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Modelling and Multi-objective Optimization of Elastic Abrasive Cutting of C45 and 42Cr4 Steels

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Elastic abrasive cutting is a new high-performance method to produce workpieces made of materials of different hardness, which ensures lower wear of cut-off wheels and higher quality machined surfaces. However, the literature referring to elastic abrasive cutting is scarce; additional studies are thus needed. This paper proposes a new approach for modelling and optimizing the elastic abrasive cutting process, reflecting the specifics of its particular implementation. A generalized utility function has been chosen as an optimization parameter. It appears as a complex indicator characterizing the response variables of the elastic abrasive cutting process. The proposed approach has been applied to determine the optimum conditions of elastic abrasive cutting of C45 and 42Cr4 steels. To solve the optimization problem, a model of the generalized utility function reflecting the complex influence of the elastic abrasive cutting conditions has been developed. It is based on the findings of the complex study and modelling of the response variables of the elastic abrasive cutting process (cut-off wheel wear, time per cut, cut piece temperature, cut off wheel temperature and workpiece temperature) depending on the conditions of its implementation (compression force F exerted by the cut-off wheel on the workpiece, workpiece rotational frequency n_w*, cut off wheel diameter* d_s*). By applying a genetic algorithm, the optimal conditions of elastic abrasive cutting of C45 and 42Cr4 steels:* d_s *= 120 mm; F = 1 daN;* n_w *= 63.7 min*$^{-1}$ *and* n_w *= 49.9 min*$^{-1}$*, respectively for C45 and 42Cr4 steels, have been determined. They provide the best match between the response variables of the elastic abrasive cutting process.*
Keywords: elastic abrasive cutting; multi-objective optimization; generalized utility function; C45 and 42Cr4 steels

Highlights

- *A new approach to modelling and multipurpose optimization of elastic abrasive cutting based on a generalized utility function has been performed.*
- *Regression models for the elastic abrasive cutting response variables depending on the cutting conditions have been built.*
- *A model of the generalized utility function as a complex indicator characterizing the response variables of the elastic abrasive cutting process has been developed.*
- *By applying a genetic algorithm, the optimum conditions of elastic abrasive cutting of C45 and 42Cr4 steels, under which the generalized utility function has a maximum, have been determined.*
- *The proposed multipurpose optimization approach ensures the best match between the response variables of the elastic abrasive cutting process.*

0 INTRODUCTION

Abrasive cutting is a high-performance, cost-effective method widely used in present-day manufacturing environments to produce workpieces made of ferrous and non-ferrous metals and alloys, and non-metallic materials of high hardness. This is a complex and varied process performed under different kinematic schema; the cut-off wheel has two motions: main rotation and radial feed [1] to [3]. The radial feed of the tool is ensured either by the cut-off machine in a kinematic way (hard abrasive cutting) or by maintaining a constant compression force F exerted by the wheel on the workpiece (elastic abrasive cutting) [4]. The workpiece is motionless, performs an oscillatory motion or rotates at a constant rotational frequency n_w.

During elastic abrasive cutting (Fig. 1), the contact arc length L and the thickness h of the layer being cut vary, while the instantaneous cross-section area of the layer being cut remains constant. The introduction of rotary motion of the workpiece leads to a decrease in the working stroke of the cut-off wheel, which ensures shorter time per cut and a wear reduction of abrasive wheels. At the same time, the tool lifetime, process production rate, cutting forces, power rate, and temperature depend on the compression force F, workpiece rotational frequency n_w, cut off wheel diameter d_s and the type of material being machined. This makes the schema for elastic abrasive cutting a topical subject of study and optimization.

The abrasive cutting process is a sophisticated multi-parameter and multi-factor subject of study, modelling, and optimization. It is characterized by a number of target parameters, each having a specific meaning yet insufficient for its optimum control. On the one hand, abrasive cutting is distinguished by its high performance, universality and low cost. On

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the other hand, the process is accompanied by high temperatures (above 1000 °C) in the cutting zone, which, in turn, results in intensive cut-off wheel wear, deterioration of the tool cutting ability, changes in the microstructure of the material being machined and the occurrence of thermal flaws [5] to [7].

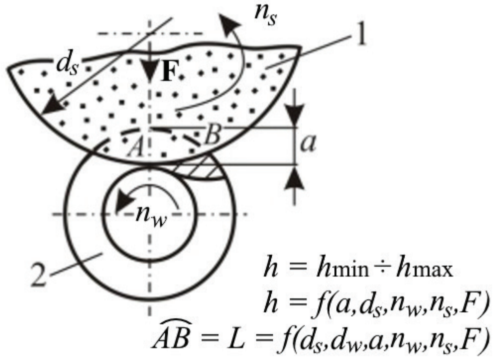

Fig. 1. *Schema of elastic abrasive cutting; 1 cut- off wheel; 2 workpiece*

The response variables of the abrasive cutting process are determined by numerous control factors: the physio-mechanical properties of the materials being machined, cutting mode components, cut-off wheel type and characteristics, type and way of supplying cooling fluids, etc. They are described in several publications.

Lopes et al. [8] studied the abrasive cut-off operation of low and medium carbon steels, using aluminium oxide discs of different feed rates. They monitored the cutting power, disc wear, and process temperature and established that an increase of 130 % in feed rate led to a decrease of approximately 57 % in maximum temperature and 84 % in diametrical wheel wear, thus improving process efficiency, but also to an increase of consumed cutting power by up to 127 %. A simulation model of high accuracy for predicting temperature was proposed that could be applied to predict and prevent thermal damages.

Luo et al. [9] studied the characteristics and wear modes of diamond grits in the cut-off grinding BK7 glass using thin diamond wheels, as well as the grinding forces, the grinding ratio, the width of cut, the straightness of cut and chipping produced during the cut-off grinding. The results showed that at a lower transverse velocity, a freer cutting ability, a better grinding ratio and a better straightness of cut were obtained. An increase of the transverse velocity led to diamond wheel wear accompanied by some macro-breakage and flattening of the tool work surface, thus resulting in unstable grinding forces, a low grinding ratio and poor straightness of cut.

Neugebauer et al. [2] studied the wear of cut-off wheels with different abrasive grains in the abrasive cutting of structural and stainless steels. They established that cubical grits were distinguished by the most extended lifetime compared to splinter-shaped grits due to their higher toughness and adhesion to the bond. By comparing the cutting performance of discs with different compositions in dry cutting of steel bars, Ortega et al. [10] observed that the abrasive type and size and disc binder were the most influential factors. On the basis of the results obtained, they concluded that discs with high grit size and protrusion, high grit retention by bond material, and closer mesh of fibreglass matrix binder were the optimal solution for abrasive cutting of mild steel parts. Riga and Scott [11] established the decisive influence of the type and composition of the cut-off wheel bond on the mechanical properties and nature of abrasive tool wear. The significant impact of the chemical composition and mechanical properties of the material being machined, the type and size of abrasive grains, the hardness of cut-off wheel and the cutting conditions (cut-off wheel speed and feed speed) on cut-off wheel wear was confirmed by the mathematical model developed by Yoshida et al. [12].

