MODELING OF TRANSFORMATION OF QUALITY INDICATORS IN THE PROCESS OF MECHANICAL PROCESSING OF PRODUCTS WITH HIGH PHYSICAL AND MECHANICAL PROPERTIES

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Abstract. Complex technologies are technologies which consist of a certain set of stages and technological processes. Using the theoretical basis of the systemic and synergetic approaches, the technological process of manufacturing of such parts has been represented as a process of qualitative and quantitative changes of the object. Taking into account the phenomena of technological heredity, it has been assumed that physical and mechanical properties, in particular, tensile strength, proportionality limit, relative narrowing and resilience, as well as characteristics of the quality of the treated surfaces and processing accuracy can be transformed during the complex technological process. To describe the transformation processes of quality indicators, a set of experimental studies of the roughness of the treated surface during machining of parts with high physical and mechanical properties has been carried out and mathematical models have been obtained. To determine the conditions of the integrated technology, it has been proposed to use a complex of dimensionless characteristics - relative changes of the coefficients of the mathematical model. The obtained mathematical models of the processes of mechanical treating of steel 38HN3MFA make it possible to determine the processing conditions that ensure the formation of a given set of quality indicators.

1. Introduction
To ensure a high level of operational reliability of special-purpose parts, complex technologies are being developed, consisting of a certain set of stages and technological processes [1-8]. Using the
2. The main part of the article

Considering the technological process of manufacturing of a product in complex, taking into account the phenomena of technological heredity, it can be assumed that the physical and mechanical properties, in particular, tensile strength, proportionality limit, relative narrowing and resilience, as well as characteristics of the quality of the treated surfaces and processing accuracy can be transformed, i.e., inherit from one stage of a complex technological process to another.

Let us represent the general structure of a complex technology as a complex multidimensional system (Fig. 1), in which to the input of the structure the characteristics of the initial material (charge) for smelting the workpiece (M₁, M₂, ..., Mₙ) come in, and the output provides the corresponding set of physical and mechanical properties (S₁, S₂, ..., Sₙ) and quality indicators (K₁, K₂, ..., Kₙ).

![Figure 1. The general structure of a complex technology](image-url)

The transformation of quality indicators is carried out as a result of the action of a set of technological factors (F₁, F₂, ..., Fₙ), characteristic of each stage of the complex technological process. As a result, the quality of finished products is characterized by a set of quality indicators (R₁, R₂, ..., Rₙ). This approach makes it possible to represent the integrated technology as a complex technological system, consisting of several structural cells - technological stages and connections between them.

The stages of the integrated technology are the technological processes of ingot smelting, forging, machining and heat treating. Let us consider each stage of the integrated technology as a set of elementary technological processes. It should be noted that the resulting quality indicators of the finished product are being formed step by step. Each stage of the integrated technology determines more-less the physical and mechanical properties and quality indicators of the part. Methods of obtaining workpieces and subsequent types and methods of heat treating play an important role in ensuring the specified performance characteristics. The quality indicators of the processed surfaces and the accuracy indicators are finally being formed at the stage of machining. However, to ensure the entire range of indicators of the finished product, it is necessary to consider the stages of complex technology in conjunction with the phenomena of technological heredity, i.e., transformation of quality indicators. In this regard, in order to design the optimal structure of an integrated technology, it is necessary to investigate the quantitative dependencies that describe the connections of the previous technological processes with subsequent technological operations.

According to [43-44], a mathematical model of an elementary technological process of machining can be represented in the form of a graph, the vertices of which correspond to a certain state of surface quality, and a set of arcs – to technological transitions or operations. Let us apply to this model the manifestation of technological heredity in the form of an expression proposed by the authors of [45]:

Theoretical basis of the systemic and synergetic approaches [9-19], the technological process of manufacturing such parts can be represented as a process of qualitative and quantitative changes of the object. At the same time, the issues of studying the reliability of machining processes while ensuring the required level of stability of quality indicators [20-29] and the competitiveness of finished products [30-42] remain relevant.
where $X_i$, $X_{i-1}$ – quality indicators for (i-1) and i-operations of the machining technological process; 
a, b – coefficients of technological heredity, which show the level of transformation of quality indicators.

To describe the transformation processes of quality indicators, a set of experimental studies of the roughness of the treated surface during machining of parts with high physical and mechanical properties has been carried out and expressions have been obtained in the form:

$$Ra_i = a \cdot Ra_{i-1}^b,$$

(2)

where $Ra_i$ is the surface roughness at the i-th operation, $\mu$m (microns);
$Ra_{i-1}$ – surface roughness at the preliminary operation, $\mu$m (microns).

