Optimization of the Cutting Process Based on Thermophysical Characteristics

Serhii Zelynskyi, Gennadii Oborskyi, Volodymyr Tonkonogyi, and Maryna Holofieieva(✉)

Odessa Polytechnic National University, 1, Shevchenko Avenue, Odessa 65044, Ukraine
mgolofeyeva@gmail.com

Abstract. In the energy sector, aviation, and other branches of modern mechanical engineering, complex-profile parts are used to determine the entire product's technical and operational properties. In manufacturing such parts, modern structural materials are often used with high strength and heat resistance, which classifies them as difficult to machine. End mills allow the processing of such parts on CNC machines. At the same time, the processing time of one product can reach tens of hours. Despite the use of wear-resistant coatings, because of wear, the end mill has to be changed repeatedly, which reduces productivity and quality of manufacturing. In conditions of high-speed machining, it is essential to have an effective technique based on which you can quickly determine the optimal cutting speed. In the presented work, the optimal conditions are investigated for the temperature field distribution between the part's material and the tool in terms of tool wear. For this purpose, the dependences of specific heat capacity and thermal conductivity on temperature were analyzed. These dependencies have a pronounced extremal character with a maximum for the heat capacity and a minimum for the thermal conductivity. According to the authors, this explains the effect of the optimal cutting temperature, characterized by the minimum intensity of tool wear. The optimal cutting temperature and the corresponding optimal cutting speed were determined by the material being processed heating temperature, at which its specific heat capacity reaches its maximum value.

Keywords: Optimal cutting speed · Cutting temperature · Temperature field distribution · Sustainable manufacturing

1 Introduction

Scientific and technological progress in mechanical engineering requires using new materials with special properties. These materials have increased strength characteristics, high thermal stability, and corrosion resistance [1]. This applies to parts of the power industry and the aircraft industry (e.g., turbine blades, unicycles) that have a complex geometric shape, the processing of which, as a rule, occurs with end mills on CNC machines [2].

In manufacturing such highly loaded aircraft products, much attention is paid to the geometric parameters and parameters of the state of the surface layer, which determine

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the quality of processing. Achieving high quality and productivity in modern conditions of digital products can only be ensured by ensuring optimal processing conditions, including cutting conditions [3].

The processing time of such parts on CNC milling machines can reach tens and hundreds of hours. At the same time, despite the presence of wear-resistant coatings, the wear of end mills can be so intense that the replacement or regrinding of the tool must be carried out several times during the processing of one part, which reduces the economic efficiency and quality of processing of such parts. Therefore, optimizing cutting conditions to achieve maximum tool life is relevant [2].

2 Literature Review

The contour milling is often the final form of surface shaping, where the specified geometric accuracy and surface roughness are provided, and residual stresses are formed that affect the technological deformations of parts. During end milling, the surface layer of parts is formed under the influence of force and temperature fields. Consequently, stable provision during milling of the parameters specified by the technical requirements for the operation, which are required for the quality of processing, especially for parts with a complex profile, such as blades, can be achieved by choosing rational cutting modes that affect the functional parameters of the process [4].

When processing such parts, end mills of small diameters with wear-resistant coatings are usually used, capable of operating in the operating temperature range of 973–1373 K, which corresponds to the temperature range for high-speed machining conditions [5].

As is known, of all cutting modes, the cutting speed has the most significant influence on the wear rate of the tool [6]. The dependence of the tool wear intensity on the cutting speed has a pronounced extreme character with a very narrow range of optimal cutting speeds. Determining the optimal cutting speed values is associated with labor-intensive tool life tests. The extreme character of such dependence has been known for a long time. However, an unambiguous explanation of this phenomenon based on the thermal physics of the cutting process has not yet existed [7].

The practical significance of studying this issue is essential for the following reasons: for parts with complex geometric surfaces, high requirements are imposed on the initial characteristics of the quality of the surface layer (roughness, depth and degree of hardening, level, and stability of residual stresses), which affect the performance of parts, fatigue strength, corrosion resistance. Processing on a CNC milling machine is often a finishing operation for such parts. There are close relationships between the wear parameters of the cutter and the quality indicators of the surface layer of parts [8, 9].

The problem of optimizing the cutting process during machining [10], the physics of cutting tool wear, considering thermophysical phenomena [11], is the subject of many works by scientists from many countries. The practical goal of these studies was to optimize cutting conditions, which provides the tool's lowest wear rate and, as a result, its maximum durability [12].