Ojolo et al. [13] found that the grinding/wear ratio and cutting time depended on the hardness and chemical composition of the material being machined. The tests were done by hard abrasive cutting of mild steel and stainless-steel rods. The grinding ratio in the elastic abrasive cutting of steel rods was also determined by Kaczmarek [5] and [14], using the results from the investigation of the cut-off wheel temperature. The author noted that the combination of a higher cut off wheel diameter and a higher feed force resulted in generating higher temperatures and obtaining lower values of G-ratio. These results were linked to cut off wheel wear and self-sharpening.

Levchenko and Pokintelitsa [7] analysed the interaction between the cut-off wheel and the cut pipe billet on the basis of heat-deforming analysis and they established the relationship between processing conditions and cutting conditions with the design parameters of the abrasive tool. To obtain lower temperatures and higher grinding ratios, Sahu and Sagar [6] proposed cut-off wheels with radial passages on their surfaces to supply the cutting fluid to the cutting zone. Upon studying four different eco-friendly water-based fluids in cutting medium carbon steel, Ni et al. [15] observed that the water-based fluid with surfactant provided the best results, as it increased the G-ratio (by 77.6 %) and decreased the cutting tilt (by 14.8 %) and lin span (by 34.5 %) in comparison with dry cutting.

Yamasaka et al. [16] studied the application of abrasive cutting with diamond wheels used for machining the electromechanical parts of brittle materials, such as alumina ceramics. They found that the straightness of the sliced surface strongly correlated with the axial deflection of a thin grinding wheel, which was caused by the side forces acting on the side surfaces of the cut-off wheel. In this regard, they recommended decreasing the side force both by decreasing the depth of cut with retaining a stock removal rate and by improving the flatness on the side surfaces of the cut-off wheel to improve straightness. The results obtained by Braz et al. [17] in relation to the abrasive cutting of titanium showed that wheels with abrasives of silicon carbide and 30 mesh grain size combined with an extremely hard bond material led to the lowest values of depth of the affected zone.

Many studies confirm that by changing the abrasive cutting conditions, the thermal flows and the distribution of temperature in the tool, chips, workpiece and cut piece can be controlled, thus providing possibilities for enhancing tool lifetime, cutting process intensity and quality of machined surfaces.

Wang et al. [18] developed a three-dimensional numerical model to calculate the grinding temperature field distribution. The effect of the workpiece feed velocity, cooling coefficient and the depth of cut on temperature distribution were considered. Eshghy [19] studied the thermal flux in the chip, cut-off wheel and ambience and pointed out that 31 % of the thermal energy was released from the chips, 18 % from the ambience, 50 % from the wheel and only 1 % from the piece. Thermal optimum conditions were defined, and a procedure for selecting optimum down-feed rates was given. Hou and Komanduri [20] developed a heat source model and calculated heat partition in cut-off operations. They established that 60 % to 75 % of the heat was removed by the chip, 20 % to 35 % by the workpiece and 1 % by the cut-off wheel. Therefore, the authors thought that the thermal softening of the bond resulted from the heat released by the flying chips.

By using finite element (FE) analysis, Putz et al. [3] modelled heat distribution inside a steel bar under different cutting conditions. By adapting the cutting parameters and cooling strategy, the critical workpiece maximum temperature was decreased by 48 %. The authors proposed an alternative grinding strategy that combined the benefits of feed rate reduction, swing grinding and increased coolant velocity and ensured a decrease of the cutting power, wheel wear and piece temperature. The FE model for studying and analysing the temperature distribution in the machined bar during grinding is presented in [21], where two basic strategies for decreasing the temperature in the cutting zone are proposed: optimization of the cutting parameters (the feed speed) and application of the cubic boron nitride (CBN)-grinding technology. As a result, thermal damage decreases, and a cutting operation of high quality is ensured.

The analytical methods to calculate grinding temperatures and their effect on thermal damages were developed by Malkin and Guo [22]. According to them, the critical factor by means of which thermal damages in abrasive cutting could be controlled was the energy partition to the workpiece, which was within the range of 60 % to 85 %. This amount was considerably smaller in abrasive cutting with CBN discs with lower feed and slower workspeeds when using appropriate cooling fluids.

By applying the method of infrared thermography and planned experiment, Stoynova et al. [23] and [24] established that the workpiece rotational frequency had the greatest effect on temperature. As it increased (approximately 3 times), the temperatures of the cut piece and cut off wheel decreased (by up to 29 % and 19 %, respectively) whereas the workpiece temperature increased by up to 12 %. Temperature models of the workpiece, chip, piece being machined, and cut-off wheel in abrasive cutting were also built [25].

The analysis of the publications related to abrasive cutting shows that each abrasive cutting process is unique and could be studied from different perspectives: technological, energetic, informational, organizational, etc. Hard abrasive cutting is a well-studied process [3], [8] to [13] and [15] to [21] and the optimum conditions for its implementation are determined, too [26] to [28].

Elastic abrasive cutting is of great interest since it is a new high-performance method ensuring the stabilization of the dynamic and thermal phenomena in the cutting zone, thus reducing cut-off wheel wear and improving the quality of machined surfaces [14], [23], [29] and [30]. However, the literature referring to elastic abrasive cutting is scarce; thus, additional studies are needed. The adjustment of cutting operations is often done on the basis of the experience of the skilled staff or by using data from handbooks. Currently, there are no mathematical models that cover all aspects of elastic abrasive cutting and connect all its parameters with the cutting conditions. To increase the efficiency and applicability of elastic abrasive cutting, it is necessary to study, model, and optimize its behaviour so as to achieve certain economic and technological criteria, taking into consideration the specific nature and conditions for its implementation.

In this regard, the paper proposes a new approach to the modelling and multipurpose optimization of elastic abrasive cutting, which reflects the specifics of its particular implementation in cutting two types of structural steels (C45 – medium carbon steel and 42Cr4 – alloy chrome steel), which are widely used in machine building for producing workpieces. The optimum conditions to implement the process are determined and verified to ensure the best match between the rate of cut-off wheel wear, time per cut, cut piece temperature, cut off wheel temperature and workpiece temperature. This will ensure higher productivity of the elastic abrasive cutting process and lower costs, as well as higher quality of the machined surfaces of the structural steels under study.

Taking into account the high productivity and low cost of the elastic abrasive process, the proposed multipurpose optimization approach and the obtained theoretical-experimental results presented in this paper could be used in every enterprise specialized in machine building.