Coefficients a and b have been obtained from regression equations. The mathematical processing of experimental researches has been carried out using the EXCEL program. Table 1 shows the results of the researches of processing of steel 38HN3MFA, obtained by the method of electroslag remelting.

The results of the research have showed that the transformation coefficients of quality indicators depend on the technological conditions of the machining processes of steel 38HN3MFA. Differences in the processes have been established, which are conditioned on not only as the result of the use of various brands of instrumental material. It should be noted that the method of the preliminary stage of complex technology also has a significant impact.

It has been experimentally identified that the surface roughness is to some extent influenced by the method of obtaining the initial metal and the type of heat treating. The physical meaning of these phenomena is explained by the fact that the ability of the metal to provide the specified physical and mechanical properties and quality indicators is initially laid at the stage of the ingot smelting, while providing a reserve for increasing the operational reliability of especially critical products [46].

With a certain degree of assumptions, one can assert that using formula (2), it is possible to characterize the quantitative and qualitative relationships of the transformation processes of quality indicators, i.e. technological heredity.

In particular, the quantitative relationships of technological heredity, depending on the choice of the method of the preliminary stage of the complex technology, are determined in formula (2) by the coefficient (b), and the main conditions of machining at a particular stage of the complex technology are determined by the coefficient (a). The obtained coefficients make it possible to quantify the degree of influence of the phenomena of technological heredity for a specific production stage of an integrated technology.

Mathematical models of the investigated processes of mechanical treating of steel 38HN3MFA have been obtained in the form:

$$Ra = a \cdot v^2 + b \cdot v + c,$$

(3)
where \( a, b, c \) – coefficients of the mathematical model; \( v \) – cutting speed, m / min; \( Ra \) – roughness of the processed surface, \( \mu m \) (microns).

In fig. 2 the regression equations are presented – the dependence of the roughness of the processed surface of the workpieces obtained by various technological methods, in particular, electroslag remelting and double remelting with microalloying, taking into account the subsequent heat treating.

The calculation of the coefficients of the mathematical model (3) has been carried out using the least squares method through regression analysis of the EXCEL program. After determining the coefficients and building models, their significance and adequacy of the whole model have been carried out. In table 2 the mathematical models of the investigated processes of machining of workpieces from steel 38HN3MFA taking into account preliminary heat treating are being presented [47].

![Regression dependences of the roughness of the machined surface on the cutting speed during machining of workpieces made of steel 38HN3MFA with VK10HOM cutting inserts](image)

\[
y = -0.2223x^2 + 2.3866x - 1.4893
\]

\[
y = -0.1527x^2 + 1.3184x + 0.1293
\]

The obtained partial dependences of the roughness of the processed surface on the elements of the machining modes make it possible to determine the optimal processing modes, to assess the degree of influence of technological factors on the quality indicators.

Experimental studies have shown that the processes of mechanical treating of 38HN3MFA steel with various tool materials differ significantly in terms of quality of the treated surfaces and the intensity of wear of cutting tools. To a certain extent, this is due to the peculiarities of obtaining the original workpiece, heat treating, as well as physicochemical processes that arise during mechanical processing. For machining processes, it is important to determine such technological conditions under which the specified quality indicators are being provided for a certain operation. When developing and implementing an integrated technology, it is important to determine such a sequence of operations and such processing conditions under which the degree of transfer of processing errors from the previous operation should be minimal, i.e. the phenomenon of technological heredity should be manifested to a minimum [48-49].
To determine such conditions, it has been proposed to use a complex of dimensionless characteristics - the relative changes of the coefficients of the mathematical model (3):

\[
\Delta a = \frac{a_{\text{ann}}}{a_{\text{norm}}}, \quad \Delta b = \frac{b_{\text{ann}}}{b_{\text{norm}}}, \quad \Delta c = \frac{c_{\text{ann}}}{c_{\text{norm}}}
\]

(4)

where \(a_{\text{ann}}, b_{\text{ann}}, c_{\text{ann}}\) are the constant coefficients of the mathematical model describing the process of mechanical treating of steel 38HN3MFA after annealing;

\(a_{\text{norm}}, b_{\text{norm}}, c_{\text{norm}}\) - constant coefficients of the mathematical model describing the process of mechanical treating of steel 38HN3MFA after normalizing with stress relieving.

