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Chapter

Remote Nondestructive Thermal Control of Elastic Abrasive Cutting

Anna Stoynova, Irina Aleksandrova and Anatoliy Aleksandrov

Abstract

High temperatures during abrasive cutting lead to increased harmful gas emissions released into the environment, intensified cut-off wheel wear, microstructural changes in the machined material, and occurrence of thermal flaws. Temperature measurement in abrasive cutting is difficult due to the small size of the heated area (only tenths of mm^2), high temperatures (above 1000°C), continuous change of the conditions within one cut-off cycle, large temperature gradient (more than 200°C), high cutting speed (above 50 m/s) and high mechanical load. The infrared thermography (IRT) application for thermal control of elastic abrasive cutting have been studied. The performed thermal measurements have been verified with the results obtained from the temperature models of workpiece, cut-off wheel, and cut piece depending on the conditions in elastic abrasive cutting of two structural steels C45 and 42Cr4. The parameters of effective abrasive cutting have been determined by applying multi-objective optimization.

Keywords: abrasive technology, elastic abrasive cutting, nondestructive thermal control, multi-objective optimization

1. Introduction

Abrasive cutting is widely used in industry due to its high production rate (machining is performed at a speed of $100\text{--}200\text{ mm}^2/\text{s}$) and low labor costs. It is characterized by high temperatures (above 1000°C) in the cutting zone, intensive wear and deterioration of the abrasive tool cutting ability, spark generation, increased emissions of environmentally harmful gases, high noise level, risk of accidents, changes in the microstructure of surface materials and occurrence of thermal flaws [1–7]. Those disadvantages are related to the high cutting speed (above 50 m/s), constant changes in cutting conditions within a cut-off cycle, and unfavorable geometry of abrasive grains (negative rake angles).

Almost all mechanical work (over 97%) converts into thermal energy and only a small part of it transforms into hidden energy to change the crystal lattice of the material being machined [8, 9].

As a result of the conversion of the mechanical energy used in the cutting process into thermal energy, various heat sources emerge and the process of generating that heat depends on cutting conditions.

As far as every physical phenomenon has two sides—quantitative and qualitative, then, as a rule, the control of the energy transfer in a specific physical phenomenon involves the measurement of two quantities. When controlling heat exchange processes, the two quantities to be measured are temperature and thermal flux. Measuring the thermal parameters of thermal non-stationary processes, in particular, a rapidly changing thermal flux remains relevant today. Among the techniques for measuring unstable thermal fluxes, those using infrared cameras are preferred [10–12]. Infrared thermography provides remote and wireless real-time measurements of temperature fields of high-speed moving objects. However, to obtain accurate measurements, all emerging noises and interferences need to be compensated or minimized, which is a kind of a “payoff” for the universality of the thermographic thermal control.

By changing the abrasive cutting conditions, which directly define the thickness of the layer of material being cut, and, as a result, the temperatures of the tool, chip, workpiece, and cut piece, the thermal fluxes are controlled and conditions for increasing the tool life, the intensity of the cutting process and the quality of the machined surfaces are provided. Therefore, to improve the effectiveness and applicability of abrasive cutting, it is necessary to study and model the parameters of the process and to optimize the conditions for its implementation. This allows us to apply thermographic monitoring for preventive detection of unexpected changes in the parameters of the elastic abrasive cutting process and for ensuring a high-quality process.

To study the thermal phenomena in elastic abrasive cutting, an innovative approach has been used. It involves a wireless thermal control provided by infrared thermography and the application of the methodology of planned experiments and multi-objective optimization. An original thermographic procedure for increasing the precision of the thermal control during abrasive cutting is offered.