1 INVESTIGATION AND MODELLING OF ELASTIC ABRASIVE CUTTING RESPONSE VARIABLES

1.1 Equipment, Materials, Methods

The purpose of this study is to establish the correlation dependencies between the response variables of the elastic abrasive cutting process: cut-off wheel wear δ_h, cut off wheel temperature $T_{s,h}$, workpiece temperature $T_{w,h}$, cut piece temperature $T_{d,h}$ and time per cut $t_{c,h}$ (h is index corresponding to the type of material being machined; h = 1 for elastic abrasive cutting of C45 steel; h = 2 for elastic abrasive cutting of 42Cr4 steel), and the conditions required to perform the process. Therefore, the cut-off wheel diameter d_s, the compression force F and the workpiece rotational frequency n_w were chosen as control factors.

To perform the elastic abrasive cutting process, a special attachment (Fig. 2) was designed. It is fixed to the main carriage of a combination lathe, supplied with a device for a stepless adjustment of workpiece rotational frequency n_w. The attachment comprises an angle grinder (2), which ensures constant rotational frequency of the cut-off wheel (n_s = 8500 min^{-1}), and a unit for adjusting the amount of the compression force F of the cut-off wheel (3) exerted on the workpiece (1). An angle grinder (GA7020 model) is attached to the front end of the arm (5), which is fixed by a bearing (4). A counterweight (6), whose weight is greater than that of the angle grinder, is fixed on the opposite end of the arm. The compression force of the abrasive wheel F exerted on the workpiece is regulated by moving the counterweight along the arm (5). The cut-off wheel stroke in cutting is limited by a locking screw. An aspirator system (7) is included to arrest, collect and remove the flying chips and sparks during abrasive cutting. The principle description of the experimental setup is shown in Fig. 2.

Fig. 2. *Work stand for elastic abrasive cutting*

Experimental studies have been conducted during counter-directional cutting with high speed reinforced cut-off wheels 41-180x22.2x3.0 A30RBF, produced by the Abrasive Tools Factory – Berkovitsa, Bulgaria [31]. The abrasive wheels are marked in compliance with EN 12413:2007: type and size of the cut-off wheel; abrasive material type; A = aluminium oxide; grit size according to ISO 8486 – 30 (Coarse); hardness grade, R = hard; bond, BF = fibre-reinforced resinoid bond.

The materials being machined are C45 (1.0503) and 42Cr4 (1.7045) steels (BS EN 10277-2:2015 [32]) (Table 1). They are in the shape of cylindrical rods of diameter d_w = 30 mm.

The general form of the models describing the relationship between the studied parameters (cut-off wheel wear, cut off wheel temperature, workpiece temperature, cut piece temperature and time per cut) and the group of independent variables (factors $d_s(X_1)$, $F(X_2)$ and $n_w(X_3)$) is:

$$y_{g,h} = b_0 + \sum_{i=1}^{3} b_i X_i + \sum_{i=1}^{3} b_{ii} X_i^2 + \sum\sum_{i<j} b_{ij} X_i X_j, \quad (1)$$

where g = 1 to 5, for index corresponding to the type of the studied elastic abrasive cutting parameter: $y_{1,1} = \delta_1$, $y_{2,1}=T_{s,1}$, $y_{3,1}=T_{w,1}$, $y_{4,1}=T_{d,1}$, $y_{5,1}=t_{c,1}$, $y_{1,2}=\delta_2$, $y_{2,2}=T_{s,2}$, $y_{3,2}=T_{w,2}$, $y_{4,2}=T_{d,2}$, $y_{5,2}=t_{c,2}$.

Table 1. *Chemical composition and physio-mechanical properties of the steels studied*

Steel type	Chemical composition				Tensile strength [MPa]	Hardness [HB]
	C [%]	Mn [%]	Cr [%]	Si [%]		
C45	0.44	0.5	0.2	0.2	750	192
42Cr4	0.4	0.5	1	0.25	1000	205

The form of the model was chosen on the basis of the theoretical and experimental studies of the effect of elastic abrasive cutting conditions on cut-off wheel wear, temperature and cutting ability as the non-linear nature of experimental dependencies $\delta_h=f(d_s,F,n_w)$, $T_{s,h}=f(d_s,F,n_w)$, $T_{w,h}=f(d_s,F,n_w)$, $T_{d,h}=f(d_s,F,n_w)$, and $T_{c,h}=f(d_s,F,n_w)$ were taken into account [23], [29] and [30].

To build the theoretical and experimental models in Eq. (1), multi-factor experiments were conducted using an orthogonal central-composite design. The number of trials is $N=2^n+2n+1=15$ ($n=3$ is the number of control factors). Three observations were made for each experiment. The variation limits of control factors are presented in Table 2. They are determined on the basis of the conducted experimental studies on the temperature in elastic abrasive cutting and the performance of cut-off wheels estimated by the parameters: wear, tool life, and cutting ability [23], [29] and [30].

The models were built using the measured values of the cut-off wheel wear, cut-off wheel maximum contact temperature, workpiece maximum instantaneous temperature, cut piece temperature at the end of the cut-off cycle and time per cut. Each measurement of wear, time per cut and temperature were performed three times.

Table 2. *Factor levels in the experimental design*

Factors		Factor levels		
		–1	0	+1
X_1	d_s [mm]	120	150	180
X_2	F [daN]	1	2	3
X_3	n_w [min–1]	22	91	160

The cut-off wheel wear was determined as a mean value of the differences between the tool diameters measured in two mutually perpendicular directions at the beginning and the end of the respective observation performed under specific cutting conditions. Cut-off wheel diameters were measured using a Mitutoyo Digital Calliper, ABSOLUTE, LCD of Range: 0 mm to 200 mm, Resolution: 0.01 mm, Accuracy: ±0.02 mm, Repeatability: 0.01 mm.

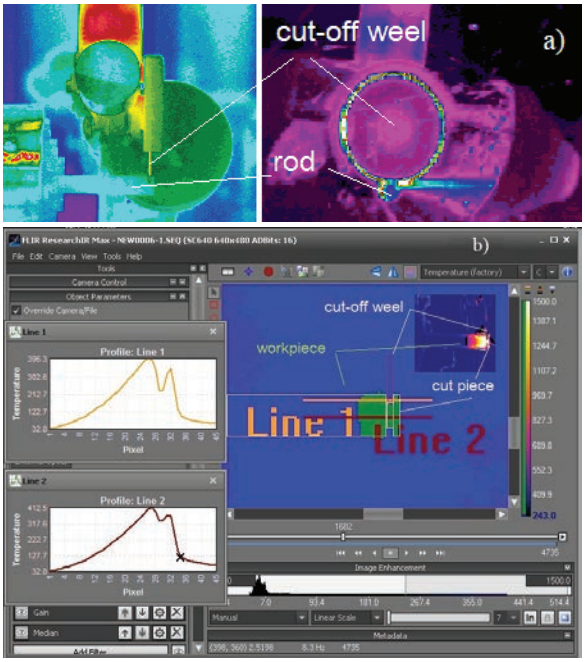

Fig. 3. *Illustration of thermography measurement process of cut-off wheel, workpiece and cut piece temperatures, respectively in elastic abrasive cutting of cylindrical rods*

The time per cut corresponds to the duration of the respective cut-off cycle. The cut-off wheel, workpiece and cut piece, and respective maximum contact temperatures during the elastic abrasive cutting of cylindrical rods, were measured using a thermal imaging camera. Non-destructive thermography measurement leads to a reduction of measurement temperature errors compared to thermocouple measurement, as described in [23] and [33]. The whole cutting process was registered by infrared cameras ThermaCam FLIR SC640, with an image resolution of 640 × 480 pixels, temperature measurement range from –40 ºC to +2000 ºC, reading accuracy of ±2 % and IP-link using FireWire. Thermovision SDK software was used to manage, change settings, and control the calibration of the cameras. The ResearchIR MAX software package was also used for real-time monitoring and temperature measurements of the cutting area, selected as the region of interest (ROI). Surface temperature measurements were recorded simultaneously in two ROI positions: cutoff wheel profile and face view of side (Fig. 3a).