The prevailing direction of well-known works was associated with the need to test the tool for resistance by various methods [13, 14]. Despite the development of various, including accelerated methods for studying resistance, their common drawback is the performance of labor-intensive, expensive, and lengthy experimental studies [15].

One of the most progressive approaches to the practical optimization of cutting speed are methods that use the position of the constancy of the optimal cutting temperature, which is of great scientific and practical importance. As shown in [16], the optimal cutting temperature is a stable value when processing the same material and does not depend on the tool's and the workpiece's geometric parameters.

In the well-known works of scientists, the thermophysical nature of the existence of the optimal cutting temperature and the phenomena that occur when using it, providing the lowest wear rate of the tool, improving the quality of the surface layer, the occurrence of a "dip in plasticity" of the material being processed, and reducing the specific cutting energy, have not yet been explained [17].

3 Research Methodology

To explain the thermophysical phenomena during processing at the optimum temperature, an analysis was made for heat transfer between the part and the tool [18].

From the standpoint of thermal physics, it can be assumed that when machining at the optimum temperature [19], conditions are created that contribute to the best distribution of cutting heat between the workpiece and the tool, considering the effect of temperature on thermal resistance material characteristics.

As is known, according to the heat balance equation [20]:

$$Q = Q_c + Q_w + Q_t + Q_e \tag{1}$$

where Q – the total amount of heat during cutting; Q_c – heat escaping into chips; Q_w – heat absorbed by the workpiece; Q_t – heat absorbed by the tool; Q_e – heat leaving the environment.

The best will be the conditions under which $Q_w + Q_c$ will be maximum, and Q_t will be minimum. The amount of heat, and hence the cutting temperature, is determined by a set of parameters: the type of blade processing, the physical and mechanical characteristics of the processed and tool materials, tool geometry, cutting conditions, and others.

Obviously, for specific processing conditions, the heat balance and heat transfer conditions will be determined by the energy parameters of the cutting process and the thermophysical characteristics of the processed and tool materials. When analyzing various thermophysical characteristics of materials from temperature, the most significant interest in thermal field control is the heat capacity and thermal conductivity of the material being processed. This can be explained by the fact that the dependences of thermal conductivity and heat capacity on temperature are of a pronounced extreme nature, which was taken as a hypothesis to explain the existence of an optimal cutting temperature.

Based on the previous, the problem is reduced to finding the cutting temperature at which the optimal combination of specific heat capacity and thermal conductivity coefficient of the processed material is achieved.

Thermal conductivity characterizes heat transfer due to the energy interaction of microparticles (molecules, atoms, electrons). The thermal conductivity of a material, which is usually given by the coefficient of thermal conductivity λ ($W\ m^{-1}.K^{-1}$), characterizes the ability to conduct heat. The specific heat capacity C_p ($J\ kg^{-1}.K^{-1}$), characterizes the ability of the material to absorb the heat transferred to the body [21].

Optimal conditions are under which the best indicators of workpiece material machinability and tool wear resistance are simultaneously achieved [22]. These are conditions under which the maximum amount of heat will be locally concentrated in the cutting zone of the material being processed, contributing to its "softening" and decompression of crystalline bonds and the ability to transfer this heat into the tool material will be the worst. This condition, based on the physical meaning of the specific heat capacity C_p and the thermal conductivity coefficient λ, can be formulated as:

$$Optimum \Rightarrow \left\{ \frac{C_p = C_p \max}{\lambda = \lambda \min} \right\} \quad (2)$$

This condition, from the standpoint of the optimal combination of thermophysical characteristics of the processed material, can be written:

$$\left\{ \frac{C_p = C_{\max}}{\lambda = \lambda_{\min}} \right. \quad (3)$$

The experimentally obtained dependencies of the specific heat capacity and the thermal conductivity coefficient of pure iron on temperature were analyzed.

Figure 1 shows the temperature dependence of the specific heat capacity $C_p = f(\theta)$ of pure iron, constructed according to the data of [22], from which a maximum specific heat capacity at a certain temperature is clearly defined seen.