2. Abrasive cutting as a subject of thermal investigation, modeling, and optimization

The manufacture of workpieces by cutting is implemented on various machines and installations (automatic lathes, band cutting machines, mechanical hacksaws, band saws circular saws, abrasive cut-off machines, presses, electric spark, and electrochemical installations) depending on the dimensions, profile, type and physico-mechanical properties of the input material and the admissible deviation from nominal dimensions. When comparing cutting methods by technological criteria, the most important criteria are cutting intensity (production rate), tool life, and material loss in the form of chips related to the cut width. Choosing an optimal variant for workpiece cutting is a technical and economic task, which has a considerable impact on the cost of the machine-building production.

Abrasive cutting is a universal method that is applied to manufacturing workpieces of metal and non-metal materials of different hardness by means of high-speed reinforced abrasive (cut-off) wheels of a diameter d_s , ranging from 115 to 400 mm and a width ranging from 2 to 3.5 mm. Abrasive cut-off wheels are highly effective self-sharpening tools that perform cutting by means of thousands of miniature “cutting tools”—abrasive grains of aluminum oxide or silicon carbide.

Reinforced cut-off wheels whose grain size is in compliance with ISO 8486—grain numbers from 24 (coarse) to 60 (fine); medium-hard (P), hard (R or S), and very

hard (T), with a BF bond—fiber-reinforced resinoid bond or an AGE bond—glass-fiber-reinforced resinoid bond providing higher safety against breakage, are used [13, 14].

Abrasive cutting is a complex and varied process performed under different kinematic schema (**Figure 1**) where the cut-off wheel performs the main rotary motion (at a rotational frequency n_c) and a radial feed (at a speed V_{fr}) (**Figure 1a**). To facilitate the cutting process, an oscillatory motion (at a speed V_{ft}) of the cut-off wheel in a direction perpendicular to the basic feed (**Figure 1b**) or a rotary motion of the workpiece (at a rotational frequency n_w) (**Figure 1c**) is introduced [1, 2, 4, 15–17].

The oscillatory motion facilitates the cutting process and helps to reduce the cost of the abrasive wheels. However, some shocks occur at both ends of the oscillatory motion, which leads to overloading the cut-off wheel, occurrence of vibrations, and an increase in wear. The implementation of such a motion makes the machine complex and costly. Those disadvantages are avoided when using the schema including a rotary motion of the workpiece (**Figure 1c**). If we compare abrasive cutting schemas, it can be seen that when performing a cut-off cycle (cutting one workpiece), the cut-off wheel working stroke upon cutting a rotating workpiece (**Figure 1c**) is approximately twice as short as that for the schemas in **Figure 1a** and **b**. It results in reducing the cut-off time and the friction forces between the lateral surfaces of the cut-off wheel and workpiece thus, on one hand, decreasing the temperature in the cutting zone and cut-off wheel wear and, on the other hand, increasing process production rate. When cutting a rotating workpiece, the lower cut-off wheel wear and the higher production rate is also due to the shorter length L of the contact arc between the cut-off wheel and the workpiece in comparison to the one used when cutting a fixed workpiece. In cutting a fixed workpiece, the chips produced in the process of cutting do not fit in the cut-off wheel pores, which results from the higher values of the contact arc L regardless of the thinner layer being cut. Therefore, the process production rate decreases, and tool wear increases.

The cut-off wheel can be fed into the workpiece at a constant speed of radial feed ($V_{fr} = \text{const}$) provided in a kinematic way by the cutting machine (rigid abrasive cutting) or can be pressed onto the workpiece with a constant force F ($V_{fr} \neq \text{const}$)—elastic abrasive cutting [3].

