ISSUES OF INCREASING THE EFFICIENCY OF CYLINDRICAL GEAR GRINDING USING COPYING METHODS THROUGH A SYSTEMATIC APPROACH

Nariman Rasulov[1], Arastun Mammadov[2], Mursal Alakbarov[3],

Elgun Shabiyev[1], Yusif Huseynov[1]

•

[1]Department of Machine Building Technology, Azerbaijan Technical University, Baku, Azerbaijan
[2]Dean of Faculty of German Engineering, Azerbaijan Technical University, Baku, Azerbaijan
[3]Department of Oil and Gas Production, BP Exploration (Caspian Sea) Limited, Baku, Azerbaijan

nariman.rasulov@aztu.edu.az, arastun.mammadov@aztu.edu.az, mursal.alakbarov82@gmail.com, elgun@aztu.edu.az, yusif.huseynov@aztu.edu.az

Abstract

The paper presents a system analysis of gear grinding with copying of cylindrical gears, subsystems associated with the gear grinding system, as well as their inputs and outputs connections; both direct and indirect ways of increasing the efficiency of gear grinding are identified, based on the management of connections by hierarchical sequence vertically and by sources of quality indicators; includes the results of an indirect increase in efficiency due to the adoption of a reasonable value for the allowance for grinding, a direct increase due to a reduction in the number of working passes while ensuring the required quality during gear grinding and also the use of a methodology for forming threads by plastic deformation; the developed methodology is recommended for use in solving similar problems when forming surfaces using other methods.

Keywords: Copying, gear grinding, system analysis, efficiency, increasing, parameter, indirect, direct, methode

I. Introduction

There is no area of industry where gear transmissions are not used. At the same time, the demand for various technical devices with high precision and operational performance continuously increases in society. To improve the quality indicators of the working surfaces of gear teeth, as well as the operational characteristics of their engagement, tooth grinding by the copying method is widely used [1-5].

It is obvious that when forming any surface by the method of material removal, the expected technological support and results depend on the parameters of its previous surfaces, functionally related to it from both the design and technological points of view [1, 6-9]. Therefore, the highest technological and economic results of the process of grinding teeth by the copying method can be achieved by implementing various innovative measures based on the system analysis of this operation. System analysis of tooth grinding is the most rational methodological mechanism for identifying and managing both direct technological measures characteristic of this operation and indirect measures related to previous operations. In this context, increasing the quality and efficiency of tooth grinding by the copying method stands out for its relevance.

II. Statement of the Problem

Each technological operation, including tooth grinding with copying (TGC), special elements related to its implementation, other structural and technological elements related to it and preventing it, mechanisms of action and a complex of connections between them form a complex system [10-14]. Thus, in TGC, the material of the gear and the methods, tools, and workpiece used in the formation of its tooth profile, along with the processing of the tooth meshing surfaces, and the prevention of wear, are all part of a highly complex system, this includes the processing of rotational, keyseats, or spline surfaces, as well as thermal treatments, and involves a variety of constructive, technological, static, kinematic, and dynamic relationships, elements, and transformations. In the context of TGC, we can say that the upper system consists of the main operation, while the associated and preventive components form the subsystems. We can say that the upper system of TGC, and the associated or preventive components, are subsystems. Each technological parameter of the tooth grinding output is a manifestation of the transformations occurring in every component and structural element of the system. Therefore, to effectively address issues related to the quality and productivity of TGC, a systematic approach is required, considering all subsystems involved in ensuring its performance (Figure 1).

The purpose of the work is to conduct a systematic analysis of the formation of technological output parameters of the tooth grinding operation with copying, to develop and test direct and indirect methods for increasing the efficiency of the operation.

III. Methodology

A hierarchical diagram was developed based on the decomposition of the TGC technical production system, ensuring its integrity and emergent properties (Figure 1), when selecting key issues for increasing efficiency using hierarchical relationships, the system's constructiveness, orientation of component elements and their interrelationships, technological factors, and goal-directed characteristics were considered. These were studied at the micro level, taking into account the internal and interrelationships between lower and upper-level components (systems) and their interactions.