Fig. 3b illustrates real-time monitoring and surface temperature measurement of the cutting area using ResearchIR MAX.

Further thermograms processing was performed in MATHLAB, for noise reduction, contouring, additional analysis, recognition and classification of the areas with the highest and lowest temperature or other ROI interesting areas.

1.2 Experimental Results and Modelling

The designs of the experiments, including the values of the studied response variables of the elastic abrasive cutting process, are presented in Table 3.

After statistical analysis of the experimental results and by applying the regression analysis method and QstatLab software [34], theoretical and experimental models of the cut-off wheel wear, cutoff wheel temperature, workpiece temperature, cut piece temperature and time per cut were made (Table 4).

The regression models include only the significant regression coefficients determined in accordance with the condition $\hat{t} > t_{g,h(\alpha/2,v)}$, where $\hat{t}$ and $t_{g,h(\alpha/2,v)}$ are, respectively, the calculated values of Student's t-criterion for each coefficient b_0, b_i, b_{ij}, b_{ii} of the regression equations, the general form of which is presented by Eq. (1) and the tabular value of Student's t-criterion ($\alpha = 0.05$ is the significance level; $v = N-k$ is the number of degrees of freedom; k is the number of coefficients in the model), presented for each model in Table 4. The constructed models are relevant since the condition $\widehat{F}_{g,h} > F_{g,h(\alpha,v_1,v_2)}$ has been met with a confidence level of 95 %. The calculated $\widehat{F}_{g,h}$ and tabular $F_{g,h(\alpha,v_1,v_2)}$ values of the Fisher criterion ($\alpha = 0.05$; $v_1 = k-1$ and $v_2 = N-k$ are degrees of freedom) for each regression model are presented in Table 4. The theoretical and experimental models extremely accurately describe the dependencies between the studied response variables and the control factors. The values of the determination coefficients are $\widehat{R}^2_{g,h} = 0.880$ to 0.999 (Table 4).

The effect of cutting conditions on the cut-off wheel wear, cutoff wheel temperature, workpiece temperature, cut piece temperature and time per cut according to the created theoretical and experimental models (Table 4) is graphically presented in Fig. 4. To determine the impact rate of control factors on the studied response variables of the elastic abrasive cutting process, an analysis of variance (ANOVA) was conducted.

1.3 Analysis of Experimental Results

The investigation of the response variables of the elastic abrasive cutting process shows that they depend, to a large extent, on the conditions for implementing the process. However, the effect of the cut-off wheel diameter, compression force, and workpiece rotational frequency on the cut-off wheel wear, time per cut, cut piece temperature, workpiece temperature and cut off wheel temperature is different, and it is related to the theoretically established influence of d_s, F and n_w on the length of the contact arc between the cut-off wheel and the workpiece, the

Table 3. *Design of the experiments and response variables of the elastic abrasive cutting process of C45 and 42Cr4 steels*

Control factors			Response variables									
			Cut-off wheel wear		Cut-off wheel temperature		Workpiece temperature		Cut piece temperature		Time per cut	
d_s [mm]	F [daN]	n_w [min-1]	δ_1 [mm]	δ_1 [mm]	$T_{s,1}$ [°C]	$T_{s,2}$ [°C]	$T_{w,1}$ [°C]	$T_{w,2}$ [°C]	$T_{d,1}$ [°C]	$T_{d,2}$ [°C]	$t_{c,1}$ [s]	$t_{c,2}$ [s]
120	1	22	0.977	1.051	160	164	970	989	201	215	10.90	12.08
180	1	22	0.551	0.583	195	200	830	850	220	235	9.91	10.80
120	3	22	1.882	1.981	175	179	989	1008	208	223	8.90	10.06
180	3	22	1.422	1.513	205	210	863	880	235	251	7.90	8.86
120	1	160	3.141	3.272	135	144	1093	1149	145	154	12.9	14.88
180	1	160	2.294	2.390	150	160	950	1000	170	180	11.87	13.64
120	3	160	4.476	4.865	160	172	1125	1184	152	161	10.94	12.69
180	3	160	4.307	4.631	180	193	965	1015	184	195	9.87	11.45
120	2	91	2.528	2.689	149	156	907	936	173	184	10.96	12.49
180	2	91	2.109	2.221	183	190	838	864	207	222	9.89	11.37
150	1	91	1.652	1.721	157	165	865	889	193	205	11.40	12.80
150	3	91	2.948	3.189	173	182	879	905	206	219	9.40	10.52
150	2	22	1.218	1.282	185	196	805	838	215	230	9.45	10.58
150	2	160	3.374	3.628	156	164	933	956	180	192	11.41	13.12
150	2	91	2.308	2.455	165	175	872	900	202	215	10.43	10.43

Table 4. *Theoretical and experimental models of cut-off wheel wear, temperature and time per cut during elastic abrasive cutting and statistical characteristics of the models*

Steel, type	Response variables	Models	Student's criterion	Fisher criterion		Determination coefficient
				Calculated	Tabular	
C45	Cut-off wheel wear	$\delta_1 = 1.218 - 0.008d_s + 0.382F + 0.011n_w + 0.003Fn_w$	2.228	294.382	3.478	0.988
	Temperature of the cut-off wheel	$T_{s,1} = 103.865 + 0.447d_s + 8F - 0.201n_w$	2.201	48.371	3.587	0.910
	Temperature of the workpiece	$T_{w,1} = 2603.317 - 19.479d_s - 194.928F + 0.0578d_s^2 + +51.557F^2 + 0.005n_w^2$	2.262	38.234	3.482	0.930
	Temperature of the cut piece	$T_{d,1} = -88.426 + 3.69d_s + 4.667F - 0.359n_w - 0.011d_s^2$	2.228	98.168	3.478	0.965
	Time per cut	$t_{c,1} = 13.486 - 0.017d_s - 0.881F + 0.015n_w - 0.029F^2 - -6.6.10^{-6} d_s n_w$	2.262	19098,664	3.481	0.999
42Cr4	Cut-off wheel wear	$\delta_2 = 1.344 - 0.008d_s + 0,391F + 0.011n_w + 0.004Fn_w$	2.228	370,829	3.478	0.991
	Temperature of the cut-off wheel	$T_{s,2} = 105.799 + 0.46d_s + 8.583F - 0.168n_w$	2.201	35.092	3.587	0.880
	Temperature of the workpiece	$T_{w,2} = 2695.024 - 21.143d_s - 140.028F + 0.063d_s^2 + +37.403F^2 + 0.006n_w^2$	2.262	38.494	3.482	0.931
	Temperature of the cut piece	$T_{d,2} = -89.928 + 3.887d_s + 5F - 0.394n_w - 0.011d_s^2$	2.228	90.495	3.478	0.962
	Time per cut	$t_{c,2} = 15.212 - 0.02d_s - 1.062F + 0.019n_w$	2.201	863.138	3.587	0.994