The kinematic schemas of rigid abrasive cutting are similar to those in external cylindrical grinding, where dependencies for defining the tool-workpiece contact area, contact arc length, and thickness of layer being cut, pointed in [14, 18–20], are

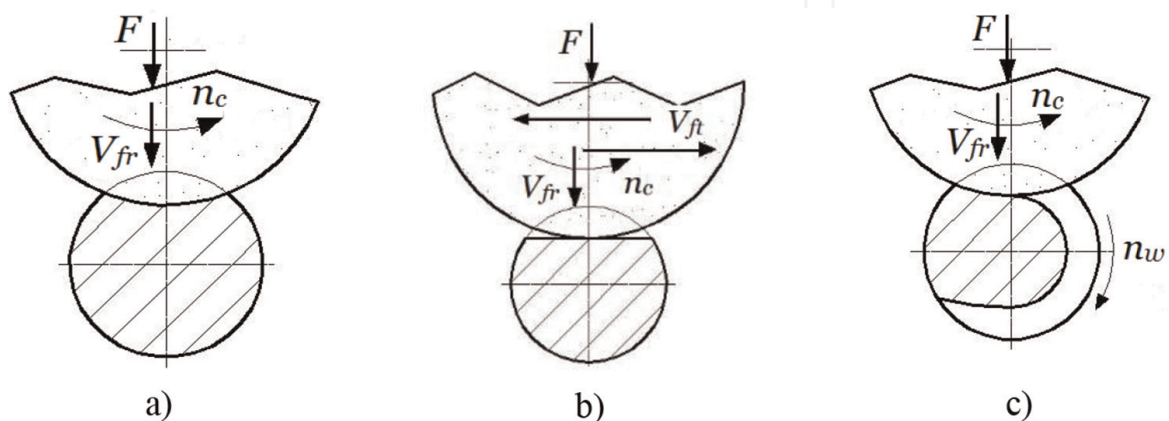


Figure 1.
Schemas of abrasive cutting.

required. The principal disadvantage of this method is the change in the power and heat loads of the cut-off wheel within one cut-off cycle, which is related to the change in the instantaneous cross-sectional area of the layer is cut. This results from the fact that with the cut-off wheel feed from the periphery to the center of the workpiece being cut the contact arc length between the cut-off wheel and the piece changes as the instantaneous thickness of the layer being cut h remains constant (with a fixed workpiece) or changes according to a particular law (with a rotating workpiece).

Within one cycle of elastic abrasive cutting, the length of the contact arc L and the thickness h of the layer being cut change, while the instantaneous cross-sectional area of this layer remains constant [8, 15, 21–23]. This ensures stabilization of the dynamic and thermal phenomena accompanying cutting and appears a precondition for more effective use of the cut-off wheel, as well as for enhancing the quality of the machined surface. Simultaneously, the contact arc length L , the thickness h of the layer being cut and the cutting depth a depend on the process operating conditions, which determines the effect of the compression force F , workpiece rotational frequency n_w and cut-off wheel diameter d_s on the process parameters—tool wear, tool life, production rate, cutting forces and power, temperatures of the cut-off wheel, workpiece, and cut piece.

1. The increase of the compression force F results in an increase in the contact arc length L and cutting depth a . It is, on one hand, a precondition for increasing the process production rate and, on the other hand, for increasing the temperature of the cut-off wheel, workpiece, and cut piece, as well as the wear of the cut-off wheel since its pores are filled with chips very fast.
2. The increase in the workpiece rotational frequency n_w results in an equivalent increase of the tangential feed rate thus increasing the thickness of the chip being cut by a single abrasive grain and faster filling the cut-off wheel pores, i.e. more intensive tool wear and longer time per cut. On the other hand, the increase of n_w leads to an increase in the contact zone between the cut-off wheel and workpiece as a result of the increase of contact arc. This, coupled with the fact that in the course of cutting the workpiece appears a tool coolant absorbing part of the released heat, which subsequently is transferred to the chip, determines the increase of the workpiece temperature and the decrease of the cut-off wheel temperature. The increase of the workpiece rotational frequency implies a decrease of the cut piece temperature on account of an increase in the thickness of the layer is cut and the cross-section of the chip being cut by one abrasive grain, as well as enhanced heat removal resulting from the longer time per cut.
3. As the cut-off wheel diameter d_s decreases, the number of abrasive grains cutting a layer per one revolution of the cut-off wheel also decreases. This causes an increase in the thickness of the chip being cut by one abrasive grain. In addition, when the cut-off wheel rotational frequency is constant, the decrease of the wheel diameter results in a decrease of speed, which further deteriorates the cutting abilities of the abrasive grains. All this is a precondition for increasing the dimension and rate of cut-off wheel wear, the time per cut, and the workpiece temperature and, on the other hand, for decreasing the temperature of the cut piece and cut-off wheel because of enhanced heat removal.