By means of system analysis it was established that the increase of efficiency of the TGC can be carried out both by direct and indirect measures (Figure 1). The essence of the indirect increasing of efficiency lies in the management of the impact on the current gear grinding process (referred to as the upper system) based on the inheritance principle of appropriate output parameters and technological results obtained in the precursor subsystems-technological processes for the gear wheel-workpliece to be ground. Thus, the positive results obtained in the upper system are only the cause and effect of the design and technological measures adopted in the subsystems.

It should be noted that in the existing literature [1, 6, 8], the impact of the quality of pre-processed surfaces on the quality parameters of the surface formed during the current operation or pass is associated with the inheritance principle and evaluated by a correction factor. Therefore, in this case, the management of the subsystems in the upper system, which is the TGC, to increase its efficiency through transformations in these subsystems should be systematically investigated, compared with direct efficiency improvement possibilities, evaluated, and a conclusion should be drawn.

The essence of directly increasing the efficiency of gear grinding for shaped surfaces involves increasing efficiency through changes, transformations, and management that are directly related to the upper system and executed within its elements. This includes increasing grinding quality and productivity by managing the gear grinding technological process, along with the technical and technological measures related to it. Thus, system analysis determines that direct improvement of TGC efficiency in gear grinding involves enhancing parameters such as: - accuracy of the teeth, surface roughness, and surface layer quality, as well as productivity, through measures specifically related to gear grinding. This can be achieved by automating and mechanizing the technological system's component elements. The systematic analysis of increaing gear grinding efficiency E(↑) can be carried out in two directions:

