K_1 \cdot K_2. \dots \cdot K_m, F: X\ \rightarrow K_1 \cdot K_2 \cdot \dots \cdot K_m$ (description of the result without reference to specific materials), P_s is the linguistic structure of the preferences of the decision maker.

The problem is to develop models, which allow determining a fuzzy utility estimate consistent with the structure of preferences P_s, if mappings $\{G_a\}$, F for each alternative $a\ \in A$ are known, and based on the obtained utility estimates, construct a fuzzy set of preferred (effective) processes [Kuric 2022].

4 CONCLUSIONS

The considered approaches allow changing the structure of technological processes for the manufacture of axisymmetric metal products, by shifting thermomechanical processing (modifications of the basic TMP scheme) at the beginning of the machine-building cycle and at the same time forming a complex of increased quality requirements and reducing subsequent mechanical processing using advanced tools.

Currently, in order to obtain optimal processing modes for HTMP SCD, it is necessary, based on the proposed formal model, to develop a decision support system of the process in order to develop and implement the appropriate software.

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