The analysis has been carried out shows that elastic abrasive cutting is a sophisticated multi-parameter and multi-factor subject of study, modeling, and optimization

[24]. It is characterized by a number of target parameters—economic (productivity and cost), dynamic (cutting forces and power) and technological (cut-off wheel wear and tool life, cutting temperature, noise, roughness and precision of machined surfaces, physico-mechanical properties of the surface layer—structure, microhardness, surface residual stresses, flaws, etc.). Each of the above parameters has a specific meaning in relation to abrasive cutting yet is insufficient for its optimum control.

The parameters of elastic abrasive cutting are determined by numerous control factors—physico-mechanical properties of the materials being machined, methods and components of the cutting mode, cut-off wheel type and characteristics, type and way of supplying cooling fluids, etc.

In the course of abrasive cutting, a number of interrelated, yet of a different type, nature, and intensity, phenomena occur and various materials, cut-off wheels, and cutting modes are used. Each abrasive cutting process is unique and could be studied from different perspectives: technological, energetic, informational, organizational, etc. When it is investigated, new experimental data and models are obtained, which differ from those of the preceding processes. Therefore, its investigation, modeling, analyzing, control, and optimization are always specific.

3. Thermal phenomena in abrasive cutting

3.1 Heat generation and heat removal in abrasive cutting

The mechanical work done in cutting involves deformation (elastic and plastic) of the material being machined, action of friction forces on the face and flank of cutting abrasive grains, and formation of new surfaces (dispersion). The amount of heat generated in cutting per unit of time, expressed by the work done in cutting and the mechanical equivalent of heat ($I = 427 \text{ kgm/kcal}$), is as follows:

$$Q = \frac{F_c V_c}{I} = 9.8 F_c V_c \quad (1)$$

where: F_c —main cutting force; V_c —cutting velocity; $V_c = V_s$ (V_s —velocity of the main rotary motion of the cut-off wheel).

Intensive thermal fluxes flow through the tool, chip, and material being machined in high-speed abrasive cutting. The large amount of heat generated in the course of abrasive cutting is transferred to the workpiece (Q_w), cut-off wheel (Q_s), and chip (Q_{ch}) and it is released into the environment (Q_p) [4, 7, 8, 21, 22, 25]. The transfer of heat in those directions is implemented by heat conduction, convection, and radiation.

A wide range of changes in the thermal flux components depending on the selected schema for process implementation (rigid or elastic abrasive cutting), the characteristic of the cut-off wheel, the physico-mechanical properties of the material being machined and the cutting mode has been established.

$Q_w = (10\% \div 85\%)Q$; $Q_s = (10\% \div 85\%)Q$; $Q_{ch} = (30\% \div 75\%)Q$; $Q_p \approx 10\%Q$ [4, 7, 8, 22, 25, 26]. This implies different temperatures of the working and lateral surfaces of the cut-off wheel, as well as different temperatures of the workpiece and chip.

Actually, the whole action of the friction forces in the contact zone below the neutral line AF (**Figure 2**) is transformed into heat (Q_f) and enters the workpiece.