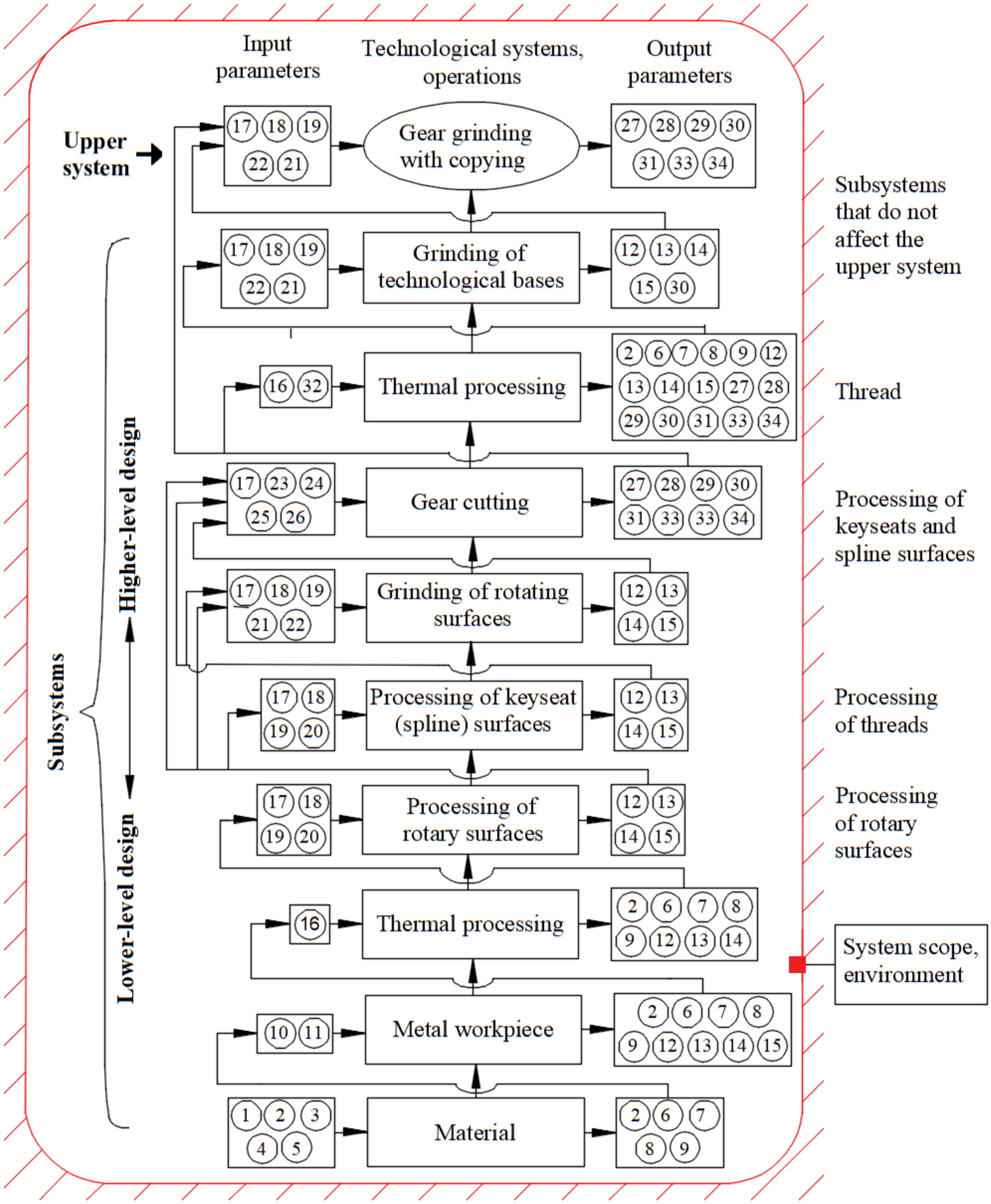

Figure 1: *System analysis of gear grinding in a hierarchical diagram*

1- Raw material, 2- Chemical elements (composition), 3- Formation method, 4- Forming conditions, 5- Environment, 6- Material structure, 7- Granularity, 8- Hardness of the material, 9- Material homogeneity, 10- Metal workpiece method, 11- Metal workpiece condition, 12- Dimensional and shape accuracy, 13- Accuracy of relative surface positions, 14- Surface roughness quality, 15- Surface layer quality, 16- Thermal processing conditions, 17- Layout scheme, 18- Processing method, 19- Cutting mode elements, 20- Cutting conditions, 21- Grinding wheel, 22- Grinding conditions, 23- Tooth cutting method, 24- Tooth cutting tool, 25- Tooth cutting mode, 26- Tooth cutting conditions, 27- Accuracy of the parameters of the diametrical dimensions, 28- Accuracy of parameters throughout the circumference, 29- Accuracy of the profile, 30- Accuracy of the circle relative to the base positioning surface (eccentricity), 31- Allowance for tooth grinding, 32- Thermal processing method, 33- Surface roughness quality of the profile, 34- Surface layer quality of the profile.

- Increasing of efficiency $E(\uparrow)$ through the management of possible sources for increasing quality or productivity, or both can be expressed by the formula:

$$E(\uparrow) => f(M_i, S_i, C_i, O_i) = \begin{cases} < M_1, M_2, M_3, M_4 > \\ < S_1, S_2, S_3, S_4 > \\ < C_1, C_2, C_3, C_4 > \\ < O_1, O_2, O_3, O_4 > \end{cases} \quad (1)$$

this can be expressed as follows. Here, i- represents the sequence number of the efficiency improvement sources, which may vary for different sources:

$M_1, \dots, M_4$– quality of the material,

$S_1, \dots, S_4$ – static technological relationships,

$C_1, \dots, C_4$ – relationships related to changes in shape, size, etc. of the design,

$O_1, \dots, O_4$ – auxiliary motion relationships that serve to change the form are efficiency increasing through the management of these elements at various stages (subsystems).

- Increasing of efficiency $E(\uparrow)$ according to the sequence of the hierarchical formation of the tooth grinding system. In this case:

$$E(\uparrow) => F_j(f(M_i, S_i, C_i, O_i)) = \begin{cases} < M_1, S_1, C_1, O_1 > \\ < M_2, S_2, C_2, O_2 > \\ < M_3, S_3, C_3, O_3 > \\ < M_4, S_4, C_4, O_4 > \end{cases} \quad (2)$$

this can be expressed as follows. Here, j- represents the sequence of hierarchical formation, which may vary for different parameters.

In the last statement, the distinction of the lower stage of teeth cutting is related to its special significance in the formation of the grinding substage and the multi-parameter tooth surfaces. In cases where the latter expressions are required, each subsystem can be represented separately and with a larger number of signifiers.