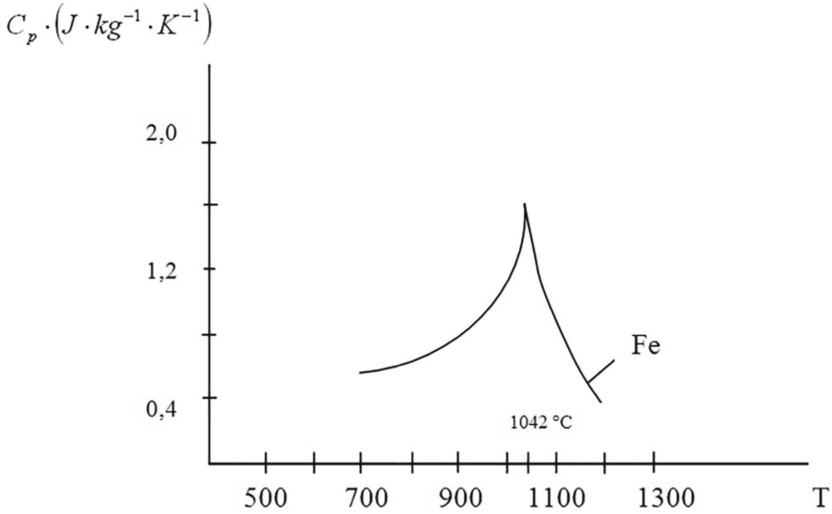

Fig. 1. Temperature dependence of the specific heat capacity of iron.

Since the basis of all steel is iron, the temperature dependencies on the heat capacity of the absolute majority of various grades of steel and alloys have a similar, extreme character [7].

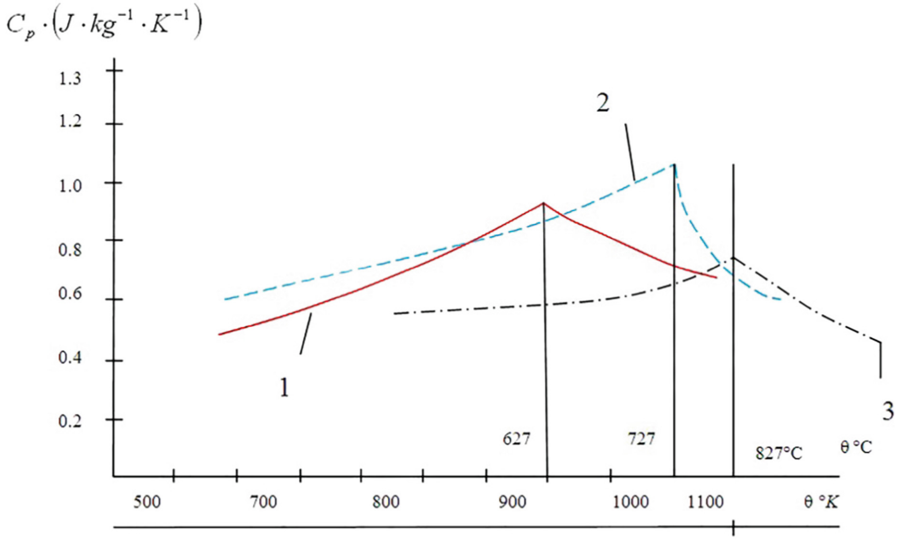

Fig. 2. Temperature dependence of the heat capacity of steels 1 – carbon steel; 2 – high-alloy steel AIS1446; 3 – low-alloy steel.

The temperature at which the maximum value of the specific heat capacity Cpmax is reached on the temperature dependence Cp = f (θ) corresponds to such a state of the processed material, which contributes to the absorption of heat to the greatest extent.

The minimum value of the thermal conductivity coefficient λmin on the temperature dependence λ = f (θ) corresponds to the best conditions for heat concentration from the cutting zone in the material being processed. For example, Fig. 3 shows the temperature dependence of the heat capacity Cp = f (θ) and thermal conductivity λ = f (θ) for steel 40 (carbon steel). The similar extreme nature of these dependencies is also characteristic of other steel grades. Moreover, for hard-to-cut materials, the extremeness of these dependencies is more pronounced.

However, the temperature at which $C_p = C_{max}$ and the temperature at which $\lambda = \lambda_{min}$ most often do not coincide. In connection with the above, the optimum cutting temperature should be in the range of these temperatures. Moreover, the smaller the value of this temperature range, the stronger the effect of processing with the optimum cutting temperature, characterized by a minimum intensity of tool wear, a «dip in plasticity» of the material being processed, and other phenomena.