During the initial contact between the abrasive grain and the workpiece, taking into account the comma-shaped cross-section of the layer being cut when $h < h_k$

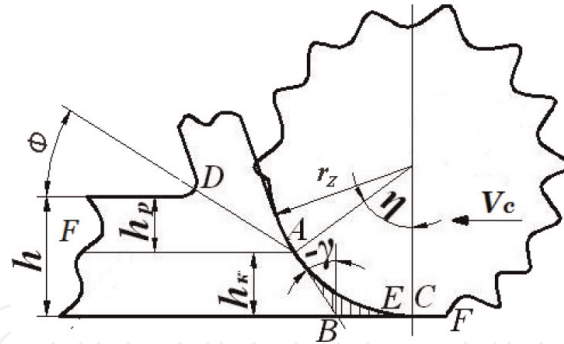


Figure 2.
Schema of chip formation in abrasive cutting.

(h_k -thickness of the layer being cut, where micro-cutting starts, and which depends on the radius of curvature of the edge of the abrasive grain), chipless plastic ejection of the material being machined occurs before the abrasive grain. There is also some heat dissipation [14, 17, 19]. Heat transfer is implemented by heat conduction and radiation.

When the values of the layer being cut are $h > h_k$, a cutting process where chips are formed starts. The heat Q_d generated as a result of deformation and used for shear along the shear surface within chip formation depends on the thickness of the material being cut h_z and the cross-section A_z of the material being cut by one abrasive grain. It is distributed as the heat transferred to the chip and heat transferred to the workpiece. It is assumed that the part of heat Q_d transferred to the workpiece is $Q_w = 0.7Q_d$ [14, 17, 19]. In fact, the heat resulting from chip formation and transferred to the chip is less due to convection losses.

The part of heat transferred to the workpiece is reduced when increasing the cutting speed because of the change in the ratio between the cutting speed and the heat dissipation rate in the deformation zone [14, 17, 19]. The dissipation rate of generated heat depends on the gradient of the temperatures along the shear surface and the heat conductivity of the material being machined. When the cutting speed, i.e. the speed at which the abrasive grain crosses the thermal flux, is low, the heat from the shear surface is transferred unobstructed to the workpiece. As the cutting speed increases, the cutting abrasive grain crosses the thermal flux faster and faster. As a result, a smaller amount of heat is transferred to the workpiece and a larger amount of heat remains in the chip:

$$Q_w = 0.7\chi Q_d \quad (2)$$

where χ is a coefficient of a decrease of the heat transferred to the workpiece caused by the change in the ratio between the cutting speed and heat dissipation rate [19, 27] $\chi = 0.3 + (80.1 - V_c)10^{-3}$.

Since a large part of heat (almost all the heat generated by plastic deformation and part of the heat generated by friction) is generated in the chip, the largest part of process heat remains there. Heat in the abrasive grain occurs externally as a result of friction and heat transfer from the hot chip to the colder abrasive grain, from plastic deformation, from the shear of the material under the neutral line, as well as from friction along the grain flank. As a consequence of conduction, the heat generated on the surface AB (**Figure 2**) is transferred to the abrasive grain and workpiece. The better the heat transfer from the surfaces being heated, the lower the temperature of those surfaces, i.e. the properties of heat conductivity and heat resistance influence the performance of cut-off wheels and the quality of machined surfaces.

The temperature of the cut-off wheel work surfaces (above 100°C) depends on the thermal flux density $\phi = dQ/dA$ (A —contact surface area of the abrasive cut-off wheel and workpiece) and tool thermal characteristics. In the course of cutting heat enters the material being machined through the contact area between the cut-off wheel and workpiece. The size of that area and, respectively, the dimensions and power of the heat source depend on the parameters of the cutting mode. The shape and dimensions of the heat source are mainly determined by the cut-off wheel thickness b_s , the wheel characteristics, and the length of the contact arc L between the tool and workpiece. In the course of cutting the workpiece appears a coolant of the tool, absorbing part of the released heat, which is consequently transferred to the chip. In this respect, it would be better to expand the contact zone (b_sL), which would result in an increase of the workpiece temperature and a decrease in the cut-off wheel temperature. Simultaneously, the temperature in the cutting zone is also affected by load of abrasive grains and the volume of the machined material removed by one abrasive grain, which are directly dependent on the wheel characteristics.