As a result of the conducted research and the system analysis of the process, the following directions for increasing the TGC efficiency are accepted:

- indirect through the provision of minimum and maximum allowances for the grinding process, based on both theoretical and experimental foundations accepted in machine engineering;
- direct by reducing the number of passes through the reduction of the actual cutting depth in tooth grinding, using the method developed at Azerbaijan Technical University (AzTU) [3, 14].

IV. Discussion

The following results of the TGC efficiency increasing experiments, based on the application of the developed methodology and the expressions (1) and (2), are discussed:

1. Ensuring the theoretical values of allowance factors for the grinding of teeth of cylindrical gears. The solution to the problem is based on the methodology accepted in machine engineering, science, and practice and is solved by considering the shape and alignment errors formed in the initial cutting stage (gear cutting), the alignment errors in the grinding area of the gear teeth, and the mechanisms affecting the allowance [2, 14]. However, the complexity of the problem arises from the fact that the parameters (errors) of the gears obtained from the cutting process are multi-parameter and repetitive according to the relevant standards. It is necessary to select and consider those parameters that have a decisive effect on the allowance, along with other analogous parameters. To do this, we categorize the standard parameter sets of the gear wheels in terms of their relationship with the allowance into four groups: (parameters with generalized relationships with the allowance; repetitive, complementary parameters specific to each gear for cutting and grinding, related to the allowance, mainly independent and random errors; parameters directly related to the formation of the allowance, non-repetitive individual indicators; parameters unrelated to the allowance).

After gear cutting and tooth grinding, analytical expressions have been derived to determine the minimum and maximum values of the grinding allowance, taking into account the characteristics of the formation of the teeth's quality parameters and the requirements for the quality of the teeth according to the standards.

Using the expressions developed and proposed for the grinding allowance (which are not presented here as they have been submitted to another journal), the grinding allowance for the teeth obtained with a 7th accuracy grade through gear cutting was calculated as follows: $2Z_{mini} = 0.28\ mm$; $2Z_{maxi} = 0.31$ mm;

In experiments conducted at the Sumqayit Technology Park, the values $2Z_{mini} = 0.28\ mm$; $2Z_{maxi} = 0.31$ mm; were accepted, and it was determined that the grinding quality has been ensured during the research.

2. Reducing the number of passes by decreasing the actual cutting depth using the method developed at AzTU. In gears with a modulus of m=4 mm, number of teeth z=40, a length of 25 mm, and made of steel 40XH, during the grinding of approximately vertically arranged teeth, it was determined that the actual total cutting depth was 1.75 times greater than the allowance (0.3 mm) at the top of the tooth, and 2.04 times greater at the start of the involute. When grinding the inclined tooth number 5, the actual total cutting depth decreases and is 1.36 and 1.47 times greater, respectively. Thus, grinding the of the inclined tooth ensures a reduction of the actual total cutting depth by $(2.04 - 1.47)Z = 0.57 \cdot 0.3 = 0.2\ mm$. In rough working passes, the radial feed is 0.1 mm. This allows for a reduction in the number of passes by one.

The increasing of the tooth grinding efficiency has been tested through experiments in two directions: grinding inclined teeth while maintaining the number of passes, and grinding inclined teeth while reducing the number of passes by one.

The grinding was performed on a Gleason Pfauter P400G model machine using the methodology accepted by the authors [12]. The three-pass grinding process consisted of two rough passes and one finish pass, with radial feeds of 0.18 mm for the first pass, 0.09 mm for the second pass, and 0.03 mm for the third pass.

The measurements and analysis showed that the accuracy parameters of the grinded surfaces, including tooth thickness, pitch, total normal length, diameter of the pitch circle, surface roughness parameters, microhardness, etc., were within the requirements for the part profiles in all cases and corresponded to the 7C accuracy grade according to GOST 1643-81.

For the tooth thicknesses, empirical distribution curves, constructed using the arithmetic average values obtained from at least three different measurements, are presented as m=F(fp) (where m is the number of measurements in each group on the empirical curve, plotted along the ordinate axis, and fp is the tooth thickness, plotted along the abscissa axis). The empirical distribution curves are shown in Figure 2. In the figure, the empirical distribution curves and histograms for the tooth thicknesses along the dividing circle of the grinded teeth are shown: with traditional grinding (curve 1), with the proposed method in a four-pass grinding process (curve 2), and with the proposed method in a three-pass grinding process (curve 3). The histograms and scatter centers of these curves have been marked as a1, a2 and a3, with their coordinates indicated.