Table 2

| Tool material grade | Heat treating of a workpiece | Mathematical model |
|---------------------|-----------------------------|--------------------|
| VK6OM               | annealing                   | \(Ra = a \cdot v^2 + b \cdot v + c\) |
| VK6OM               | normalizing with stress relieving | \(Ra = -0,3179 \cdot v^2 + 3,0321 \cdot v - 0,5796\) |
| T15K6               | annealing                   | \(Ra = -0,1667 \cdot v^2 + 1,4583 \cdot v + 0,6429\) |
| T15K6               | normalizing with stress relieving | \(Ra = -0,097 \cdot v^2 + 0,8351 \cdot v + 0,2143\) |

The analysis of the obtained dimensionless characteristics (Table 3) makes it possible to assess the degree of change of qualitative indicators from one operation to another.

Determination of the optimal conditions for mechanical treating is based on identifying a stable technological process in terms of minimizing the degree of change of qualitative indicators. Thus, the most optimal grade of instrumental material is the one for which the relative changes of the coefficients are minimal.

Table 3

| Tool brand | Relative changes of the coefficients | |
|------------|-------------------------------------|--|
|            | \(a\)                               | \(b\) | \(c\) |
| BK10XOM    | 1,4558                              | 1,8102| 11,518|
| BK6OM      | 1,907                               | 2,079 | 0,9015|
| T15K6      | 1,0309                              | 1,342 | 0,033 |

Similar researches have been carried out for analyzing of the wear of cutting tools of various brands used in production. Regression dependences have been obtained, which made it possible to reveal the influence of technological factors on the wear of cutting tools, taking into account the phenomena of transformation of qualitative indicators.

3. Conclusions

In conclusion, it should be noted that the obtained mathematical models of the processes of
mechanical treating of steel 38HN3MFA make it possible to determine the processing conditions that ensure the formation of a given set of quality indicators. The conducted researches create the basis for the automation of the design of complex technologies for the manufacture of critical products.

4. References

[1] Parshina E.A  Synergetical approach to the management of product’s competitiveness. Scientific Reports on Recourse Issues 2010. Freiberg: Technische Universität Bergakademie Freiberg, Germany, Volume 1, 2010. Pp. 398–404.

[2] Parschina E. The Investigetion of Stability of Technological Systeme of Cutting Processing. Proceedings of the International Scientific Conference MECHANIKA-98, June 1998. – Rzeszow: Rzeszow University of Technology, Poland, 1998. Pp.205–210.

[3] Parshyna O., Parshyn Yu. (2020). Analytical platform to provide competitiveness of ore-mining machinery manufacturing. Mining of Mineral Deposits, 14(3), Pp. 61–70. https://doi.org/10.33271/mining14.03.061

[4] Savchenko Iu, Gurenko A and Naumenko O 2016 The cutting-edge industrial technology of mining tool manufacturing Mining of Mineral Deposits 10 4 105–110

[5] Bast J, Gorbatyuk S M, and Kryukov I Yu 2011 Horizontal hcc-12000 unit for the continuous casting of semifinished products Metallurgist 55(1-2) 116-118

[6] Surianinov M and Krutii Y 2018 To the solution of the problem of bending of a cylindrical shell by the boundary elements method MATEC Web of Conferences 230

[7] Krutii Y, Suriyaninov M and Vandynskyi V 2018 Analytic formulas for the natural frequencies of hinged structures with taking into account the dead weight MATEC Web of Conferences 230

[8] Kondratenko V, Sedykh L, Mirzakarimov A and Aleksakhin A 2020 Static analysis and strength calculation of drive shaft of large-scale cone crusher E3S Web of Conferences 193

[9] Malinov L, Malycheva I, Klimov E, Kukhar V and Balalayeva E 2019 Effect of Particular Combinations of Quenching Tempering and Carburization on Abrasive Wear of Low-Carbon Manganese Steels with Metastable Austenite. Materials Science Forum 945 574–578

[10] Khrebtova O, Zachepa N, Zachepa I, Mykhalchenko G and Prokopenko V 2020 Formation of Starting Torque of Double-Fed Induction Motor Proceedings of the 25th IEEE International Conference on Problems of Automated Electric Drive. Theory and Practice 9240786

[11] Khrebtova O 2020 Forming the induction motor torque when starting Technical Electrodynamics (5) 40-44

[12] Bogoboyashchii V, Vlasov A and Izlnin I 2001 Mechanism for conversion of the conductivity type in arsenic-doped p-Cd_{x}Hg_{1-x}Te subject to ionic etching Russian Physics Journal 44(1) 61-70

[13] Markov O, Kukhar V, Zlygoriev V, Shapoval A, Khvashchynskyi A and Zhytnikov R. 2020 Improvement of Upsetting Process of Four-Beam Workpieces Based on Computerized and Physical Modeling Molding Transactions 48(4) 946–953