As can be seen from the comparison of graphs of temperature dependences $C_p = f(\theta)$ and $\lambda = f(\theta)$ (Fig. 3), the dependence of specific heat on temperature has a more pronounced extremum than the dependence of thermal conductivity. This suggests that the heat capacity has a more significant influence on the effect of "ductility dip" than the coefficient of thermal conductivity by influencing the local cutting temperature.

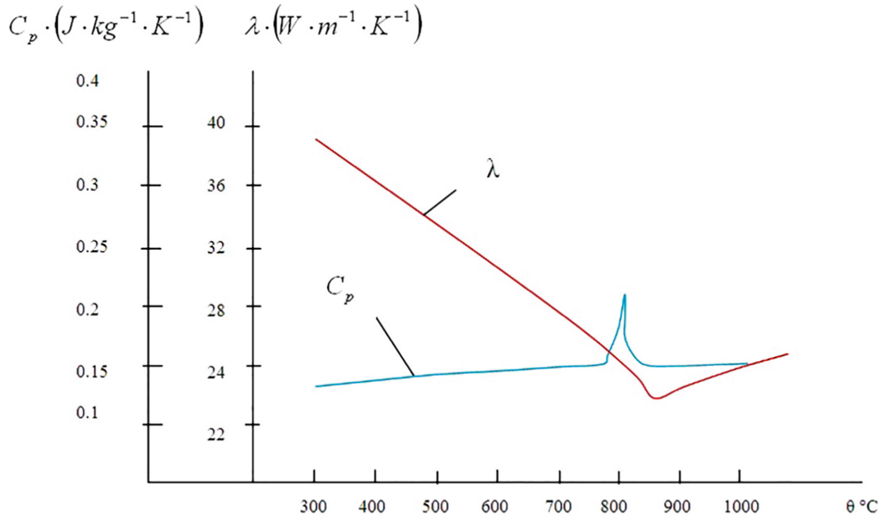

Fig. 3. Temperature dependence of heat capacity $C_p = f(\theta)$ and thermal conductivity $\lambda = f(\theta)$ for steel 40X.

The latter assumption is also confirmed by the well-known Cronenberg [20] dimensional ratio, which shows the relationship between the cutting temperature θ and the energy parameters of the cutting process, taking into account the thermophysical characteristics of the material being processed:

$$\theta = \frac{C_0 U_8 \cdot V^{0.44} \cdot A^{0.22}}{\lambda^{0.44} \cdot C_p^{0.56}} \tag{4}$$

where θ - cutting temperature; U8 – specific cutting energy; V – cutting speed; A – the cut area; λ – thermal conductivity of the processed material; Cp is the heat capacity of the processed material.

The more significant influence of the heat capacity of the machined material on the cutting temperature is confirmed by the greater value of the exponents at C_p than at λ. Based on the foregoing, we can conclude that the optimal cutting temperature can be determined by the heating temperature of the processed material at maximum heat capacity.

4 Results and Discussion

To implement the proposed method under production conditions, the optimal cutting speed can be determined by the heating temperature of the material being processed, at which the specific heat capacity is maximum.

The method is carried out as follows:

1. When cutting the material under study, the dependence of the cutting temperature on the cutting speed is plotted $T = f(V)$

2. To determine the dependence of the specific heat of the material on the temperature of its heating by one of the known methods and build a graph of dependence of Cp $= f(\theta)$.
3. The optimal cutting speed is determined according to the graph $T = f(V)$ according to the temperature at which the specific heat capacity takes on a maximum value.

This method of determining the optimal cutting speed makes it possible to exclude the cutting tool's labor-intensive and rather expensive resistance tests to determine the optimal speed when machining new high-strength materials and alloys. This is especially true when milling complex-profile parts on CNC machines in modern conditions of high-speed cutting.

The correlation of temperatures corresponding to the extreme values of the dependences $C_p = f(273\ K)$ and $\lambda = \varphi(273\ K)$ with the experimentally determined optimal cutting temperatures is shown in Fig. 4 when milling iron and steel.