depth of cut and the thickness of the layer of material being cut by one abrasive grain [29] and [35].

The analysis of the theoretical and experimental models (Table 4) and the graphics plotted on the basis of them (Fig. 4), as well as the interpretation of ANOVA results, allow us to draw the following conclusions:

(1) The workpiece rotational frequency has the highest effect on the elastic abrasive cutting process response variables. The increase of n_W within the range being studied results in increasing cut-off wheel wear (from 2.4 to 4.2 times depending on the compressive force and cut off wheel diameter), time per cut (by up to 25 %), and workpiece temperature (by up to 18 %), as well as in decreasing cut piece temperature (by up to 29 %) and cut off wheel temperature (by up to 17.6 %). The intensified cut-off wheel wear and the increased time per cut are connected with the increased thickness of the layer being cut off by one abrasive grain, thus resulting in increasing the load of abrasive grains and establishing preconditions for faster filling of the cut off wheel pores with chips [29] and [35], as well as with the change of the ratio between the normal and main cutting force, which results in deteriorating the possibilities for abrasive grain cutting [30]. The decrease of cut piece temperature is caused by the enhanced heat removal resulting from the thicker layer being cut and the cross section of the chip being cut off by one abrasive grain [29] and [35], as well as the time per cut. The increased workpiece temperature and the decreased cut off wheel temperature are linked to an increase of the contact area between the cut-off wheel and the workpiece, as well as to the fact that in the course of cutting the workpiece appears a tool coolant absorbing part of the released heat, which consequently is transferred to the chip.

(2) As the cut-off wheel diameter d_s decreases within the range under study, both the tool wear size and time per cut increase, from 11 % to 94 % and from 9 % to 14 %, respectively. That tendency could be explained with the decrease in the number of abrasive grains involved in the removal of the layer being cut per revolution of the cut-off wheel, the increase of the thickness of the chip being cut by one abrasive grain, respectively, the load on the abrasive grains, as well as with the inevitable decrease of the cut-off wheel speed since the rotational frequency n_s is constant [29] and [35]. All this deteriorates the cutting ability of the abrasive grains and logically results in intensifying tool wear and increasing time per cut. The influence of cut-off wheel diameter on tool wear and time per cut depends on the compression force, workpiece rotational frequency, and the effect of d_s on the wear decreases as the compression force and workpiece

rotational frequency increase. As the workpiece rotational frequency increases and the compression force decreases, the effect of d_s on the time per cut increases.

(3) As d_s decreases, the temperatures of the cut piece and cut-off wheel also decrease, whereas the workpiece temperature increases within a range of 11 % to 17 %. That is linked to an increase of the thickness of the layer of material being cut and the cross-section of the chip being cut by one abrasive grain [29] and [35], which enhances heat removal and to an increase of time per abrasive cut and a decrease of cutting speed.

(4) The increase of the compression force F results in decreasing elastic abrasive time per cut (by 14 % to 20 %), respectively, increasing process performance in increasing cut-off wheel wear (from 1.6 to 2.7 times). That is linked to the increase of the length of contact arc and the depth of cut [29] and [35], as a result of which cut off wheel pores are filled with chips and abrasive particles faster. The effect of the compression force increases when the cut-off wheel diameter increases and the workpiece rotational frequency decreases.

(5) The compression force has little effect on temperature. As it increases, the temperatures of the cut piece, cut-off wheel and workpiece increase by 5 % to 11 %. The minimum effect of the compression force is related to the fact that when F increases, elastic abrasive time per cut decreases and, in contrast, the length of contact arc and the depth of cut increase [29] and [35].

(6) The nature and level of influence of workpiece rotational frequency, cut off wheel diameter and compression force on cut-off wheel wear, time per cut and elastic abrasive cutting temperature are equal for the two materials being machined (C45 and 42Cr4 steels). Nevertheless, the temperatures of cut-off wheel, workpiece, and cut piece are higher when machining 42Cr4 steel (by 1.9 % to 7.5 %), which is related to the higher hardness and strength of this material. The values of cut-off wheel wear and time per cut are also higher, respectively by 4.2 % to 8.7 % and by 9 % to 16 %.

2 OPTIMIZATION OF ELASTIC ABRASIVE CUTTING CONDITIONS

2.1 Optimization Method

The undertaken investigation, modelling, and analysis of the response variables of the elastic abrasive cutting process show complicated and different nature of change of cut-off wheel wear, cut-off