Focusing only on the proposed method with a four-pass grinding process (curve 2), it can be noted that the smallest deviation in tooth thickness in the grinding process was $E_s = 29\ mkm$, and the scatter area of the deviations in tooth thickness has been accepted within 52 mkm. For the conventional method, the smallest deviation in tooth thickness during grinding was $E_s = 32\ mkm$, and the scatter area of the deviations in tooth thickness was 56 mkm. Overall, the closeness of the results is attributed to the high precision of the machine tool and the minimization of external factors affecting the results during the experiments. Furthermore, the mathematical expectation of the pitch a in the proposed grinding methods (a3 = 6.221 mm for four-pass; ; a2 = mm for three-pass) is closer to the high precision compared to the traditional grinding method (a1 = 6.220 mm). It seems that these positive aspects are related to the fact that the cutting conditions of the grinding process with the proposed method are more stable compared to the traditional method.

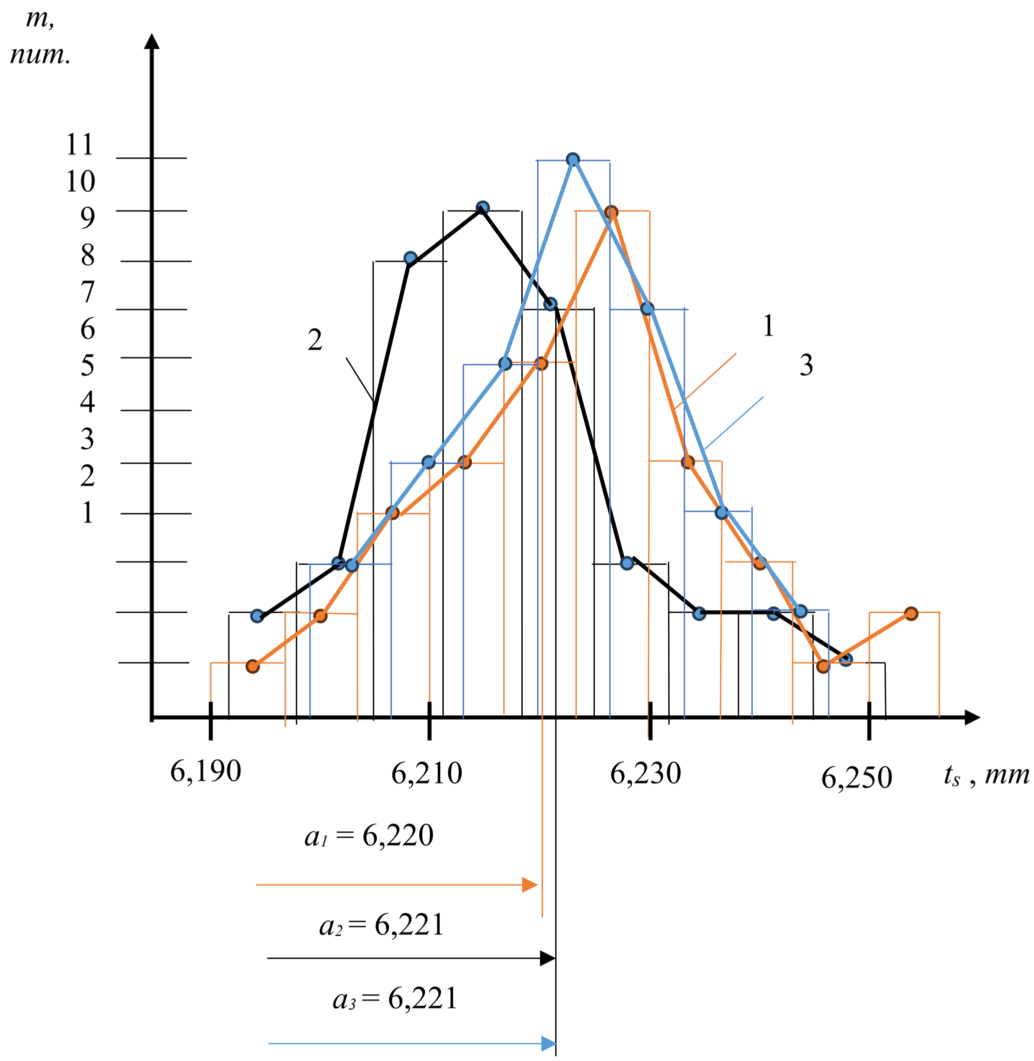

Figure 2: *Empirical curves of tooth thickness dispersion along the pitch circle for ground teeth: 1) traditional method, 2) proposed method (PM), four-pass processing, 3) PM, three-pass processing*

Thus, with the system analysis of the TGC process and the proposed systematic approach, the increasing of tooth grinding efficiency and the reduction of the tooth grinding time standard are achieved.

3. Increasing the efficiency of forming by plastic deformation of the material. By applying the methodology presented above, the processes of thread formation by plastic deformation of the material were studied, and it was determined that in the threading process with tangential rolling heads, the tool-workpiece contact area is large, resulting in higher rolling forces. As a result, problems arise in the threading of relatively long threads, as well as in the threading of pipes, when using tangential feed [15-17]. Through a systematic approach, the tool-workpiece contact area, and thus the rolling force, in tangential threading was controlled, which allows for increasing the efficiency of tangential threading and managing the technological capabilities of the tools, a method and means for tangential threading, enabling control of these factors, has been developed at the patent level.

V. Conclusions