[14] Markov O E, Gerasimenko O V, Shapoval A A, Abdulov O R and Zhytnikov R U 2019 Computerized simulation of shortened ingots with a controlled crystallization for manufacturing of high-quality forgings Int J of Advanced Manufacturing Technology 103(5–8) 3057–3065

[15] Shapoval A, Savchenko I and Markov O 2021 Determination coefficient of stress concentration using a conformed display on a circle of a single radius Solid State Phenomena 316 928-935

[16] Zagirnyak M, Mamchur and Kalinov A 2010 Elimination of the influence of supply mains low-quality parameters on the results of induction motor diagnostics The XIX International Conference on Electrical Machines - ICEM 2010

[17] Zagirnyak M, Maliakova M and Kalinov A 2015 Analysis of electric circuits with semiconductor converters with the use of a small parameter method in frequency domain”, COMPEL – The international journal for computation and mathematics in electrical and electronic engineering 34 3 808-823
[18] Lutsenko I 2015 Identification of target system operations Development of global efficiency criterion of target operations. Eastern-European Journal of Enterprise Technologies 2 2 35–40
[19] Lutsenko I, Vihrova E, Fomovskaya E and Serdiuk O 2016 Development of the method for testing of efficiency criterion of models of simple target operations. Eastern-European Journal of Enterprise Technologies 2 4 42–50
[20] Gorbatyuk S, Shapoval A, Mos’pan D and Dragobetskii V 2016 Production of periodic bars by vibrational drawing. Steel in Translation 46 7 474-478
[21] Kurpe O, Kukhar V, Puzyr R, Burko V, Balalayeva E and Klimov E 2020 Electric Motors Power Modes at Synchronization of Roughing Rolling Stands of Hot Strip Mill. CONFERENCE 2020, PAEP 510
[22] Kukhar V, Grushko A and Vistbak I 2018 Shape indexes for dieless forming of the elongated forgings with sharpened end by tensile drawing with rupture. Solid State Phenomena 284 408–415
[23] Grushko A, Kukhar V and Slobodyanyuk Y 2017 Phenomenological model of low-carbon steels hardening during multistage drawing. Solid State Phenomena 265 114–123
[24] Haikova T, Puzyr R, Savelov D, Dragobetsky V, Argat R and Sivak R 2020 The Research of the Morphology and Mechanical Characteristics of Electric Bimetallic Contacts. CONFERENCE 2020, PAEP 579
[25] Shapoval A, Drahobetskyi V, Savchenko I, Gurenko A and Markov O 2020 Profitability of production of stainless steel + zirconium metals combination adapters. Key Engineering Materials 864 285-291
[26] Zarapin A, Shur A and Chichenev N 1999 Improvement of the unit for rolling aluminum strip clad with corrosion-resistant steel. Steel in Translation 29(10) 69-71
[27] Artiukh V, Mazur V and Adamtevich A 2017 Priority influence of horizontal forces at rolling on operation of main sheet rolling equipment. MATEC Web of Conferences 106
[28] Savchenko I, Shapoval and Gurenko A 2020 Modeling dynamic parameters of hard alloys during shock wave regeneration. IOP Conference Series: Materials Science and Engineering. 969(1)
[29] Zagirnyak M, Kalinov A, Melnykov V and Kochurov I 2015 Correction of the operating modes of an induction motor with asymmetrical stator windings at vector control. International Conference on Electrical Drives and Power Electronics 259
[30] Hrudkina N, Aliieva L, Markov O, Marchenko I, Shapoval A, Abhari P and Kordenko M 2020 Predicting the shape formation of hollow parts with a flange in the process of combined radial-reverse extrusion. Eastern-European Journal of Enterprise Technologies 4 1 (106) 55-62.
[31] Shvab’yuk V, Krutii Y and Sur’yaninov M 2016 Investigation of the Free Vibrations of Bar Elements with Variable Parameters Using the Direct Integration Method. Strength of Materials 48(3) 384-393
[32] Markov O, Gerasimenko O, Aliieva L and Shapoval A 2019 Development of the metal rheology model of high-temperature deformation for modeling by finite element method. EUREKA, Physics and Engineering (2) 52-60
[33] Puzyr R, Shchetynin V, Arhat R, Sira Yu, Muravlov V and Kravchenko S 2021 Numerical modeling of pipe parts of agricultural machinery expansion by stepped punches. IOP Conference Series: Materials Science and Engineering 1018
[34] Shapoval A, Kantemyrova R, Markov O, Chernysh A, Vakulenko R and Savchenko I 2020 Technology of production of refractory composites for plasma technologies. Proceedings of the 25th IEEE Int. Conf. on Problems of Automated Electric Drive Theory and Practice 9240830
[35] Khrebtova O, Shapoval A, Mos’pan D, Dragobetsky V, Gorbatyuk S and Markov O 2021 Automatic temperature control system for electrocontact annealing of steel welding wire. Metallurgist 65 (3–4)
[36] Zagirnyak M, Maliakova M and Kalinov A 2016 Analysis of operation of power components compensation systems at harmonic distortions of mains supply voltage Joint International Conference – ACEMP 2015: Aegean Conference on Electrical Machines and Power Electronics, OPTIM 2015: Optimization of Electrical and Electronic Equipment and ELECTROMOTION 2015: International Symposium on Advanced Electromechanical Motion Systems 355