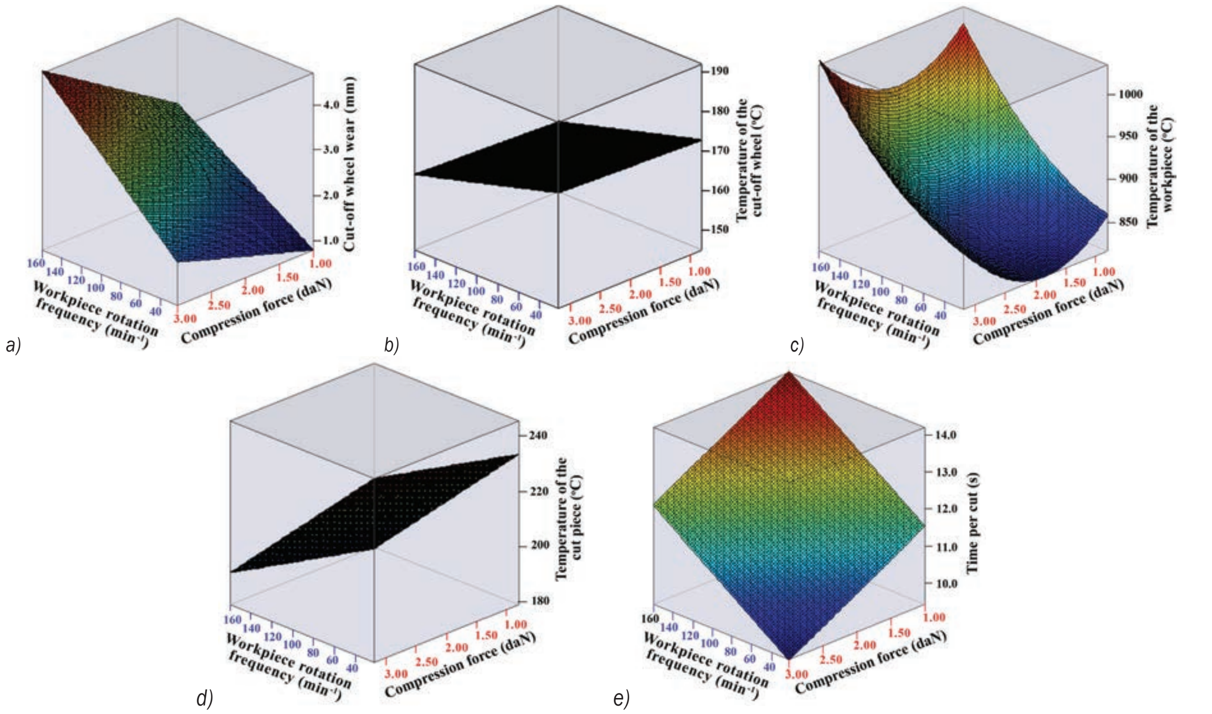

Fig. 4. *Effect of the elastic abrasive cutting conditions on the cut-off wheel wear δ_s; a), cut off wheel temperature T_s, b), workpiece temperature T_w, c), cut piece temperature T_d, d) and time per cut t_c, e) (for steel 42Cr4, d_s = 150 mm)*

wheel temperature, workpiece temperature, cut piece temperature and time per cut depending on the cut-off wheel diameter, the compression force exerted by the cut-off wheel on the workpiece and the workpiece rotational frequency. This implies that the optimum values of the investigated response variables will be obtained at different combinations of values of control factors (d_s, F and n_w). Hence, the optimization of the elastic abrasive cutting process by one parameter is irrelevant. Multi-objective optimization will provide much more information so as to make a justified decision on the selection of optimum cutting conditions.

The common multi-objective optimization methods can be classified into three main groups [36] to [38]. The first group includes methods that use one of the response variables as an objective function and the rest of the response variables are considered to be limits. The major disadvantage of those methods is that they do not apply the main idea of multi-objective optimization: specifically, all response variables to be considered simultaneously. The proposed procedures from this category would result in unreal solutions, especially when there are conflicting objectives. In addition, in many cases, it is difficult to choose one of the response variables as an objective function. When applying the methods from the second group, a domain where different response variables meet specific requirements occurs. This approach is effective in the case of a small number of control factors (2 or 3) and response variables (up to three). The third group comprises methods that combine a set of response variables in a generalized objective function defined as a utility function, desirability function, loss function, or proportion of conformance. In those cases, the optimization problem is solved as a single-objective one.

To define the optimum elastic abrasive cutting conditions, the generalized utility function method was chosen [36], [37] and [39]. It is based on the idea that the quality of a product or process with a set of response variables is unacceptable if one of the response variables is outside the utility limits. This method defines the result as a combination of response variables and chooses a set of factors where the result is a maximum value. The generalized utility function has many advantages compared to other combining methods, mainly due to its flexibility since it makes it possible to maximize some output quantities and minimize others simultaneously.

The generalized utility function could be defined as a geometric-mean value $\Phi_{G,h}$ or an arithmetic-mean value $\Phi_{A,h}$ of the partial utility functions $\eta_{g,h}$ obtained by transforming the studied and modelled response variables of the elastic abrasive cutting process $y_{g,h}$ (Table 4) into dimensionless quantities [37] and [39]. To solve the specific optimization problem, the generalized geometric-mean utility function was chosen as an optimization parameter since if one of the response variables of the elastic abrasive cutting process does not meet the requirements of utility limits, then $\Phi_{G,h}=0$. In this case, the arithmetic generalized utility function is $\Phi_{A,h}\neq 0$ and could have a maximum value but the elastic abrasive cutting conditions under which this value of $\Phi_{A,h}$ has been obtained are not optimum.

The generalized geometric-mean utility function is a complex indicator, which is determined in conformity with the dependency [37] and [39]:

$$\Phi_{G,h} = \sqrt{\prod_{g=1}^{5} \eta_{g,h}} = \sqrt[5]{\prod_{g=1}^{5} \frac{k_g\left(y_{g,h} - y_{g(u)}\right)}{\Delta y_g}}, \quad (2)$$

where k_g is utility coefficient ($k_g=+1$), when the increase of the studied response variable $y_{g,h}$ is useful; ($k_g=-1$), when the decrease of $y_{g,h}$ is useful); $y_{g,u}$ is the most useless result of the response variable $y_{g,h}$, obtained within the limits of the permissible space; $\Delta y_g = y_{g\max} - y_{g\min}$; $y_{g\max}$ and $y_{g\min}$ is utility limits (maximum and minimum value of $y_{g,h}$).

The solution of the optimization problem is reduced to defining the combination of the control factors of the elastic abrasive cutting process; cut-off wheel diameter d_s, compression force F and workpiece rotational frequency n_w, where the generalized geometric-mean utility function has a maximum. The problem is solved for each material being machined (C45 and 42Cr4 steels).

2.2 Modelling of Generalized Utility Function

To solve the optimization problem, mathematical models for defining the generalized geometric-mean utility function depending on the control factors of the elastic abrasive cutting process were built. The general form of the models, assumed on the basis of the performed analysis of the influence of elastic abrasive cutting conditions on its response variables: cut off wheel wear δ_h, cut-off wheel temperature $T_{s,h}$, workpiece temperature $T_{w,h}$, cut piece temperature $T_{d,h}$, and time per cut $t_{c,h}$, is:

$$\Phi_{G,h} = A_0 + \sum_{i=1}^{3} A_i X_i + \sum_{i=1}^{3} A_{ii} X_i^2 + \\ + \sum\sum_{i<j} A_{ij} X_i X_j + A_{123} X_1 X_2 X_3. \quad (3)$$