The cutting process in abrasive cutting is accompanied by melting of chips and plenty of sparking, which result from a large amount of heat generated in the cutting zone by friction forces, deformation of the material being machined, and reaction during burning. During burning every material has a specific point at which it ignites. When reaching the ignition temperature under the influence of oxygen, the physically and chemically clean surfaces of the steel workpieces being machined are oxidized to form iron oxide and slag. During oxidation, a considerable amount of heat is released, which provides additional heating of the very small volumes of metal of the chips removed by the abrasive grains up to the melting temperature. The presence of carbon in the material being machined increases burning and the temperature in the cutting zone, which is the reason for the different colors of the formed sparks in abrasive machining. Under the influence of the high speed of the abrasive cut-off wheel grains, the slag and iron oxide been formed are removed as glowing sparks [17]. The oxidation of the chip and the material being machined is useful since the oxide crust is fragile and facilitates chip removal. In accordance with the foregoing, the melting of the chip can be viewed as a positive factor because after melting the chip decreases its dimensions, which contributes to its easier removal by the cut-off wheel and to avoiding the filling of the tool pores with chips.

The burning of materials in abrasive cutting does not allow us to directly measure the temperature of the removed chip since it ignites when it forms or immediately after that. The brightness and type of sparks formed during abrasive machining (a product of burning) are defined solely by the content of the chemical elements in the material being machined. The density and length of the spark flow depend on the components of the cutting mode.

The increase of the heat entering the cut-off wheel intensifies tool wear and decreases tool reliability and cutting intensity as a result of a decrease in the relative pressure of the abrasive grains on the surface being machined (because of the softening of the cut-off wheel bond). Heating up the workpiece in the cutting zone leads to changes in the microstructure of the surface material and the occurrence of thermal flaws. Structural changes in the cross-section of the cut, which require further machining, also occur as a result of smearing and chipping parts of the cut-off wheel, as well as of friction between its lateral surfaces and workpiece face [6, 7]. All the above mentioned demonstrates the decisive role of temperature in abrasive cutting regarding cut-off wheel performance and quality of machined surfaces. It also shows that the heat released in the course of abrasive cutting is an important informative

factor for optimizing the operating conditions in abrasive cutting and enhancing the effectiveness of the process and the quality of machined surfaces. Therefore, it needs to be studied, modeled, and optimized. The investigation and measurement of temperature distribution in abrasive cutting play a key role in machine building.

A great number of studies [4, 7, 15, 21, 22, 28] show that by controlling the thermal fluxes in the cutting zone, possibilities for improving the cut-off thermal mode are provided thus ensuring longer tool life, higher intensity of the cutting process and higher quality of machined surfaces. This could be achieved not only by changing abrasive cutting conditions (cutting schema and parameters of cutting mode), which directly determine the thickness of the layer being cut, and respectively the temperatures of the tool, chip, workpiece, and cut piece, but also by choosing the cut-off wheel characteristic.

3.2 Methods and tools for investigating temperature in abrasive cutting

Depending on the specific nature of cutting processes, various methods for investigating temperature are applied [27]:

1. Analytical and numerical methods (heat source method; finite difference method; finite element method)—They are based on the heat balance equation and the differential equation of heat conduction [27]:

$$\lambda \left(\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2} \right) - \rho C_p \left(V_c \frac{\partial \theta}{\partial x} + V_f \frac{\partial \theta}{\partial y} \right) + \dot{Q} = 0 \quad (3)$$

where: λ —thermal conductivity coefficient; C_p —specific heat capacity of the chip material; ρ —material density; θ —temperature of a point with coordinates x, y ; $\dot{Q} = \tau_s \dot{\epsilon}$ —heat exchange rate per unit of volume (τ_s —stress of cutting; $\dot{\epsilon}$ —speed of plastic deformation).