1. A system analysis of tooth grinding with copying has been conducted, a methodology for increasing its efficiency with a systematic approach has been developed, and the sources of efficiency increasing and their management in the hierarchical formation sequence of the tooth grinding system have been determined, the directions of increasing efficiency in direct and indirect ways have been determined.

2. When grinding a tooth located inclinely in the grinding zone, a significant reduction in the actual cutting depth is ensured, when grinding the tooth number 5, located inclinely on gears with a module of 4 mm, a number of teeth of 40, a length of 25 mm and steel material 40XH, when four working passes are replaced by three passes, the quality of gear grinding is ensured by all parameters as an analogue of four-pass grinding, efficiency in terms of productivity increases.

3. The increasing of tooth grinding efficiency by in directly managing the share of pre-grinding allowance, as well as enhancement of the efficiency of threads formation using tangential rolling heads through the control of actual rolling force, is presented.

References

[1] DeGarmo's, Materials and Processes in Manufacturing, (2019). 13th Edition, J. T. Black, Ronald A. Kohser, Edition Wiley, ISBN: 978-1-119-49282-5, May 2019, 896. https://www.wiley.com/enus/DeGarmo's+Materials+and+Processes+in+Manufacturing%2C+13th+Edition-p-9781119492825

[2] Lishchenko N.V. Optimization of profile gear grinding on a CNC machine and an allowance measurement system / N.V. Lishchenko, V.P. Larshin, V.V. Nezhebovsky // High technologies in mechanical engineering: zb. Sci. fuck off. - Kharkiv, NTU "KhPI", 2016. - Vip.1 (26). — P. 50 — 61 (in Russian). https://repository.kpi.kharkov.ua/handle/KhPI-Press/25662

[3] Nariman Rasulov, Elgun Shabiyev, Gulbaniz Damirova, Mursal Alakbarov, Yusif Huseynov. Increasing the Efficiency of Forming Complex Rotating Surfaces with the Controlling of Technological Connections, Key Engineering Materials, ISSN: 1662-9795, 2024, Vol. 979, pp 55-62, https://doi.org/10.4028/p-jc7ovu

[4] Rasulov, N.M., Alekberov, M.Z., Nadirov, U.M. More Efficient Copy Grinding of Complex Surface. Russ. Engin. Res. 41, 829-831 (2021).
https://link.springer.com/article/10.3103/S1068798X21090227

[5] Rikard Hjelm, Linus Everlid, Ellen Bergseth, Florian Reinle, Boris Brodmann, Minghui Tu, Lucas Bard, Jens Wahlström. A multi-perspective method for gear efficiency and contact analysis. Results in Engineering Vol. 20, December 2023, 101582. https://doi.org/10.1016/j.rineng.2023.101582