Figure 4 shows that when turning "pure" iron with a cutter made of P20 carbide, the plasticity and hardness of the machined material on minimum values and internal stresses

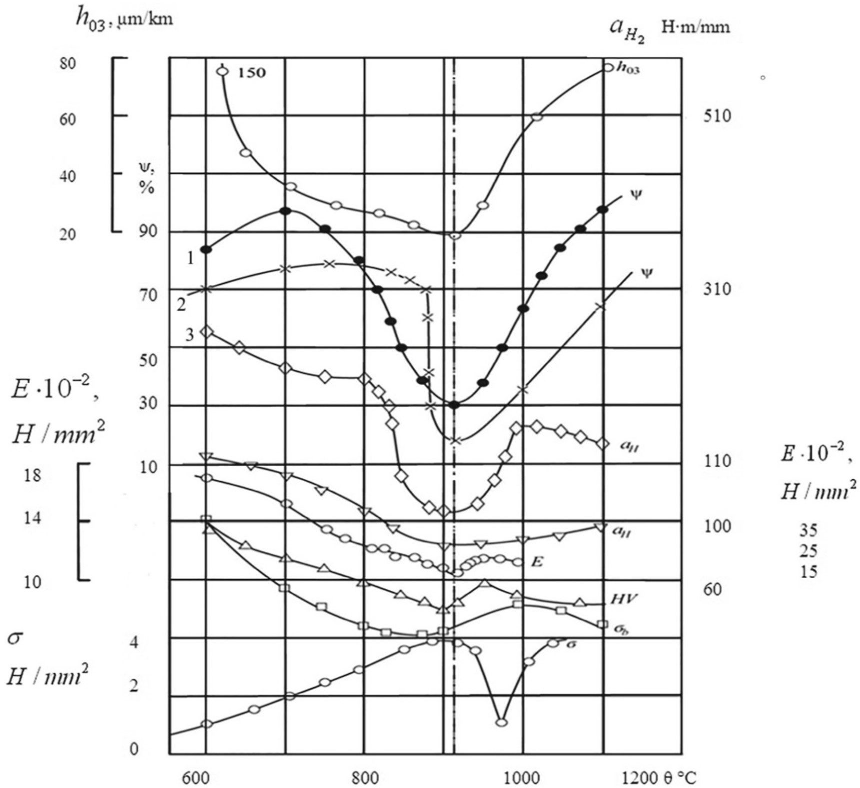

Fig. 4. The effect of temperature on the mechanical properties of technical iron and the wear rate of the cutter made of P20 carbide when turning a part made of steel. 1 - deformed iron; 2 - cast iron; 3 - pure iron (99.99%).

are maximum at the same temperature (1160 K). At the same temperature, the minimum intensity of cutter wear is achieved. As can be seen from the graph, the indicated temperature lies in the temperature range between the temperatures that correspond to $C_p = C_{pmax}$ and $\lambda = \lambda_{min}$. This confirms the conclusion that the temperature between C_p and λ creates a cumulative effect of thermophysical and mechanical conditions under which the tool wear rate is minimal.

5 Conclusions

The conditions for the optimal temperature field distribution between the tool and the workpiece during edge processing are formalized, taking into account the relationship between the thermophysical parameters of the material and temperature.

The extremal nature of the temperature dependencies of the specific heat capacity and thermal conductivity coefficient is shown with a maximum for the specific heat capacity and a minimum for the thermal conductivity coefficient, using the example of pure iron.

A method is proposed for determining the optimal cutting speed by the optimal cutting temperature, defined as the heating temperature of the processed material, at which its specific heat capacity has a maximum value.

The implementation of the proposed method makes it possible to determine the optimal cutting speed for high-speed machining of new hard-to-cut materials without the need for laborious durability tests, which makes it possible to reduce the complexity of determining the optimal cutting speed by 1.5–2.5 times, which will increase the cutting tool life in production conditions. 1.2–1.3 times, as well as the quality of the machined parts.

In the future, it is planned to search for optimal combinations of processed and tool materials in terms of the optimal combination of their thermophysical characteristics, as well as the creation of a database values the specific heat capacity of materials versus temperature, which will simplify the implementation of the method in production conditions.

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References

1. Klimenko, S.A.: Superhard Materials. Obtaining and application: In 6 Volumes, vol. 5: Processing of Materials with a Blade Tool. Bakul ISM, Kyiv (2006)
2. Hochrainer, T., et al.: An integrated approach to the modeling of size-effects in machining with geometrically defined cutting edges. In: Proc. of 8th CIRP International Workshop on Modeling of Machining Operations, pp. 123−130 (2005)
3. Pasko, N.I.: Generalized Stochastic Model of Cutter Failures and Its Application. Publishing House of Tula, Tula (2016)
4. Wang, Z., Nakashima, S., Larson, M.: Energy efficient machining of titanium alloys by controlling cutting temperature and vibration. Procedia CIRP **17**, 523–528 (2014). https://doi.org/10.1016/j.procir.2014.01.134