2. Experimental methods—They are used to measure the average and local temperatures, determine the zone of temperature distribution, and to visualize the temperature field. According to the way of measurement they are as follows:

- Contact methods—Indirect (calorimetric technique, microstructural analysis technique, method of chip coloring, thermal pain technique, and electrical modeling) and direct—thermocouple technique (artificial, semi-artificial, natural, and running). With those methods, the energy exchange between the environment and thermometric substance is based on heat conduction [29].
- Wireless measurement methods—They are based on the laws of thermal radiation of bodies. The wireless temperature measurement devices used in practice are as follows: optical pyrometers, spectral ratio pyrometers, radiation pyrometers, infrared thermometers, thermal imaging cameras [29, 30]. Choosing a proper device depends on a number of factors—temperature range, material, object dimensions, distance, ambient temperature. It should also be taken into account that the devices record the total energy in their range of vision. When measuring, they also include additional energy sources, including reflected energy, if they are in the range of vision.

Measuring temperature in abrasive cutting is difficult because of the small dimensions of the zone being heated (only tenths of mm^2), high temperatures (hundreds of degrees Celsius), high-temperature gradient (more than $200^\circ\text{C}/\text{mm}^2$), high mechanical load, and high heating speed. This predetermines the preferential use of analytical and numeric methods, as well as wireless methods, for investigating the thermal phenomena in that process.

The thermal phenomena in rigid abrasive cutting are well studied unlike those in elastic abrasive cutting. Numeric, analytical, and finite-element models were developed to define and analyze temperature distribution [3, 13, 18, 20, 31]. Thermal fluxes were investigated under different cutting conditions and strategies for optimizing the parameters of rigid abrasive cutting with regard to decreasing the temperature in the cutting zone were proposed [32–41]. In addition, a high-accuracy simulation model for forecasting temperature was proposed. It can be used for forecasting and preventing thermal flaws [33].

Analytical models for determining the temperature in elastic abrasive cutting were also proposed. On the basis of the analysis of thermal phenomena, the inability to directly measure chip temperature was justified and a methodology and an analytical dependency for the theoretic definition of chip temperature, reflecting the effect of the cutting speed and the workpiece rotational frequency, were proposed [42]. A model of the chip temperature, proving the decisive influence of the thickness of the layer being cut by one abrasive grain on it, was developed. An approach to the theoretical and experimental definition of the amount of heat released for one cut-off cycle and transferred to the workpiece being machined, as well as of the cut piece temperature, was proposed [43].

By applying the calorimetric technique for measuring temperature and the methodology of the planned experiment, a theoretical and experimental model for the temperature of the cut piece made of C45 steel depending on the cut-off wheel speed and workpiece rotational frequency was built. It was established that cut piece temperature decreases as cutting speed decreases and workpiece rotational frequency increases. This effect is related to the enhanced heat removal resulting from an increase in the thickness of the layer being cut, the cross-section of the chip being cut by one abrasive grain, and time per cut.

The possibilities for wireless temperature measurement and monitoring by applying infrared thermography are studied in [4, 7, 25, 44]. It was found that the cut-off wheel compression force on the workpiece had the greatest effect on the maximum cut-off wheel temperature, respectively on the tool life [4, 7]. It was also found that temperature increased as the workpiece diameter increased. Furthermore, when cutting fixed workpieces, the combination of larger cut-off wheel diameter and a greater compression force results in generating higher temperatures and obtaining lower values of G-ratio. Studies were done with a focus on the possibilities of using infrared thermography as a tool for wireless and non-invasive thermal investigation of the process and tools of elastic abrasive cutting of rotating workpieces [25, 44]. Experimental data from thermographic measurements done by an infrared camera regarding the effect of workpiece rotational frequency, compression workforce, and cut-off wheel diameter when machining various materials on the temperature distribution on workpiece surface, cut-off wheel, and cut piece were presented.