The models in Eq. (3) under the conditions of elastic abrasive cutting of C45 and 42Cr4 were built on the basis of the results from the experiments carried out according to an optimum design involving the following number of trials $N=2^n+2n+1=15$ ($n=3$ is the number of control factors) in Table 5. With each trial, the generalized geometric-mean utility function was determined in compliance with dependency in Eq. (2), as the values of the most useless result and the utility limits of the response variables of the elastic abrasive cutting process were determined in compliance with the following equations:

$$\delta_{(u)}=(\delta_h)_{\max};\ T_{s(u)}=(T_{s,h})_{\max};\ T_{w(u)}=(T_{w,h})_{\max};$$
$$T_{d(u)}=(T_{d,h})_{\max};\ t_{c(u)}=(T_{c,h})_{\min};$$

$$\Delta\delta=(\delta_h)_{\max}-(\delta_h)_{\min};\ \Delta T_s=(T_{s,h})_{\max}-(T_{s,h})_{\min};$$
$$\Delta T_w=(T_{w,h})_{\max}-(T_{w,h})_{\min};\ \Delta T_d=(T_{d,h})_{\max}-(T_{d,h})_{\min};$$
$$\Delta t_c=(t_{c,h})_{\max}-(t_{c,h})_{\min};$$

where $(\delta_h)_{\min}$, $(\delta_h)_{\max}$, $(T_{s,h})_{\min}$, $(T_{s,h})_{\max}$, $(T_{w,h})_{\min}$, $(T_{w,h})_{\max}$, $(T_{d,h})_{\min}$, $(T_{d,h})_{\max}$, $(T_{c,h})_{\min}$, $(T_{c,h})_{\max}$ are, respectively, the minimum and maximum values of cut off wheel wear, cut-off wheel temperature, workpiece temperature, cut piece temperature and time per cut, calculated by using the regression models in Eq. (1) (Table 4).

The models in Eq. (3), Table 6, were built on the basis of the defined values of the generalized geometric-mean utility function (Table 5) by applying the regression analysis method and QstatLab software [34]. They include only the significant regression coefficients defined according to the condition $\hat{t}>t_{h(\alpha/2,v)}$, where $\hat{t}$ and $t_{h(\alpha/2,v)}$ are respectively the calculated values of Student's t-criterion for each coefficient of the regression equations and the tabular value of Student's t-criterion ($\alpha=0.05$) is the significance level; $v=N-k$ is the number of degrees of freedom; k is the number of coefficients in the model). The tabular values of Student's t-criterion for each model are: $t_{1(0.025,6)}$ = 2.447 and $t_{2(0.025,9)}=2.262$. The constructed models are relevant since the condition $\hat{F}_h>F_{h(\alpha,v_1,v_2)}$ has been met with a confidence level of 95 %. They extremely accurately describe the dependencies between the studied response variables and control factors. The calculated $\hat{F}_h$ and tabular $F_{h(\alpha,v_1,v_2)}$ values of Fisher criterion ($\hat{F}_h=0.05$; $v_1=k-1$ and $v_2=N-k$ are degrees of freedom), as well as the values of the determination coefficient $\hat{R}_h^2$ for each regression model in Eq. (3) are shown in Table 6.

The effect of cutting conditions on the generalized utility function according to the created theoretical and experimental models (Table 6) is graphically presented in Figs. 5 and 6.

Table 5. *Design of the experiment and generalized utility functions during elastic abrasive cutting of C45 and 42Cr4 steels*

Control factors			Generalized utility function	
d_s [mm]	F [daN]	n_w [min^{-1}]	$\Phi_{G,1}$	$\Phi_{G,2}$
120	1	22	0.604	0.497
180	1	22	0.437	0.000
120	3	22	0.486	0.365
180	3	22	0.474	0.000
120	1	160	0.484	0.000
180	1	160	0.563	0.400
120	3	160	0.335	0.000
180	3	160	0.400	0.215
120	2	91	0.593	0.473
180	2	91	0.498	0.285
150	1	91	0.608	0.478
150	3	91	0.475	0.323
150	2	22	0.480	0.311
150	2	160	0.541	0.395
150	2	91	0.574	0.447

To determine the impact rate of control factors on the generalized utility function, ANOVA was

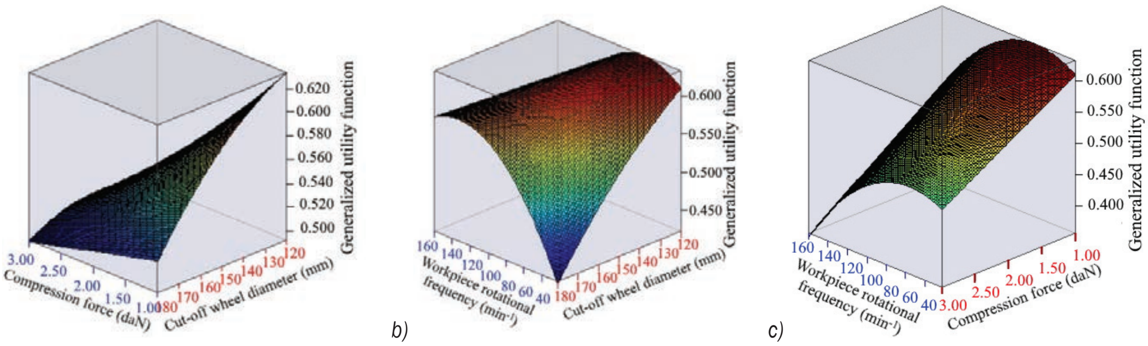

Fig. 5. *Generalized utility function in elastic abrasive cutting of C45 steel; a) n_w = 63.7 min–1 , b) F = 1 daN; and c) d_s = 120 mm*

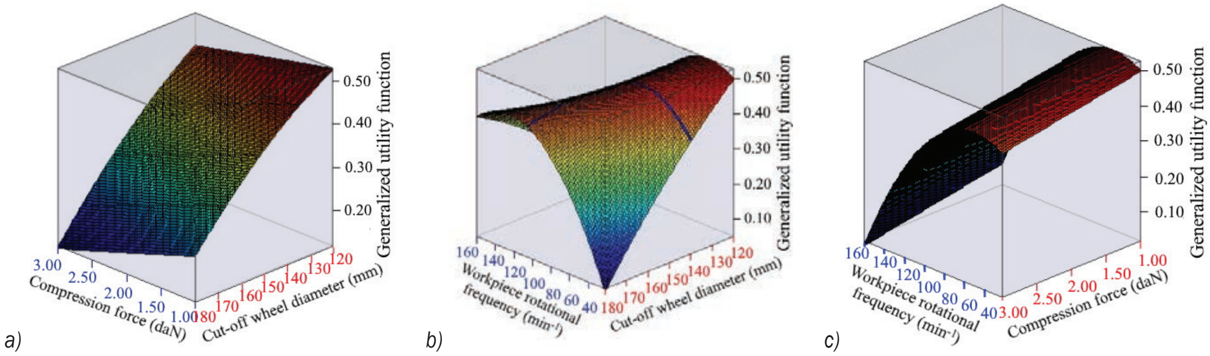

Fig. 6. *Generalized utility function in elastic abrasive cutting of 42Cr4 steel; a) n_w = 49.9 min⁻¹, b) F = 1 daN, c) d_s = 120 mm*

conducted. QstatLab software **[34]** was used, and the interaction between the factors was considered.