5. Huang, P., et al.: Milling force vibration analysis in high-speed-milling titanium alloy using variable pitch angle mill. Int. J. Adv. Manuf. Technol. **58**, 153–160 (2012). https://doi.org/10.1007/s00170-011-3380-9
6. Fu, Z., Yang, W., Wang, X., Leopold, J.: An analytical force model for ball-end milling based on a predictive machining theory considering cutter runout. Int. J. Adv. Manuf. Technol. **84**(9–12), 2449–2460 (2015). https://doi.org/10.1007/s00170-015-7888-2
7. Shin, Y.C., Dandekar, C.: Mechanics and modeling of chip formation in machining of MMC. In: Davim, JPaulo (ed.) Machining of Metal Matrix Composites, pp. 1–49. Springer, London (2012). https://doi.org/10.1007/978-0-85729-938-3_1
8. Balogun, V.A., Edem, I.F., Mativenga, P.T.: Specific energy based characterization of tool specific energy based characterization of tool. Int. J. Sci. Eng. Res. **6**, 1674–1680 (2015)
9. Kostyk, K., et al.: Simulation of diffusion processes in chemical and thermal processing of machine parts. Processes **9**(4), 698 (2021). https://doi.org/10.3390/pr9040698
10. Shvets, S.V., Machado, J.: Numerical model of cutting tool blade wear. J. Eng. Sci. **8**(2), A1–A5 (2021). https://doi.org/10.21272/jes.2021.8(2).a1
11. Usov, A., Tonkonogyi, V., Dašic, P., Rybak, O.: Modelling of temperature field and stress-strain state of the workpiece with plasma coatings during surface grinding. Machines **7**(1), 20 (2019). https://doi.org/10.3390/machines7010020
12. Zhou, F., Wang, X., Hu, Y., Ling, L.: Modeling temperature of non-equidistant primary shear zone in metal cutting. Int. J. Therm. Sci. **73**, 38–45 (2013)
13. Qing, Z., Song, Z., Jianfeng, L.: Three dimensional finite element simulation of cutting forces and cutting temperature in hard milling of AISI H13 steel. Procedia Manuf. **10**, 37–47 (2017). https://doi.org/10.1016/j.promfg.2017.07.018
14. Ivanov, V., Pavlenko, I., Kuric, I., Kosov, M.: Mathematical modeling and numerical simulation of fixtures for fork-type parts manufacturing. In: Knapčíková, L., Balog, M. (eds.) Industry 4.0: Trends in Management of Intelligent Manufacturing Systems. EICC, pp. 133–142. Springer, Cham (2019). https://doi.org/10.1007/978-3-030-14011-3_12
15. Liu, W.W., Wang, D.F., Li, F., Chen, H., Wang, C.Z.: Research on milling parameters optimization based on surface residual stress for aviation stainless steel. Appl. Mech. Mater. **526**, 3–8 (2013). https://doi.org/10.4028/www.scientific.net/AMM.526.3
16. Makarov, A.D.: Optimization of Cutting Processes. Mechanical engineering, Moscow (1976)
17. Oborsky, G.O., Usov, A.V.: Influence of thermophysical phenomena on the dynamic stability of the cutting process. New Materials and Technologies in Metallurgy and Machine-Building. Sciences Magazine **14**(1), 36−41 (2014). https://doi.org/10.21062/ujep/x.2014/a/1213-2489/MT/14/1/36
18. Loveday, M.S.: Consideration of High Temperature Friction Measurement Uncertainty. CMMT(NH)070. http://resourse.npl.co.uk/cgi-bin/download (2000). Last Accessed 02 Jul 2022
19. Zhao, Z., Qian, N., Ding, W., Wang, Y., Fu, Y.: Profile grinding of DZ125 nickel-based superalloy: grinding heat, temperature field, and surface quality. J. Manuf. Process. **57**, 10–22 (2020)
20. Armarego, E.J.A., Brown, R.H.: The Machining of Metals. Prentice-Hall. Inc. (1969)
21. Yakimov, O.V., Usov, A.V., Slobodyanik, P.T., Iorgachev, D.V.: Thermophysics of Mechanical Processing. Astroprint, Odessa (2000)
22. Larikov, L.N., Yurchenko, Yu, F.: Thermal Properties of Metals and Alloys. Directory. Scientific Thought, Kyiv (2005)