[6] V.I. Averchenkov, A.S. Vasiliev, M.L. Heifetz. Technological heredity at quality formation of parts manufactured. «Science intensive technologies in mechanical engineering», No10, 2018. No. 10 (88), p. 27-32, DOI: 10.30987/article_5bb4b1fa81a7f8.26650961.
https://naukaru.ru/ru/nauka/article/23024/view

[7] Rasulov, N.M., Nadirov, U.M., Alekberov, M.Z. Generalized Assessment of Machined Surfaces Quality. Russ. Engin. Res. 40, 822-825 (2020).
https://link.springer.com/article/10.3103/S1068798X20100202

[8] Safarov D.T., Kondrashov A.G. Reduction of errors in the profile of the teeth of gears in the processes of gear milling with worm cutters. Fundamental and Applied Problems of Engineering and Technology. No. 3 (347) 2021, p. 63-72. D.T. Safarov/ (in Russian). DOI: 10.33979/2073-7408-2021-347-3-63-72. https://www.researchgate.net/publication/353527897

[9] Shipulin, L.V., Yusubov, N.D., Frolov, A.A. (2023). Study of the Microrelief Obtained During Single Abrasive Grain Cutting. In: Radionov, A.A., Gasiyarov, V.R. (eds) Proceedings of the 8th International Conference on Industrial Engineering. ICIE 2022. Lecture Notes in Mechanical Engineering. Springer, Cham. https://doi.org/10.1007/978-3-031-14125-6_97

[10] Alan Dennis, Barbara Haley Wixom, Roberta M. Roth, Systems Analysis and Design, John Wiley & Sons, 2014 M11 11 - 448 p.

https://books.google.az/books/about/Systems_Analysis_and_Design.html?id=PxZ6oAEACAAJ&redir_esc=y

[11] Mahbubur Rahman Syed, Sharifun Nessa Syed, Handbook of Research on Modern Systems Analysis and Design Technologies and Applications, DOI: 10.4018/978-1-59904-887-1, 2009, 698 p. https://www.igi-global.com/book/handbook-research-modern-systems-analysis/490

[12] N.M. Rasulov, U.M. Nadirov, M. Z. Alakbarov, Improving the efficiency of grinding teeth by copying with the control of dynamic technological connections. / SOCAR Proceedings. Special Issue 1 (2022) 029-035. DOI: 10.5510/OGP2022SI100697. https://proceedings.socar.az/en/journal/85

[13] Dalsky A.M., Bazrov B.M., Vasiliev A.S. and others - Technological heredity in mechanical engineering // Ed. A.M. Dalsky. Scientific publication. - M.: MAI Publishing House, 2000. - 364 p. https://disk.yandex.ru/i/GlqimQ

[14] N.M. Rasulov, E.T. Shabiev. Increasing the efficiency of grinding gear teeth using the copying method based on controlling the depth of cut. News of Mechanical Engineering Universities, MSTU named after N. E. Bauman, 2017, No. 2, 90-97. DOI 10.18698/0536-1044-2017-2-90- 97. (in Russian). https://izvuzmash.bmstu.ru/eng/catalog/tpmachines/hidden/1398.html

[15] Afonin A.N. Increasing the efficiency of thread rolling. Auto. dis. on sois. uch. Art. Doctor of Technical Sciences according to special 02/05/07., Orel-2010.-34 p.
https://rusneb.ru/catalog/000199_000009_004610263/?ysclid=lqxxwjb1bl615980626

[16] N. M. Rasulov, G. V. Damirova, İ. A. Abbasova, Y. E. Huseynov. Improving the efficiency of thread rolling with management of technological connections. / SOCAR Proceedings. Special Issue 1 (2022) 011-015. DOI: 10.5510/OGP2022SI100694. https://proceedings.socar.az/en/journal/85

[17] S. Zhang, S. Fan, Q. Wang, et al. Deformation characteristics of self-infeed rolling process for thread shaft. Int J Adv Manuf Technol, 103 (5-8) (2019), pp. 2941-2951; https://link.springer.com/article/10.1007/s00170-019-03677-3