It has been established that the elastic abrasive cutting conditions have different effects, in terms of nature and level, on the generalized geometric-mean utility function, depending on the type of material being machined. In the elastic abrasive cutting of C45 steels, the highest effect is exerted by the compression force. As F decreases, the generalized utility function value $\Phi_{G,1}$ increases. The effect of the compression force increases as the workpiece rotational frequency n_w increases and the cut-off wheel diameter d_s decreases. In the elastic abrasive cutting of 42Cr4 steels, the highest effect on the generalized utility function $\Phi_{G,1}$ is exerted by the workpiece rotational frequency and the relationship $\Phi_{G,2} = f(n_w)$ has a maximum whose value depends on the cut-off wheel diameter and compression force. The effect of n_w on $\Phi_{G,2}$ increases as the cut-off wheel diameter decreases and the compression force increases. It is highest when cutting with abrasive wheels of diameter d_s = 120 mm and compression force F = 3 daN.

2.3 Definition of Optimum Elastic Abrasive Cutting Conditions

The optimization problem was solved upon elastic abrasive cutting of C45 and 42Cr4 steels by using a genetic algorithm and QStatLab software **[34]**. The defined optimum conditions (cut-off wheel diameter d_s, compression force F and workpiece rotational frequency n_w), where the generalized utility function $\Phi_{G,h}$ has a maximum, are presented in Table 7 and Figs. 5 and 6. The elastic abrasive cutting under these conditions ensures the best possible match between the rate of cut off wheel wear, time per cut, cut piece temperature, cut-off wheel temperature and workpiece temperature, respectively, in the elastic abrasive cutting of C45 steels: δ_1 = 1.532 mm, $T_{s,1}$ = 1.527 °C, $T_{w,1}$ = 975 °C, $T_{d,1}$=177.8 °C and $t_{c,1}$ = 8.21 s; in the elastic abrasive cutting of 42Cr4 steels: δ_2 = 1.524 mm, $T_{s,2}$ = 161.2 °C, $T_{w,2}$ = 977.4 °C, $T_{d,2}$ = 212.6 °C, and $t_{c,2}$ = 12.7 s.

Under the predicted optimum elastic abrasive cutting conditions (cut-off wheel diameter d_s = 120 mm, compression force F = 1 daN; workpiece rotational frequency n_w = 63.7 min⁻¹ and n_w = 49.9 min⁻¹, respectively for C45 steels and 42Cr4 steels), confirmation run experiments were performed, where cut off wheel wear, cut-off wheel temperature, workpiece temperature, cut piece temperature and time per cut were determined. The experimental values of the elastic abrasive cutting process response variables are presented in Table 7. They are determined as an arithmetical mean of the four observations done for each of them. A comparison between the experimental

Table 6. *Theoretical and experimental models of the generalized utility function and statistical characteristics of the models*

Steel type	Models	Fisher criterion		Determination coefficient
		Calculated	Tabular	
C45	$\Phi_{G,1} = 0.899 - 0.25F - 0.003n_w - 1.791.10^{-5}d_s^2 - 1.318.10^{-5}n_w^2 + 0.001Fn_w + 0.002d_sF + 4.08.10^{-5}d_sn_w - 1.058.10^{-5}d_sFn_w$	5.425	4.147	0.717
42Cr4	$\Phi_{G,2} = 0.917 - 0.007n_w - 3.06.10^{-5}d_s^2 - 3.61.10^{-5}n_w^2 + 9.107.10^{-5}d_sn_w - 3.057.10^{-4}d_sF$	12.553	3.482	0.804

Table 7. *Optimum elastic abrasive cutting conditions*

Steel type	Optimal conditions of elastic abrasive cutting			Response variables										Generalized utility function, $\Phi_{G,h}$
				Cut off wheel wear, δ_h [mm]		Temperature of the cut off wheel, $T_{s,h}$ [°C]		Temperature of the workpiece, $T_{w,h}$ [°C]		Temperature of the cut piece, $T_{d,h}$ [°C]		Time per cut, $t_{c,h}$ [s]		
	d_s [mm]	F [daN]	n_w [min^{-1}]	PV	EV	PV	EV	PV	EV	PV	EV	PV	EV	
C45	120	1	63.7	1.532	1.578	152.7	155	975	960	177.8	183	8.21	8.33	0.634
42Cr4	120	1	49.9	1.524	1.561	161.2	167	977.4	965	202.6	212	12.7	12.95	0.528

EV = experimental value; PV = predicted value

and the predicted, according to the models, Eq. (1), Table 4, values of the elastic abrasive cutting process response variables (Table 7) shows that error percentage is: 2.37 % to 2.92 % for cut off wheel wear; 1.48 % to 3.47 % for cut off wheel temperature; 1.28 % to 1.56 % for workpiece temperature; 2.84 % to 4.43 % for cut piece temperature; 1.44 % to 1.93 % for time per cut. These results prove that the recommended elastic abrasive cutting conditions are optimum and correct.

3 CONCLUSIONS

This paper proposes a new approach for optimizing the elastic abrasive cutting process, which takes into consideration the specifics of its particular implementation. The generalized geometric-mean utility function has been chosen as an optimization factor. It appears to be a complex indicator characterizing the technological and economic parameters of elastic abrasive cutting.

The proposed optimization approach has been applied to determine the optimum conditions of elastic abrasive cutting of C45 and 42Cr4 steels. The following results have been achieved:

(1) To determine the generalized utility function, theoretical and experimental models reflecting the complex influence of the control factors of the process (cut-off wheel diameter d_s, compression force F and workpiece rotational frequency n_w) have been developed. The models are based on the findings of complex studies and modelling of the parameters of the elastic abrasive cutting process (cut off wheel wear, time per cut, cut piece temperature, cut-off wheel temperature, and workpiece temperature) depending on the conditions of its implementation.

(2) By applying the generalized utility function and genetic algorithm, the optimum conditions for implementing the process have been determined as follows: cut-off wheel diameter d_s=120 mm; compression force F=1 daN; workpiece rotational frequency n_w = 63.7 min^{-1} and n_w = 49.9 min^{-1}, respectively for C45 and 42Cr4 steels. The authenticity of the determined optimum conditions has been proven by an experimental study of the response variables of the elastic abrasive cutting process. It has been established that they ensure the best possible match between the rate of cut off wheel wear ($\delta \leq 1.58$ mm), the cut off wheel temperature ($T_s \leq 167$ °C), the workpiece temperature ($T_w \leq 965$ °C), the cut piece temperature ($T_d \leq 212$ °C) and the time per cut ($t_c \leq 12.95$ s).

The results obtained in applying the new optimization approach provide possibilities for enhancing efficiency and controlling the elastic abrasive cutting process by choosing optimum conditions in accordance with the specifics and implementation of the particular abrasive cutting process. They also confirm the key role of the workpiece rotational frequency, compression force and cut-off wheel diameter for the cut off wheel lifetime, the productivity of the elastic abrasive cutting process and the temperature distribution within the tool, workpiece and cut piece. Taking into account the high productivity and low cost of the elastic abrasive process, the proposed multipurpose optimization approach and the obtained theoretical-experimental results, presented in this paper, could be used in every enterprise specialized in machine building.

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