[37] Haikova T, Puzyr R and Levchenko R 2020 Experimental Studies on the Stress-Strain State under Drawing Aluminum–Copper Bimetal Parts Rectangular in Plan Russian Journal of Non-Ferrous Metals 61 4 404–412

[38] Zagirnyak M, Zagirnyak V, Moloshpan D, Drahobetskyi V and Shapoval A 2019 A search for technologies implementing a high fighting efficiency of the multilayered elements of military equipment Eastern-European Journal of Enterprise Technologies 6/1 (102) 33–40

[39] Dragobetskii V, Savchenko I, Pavlenko O, Parschina E, Gurenko A and Markov O 2020 Comparative Assessment of Multilayer Waveguide Manufacturing Technologies Proceedings of the 25th IEEE International Conference on Problems of Automated Electric Drive. Theory and Practice 9240865

[40] Bogoboyashchii V and Inzhin I 2000 Mechanism for conversion of the type of conductivity in p-Hg1-xCdTe crystals upon bombardment by low-energy ions Russian Physics Journal 43 8 627–636

[41] Belas E, Bogoboyashchyy V, Grill R, Izhin I, Vlasov A and Yudenkov V 2003 Time relaxation of point defects in p- and n-(HgCd)Te after ion milling Journal of Electronic Materials 32 7

[42] Zagirnyak M, Prus V and Nikitina A 2006 Grounds for efficiency and prospect of the use of instantaneous power components in electric systems diagnostics Przeglad Elektrotechniczny 82 12 123–125

[43] Prus V, Nikitina A, Zagirnyak M and Miljavec D 2011 Research of energy processes in circuits containing iron in saturation condition Przeglad Elektrotechniczny 87 3 149-152

[44] Zagirnyak M, Mamchur D and Kalinov A 2012 Comparison of induction motor diagnostic methods based on spectra analysis of current and instantaneous power signals Przeglad Elektrotechniczny 88 12 221–224

[45] Zagirnyak M, Mamchur D and Kalinov A 2012 Induction motor diagnostic system based on spectra analysis of current and instantaneous power signals IEEE SOUTHEASTCON 2014 1

[46] LutsenkoI, Fomovskaya E, Oksanych I, Koval S and Serdiuk O 2017 Development of a verification method of estimated indicators for their use as an optimization criterion Eastern-European Journal of Enterprise Technologies 2 486 17-23

[47] Salenko Y, Puzyr R, Shevchenko O, Kulynych V and Pedun O 2020 Numerical Simulation of Local Plastic Deformations of a Cylindrical Workpiece of a Steel Wheel Rim Simulation and Manufacturing III. DSMIE 2020 1 442 – 451

[48] Use of Balanced Scorecard for Enterprise Competitiveness Assessment / S.O. Faizova, M.I. Ivanova, O.L Faizova, V.L. Smiesova, O.A. Parshyna, O.O. Zavorodorodnia. Journal of Advanced Research in Law and Economics, [S.l.], v. 11, n. 2, Pp. 349–361, mar. 2020. ISSN 2068-696X. Available at: <https://journals.aserspublishing.eu/jarle/article/view/5103>. Date accessed: 03 july 2020. doi: https://doi.org/10.14505/jarle.v11.2(48).08.

[49] Enterprise Competitiveness Management by Introducing Virtual Reality Technologies / Hanna Andrushchenko, Natalia Shandova, Zoriana Hbur, Nadiya Yavorska, Olena Parshyna / Academy of Strategic Management Journal / Print ISSN: 1544-1458; Online ISSN: 1939-6104 / 2019, Vol: 18 Issue: 1. (https://www.abacademies.org/articles/enterprise-competitiveness-management-by-introducing-virtual-reality-technologies-8715.html)