The analysis of the methods and approaches used for investigating and monitoring temperature in abrasive cutting shows the advantages of wireless measurement methods such as infrared thermography (IRT). This method is increasingly recognized and widely used as a reliable and effective tool for thermal wireless

non-destructive testing under real conditions of dynamic processes such as abrasive cutting [4, 7, 12, 25, 29, 44]. Its application allows us to enhance the effectiveness of abrasive cutting. However, the use of IRT has some disadvantages.

The availability of metal parts in equipment leads to a number of reflections that impede temperature measurements on the surfaces under study and vary depending on their orientation, temperature, and wavelength. Temperature measurements by using thermography do not provide us with absolute temperature values. To obtain such values, we should use modeling and look for a correlation with the change in surface temperature. IRT measurements are indirect with regard to temperature measurements in the cutting zone. Although the cut-off zone can be observed from the side at a specific position of the camera, the infrared radiation from the cut-off wheel, workpiece, and produced chips affect the results from the temperature measurement of the surface being observed. Therefore, a thorough study of the possibilities for applying infrared thermography in abrasive cutting is required.

4. Infrared thermal control of elastic abrasive cutting

There is a qualitative and quantitative non-contact thermographic temperature control. Qualitative control does not require obtaining an accurate surface temperature, but it is sufficient to obtain thermal signatures, which are characteristic models of relative temperature phenomena at different combinations of the abrasive cutting process control factors values. The relative temperature values of the objects in the cutting area to the temperatures of the other equipment objects with similar conditions are used. Quality visual inspection is appropriate for collecting a large number of detailed data and transmitting them for easy interpretation. It is suitable for controlling the efficiency of the process by monitoring the temperatures of the cut-off wheel, workpiece, cut piece, and chip under certain conditions of the abrasive cutting process.

In quantitative thermographic measurement, the ambient temperature is the reference. The observation of the abrasive cutting is established by measuring the absolute temperature of the studied object, under the same environmental conditions. As the reference temperature must be measured, this requires even better knowledge of the variables affecting the radiometric measurement, as well as taking into account the limitations.

The transition from qualitative to quantitative thermographic control is associated with the need to solve four tasks:

- Methodical provision of the procedure for determining the surface temperature of the objects participating in the cutting process with the respective metrological analyses;
- Obtaining information about the spectral normal emissivity of the object and its surrounding background for the entire spectral range of the optoelectronic system;
- Taking into account the influence of the layers covering the surface of the controlled objects, partially transparent to the heat radiation, on the accuracy of determining the surface temperature by non-contact methods;
- Measurement of temperatures comparable to the temperature background, taking into account the influence of the background heat radiation on the experimental results.

The aim of the study is first to develop a methodology for monitoring the evolution of surface temperature to identify the process of elastic abrasive cutting by IRT. For this purpose, a modular thermographic measuring system is proposed to monitor the process from different positions.

The illustrated in **Figure 3a** and **b** setup is a part of the more complex experimental framework, which is not the object of the present study [13, 25, 31, 44, 45].

Special attachment is developed, which is fixed to the main carriage of a combined lathe, having a device for step-less adjustment of rotational frequency workpiece to perform the elastic abrasive cutting process [46, 47]. In this way, a constant rotational frequency of the cut-off wheel can be provided and adjust the amount of compression power F of the cut-off wheel (2) on the workpiece (1). High-speed reinforced cut-off wheels 41–180 × 22.2 × 3.0 A30RBF have been used during counter-directional cutting. Steel cylindrical rods with a diameter of 30 mm of C45 (1.0503) and 42CR4 (1.7045) were processed. **Figure 3c** and **d** shows the raw thermograms and the regions of interest (ROI) for the IRT control.

- a. Cut-off area of the workstand for elastic abrasive cutting
- b. Setup of abrasive cutting's remote non-destructive thermal control
- c. Raw thermogram from the camera (3) Raw thermogram from the camera (4)

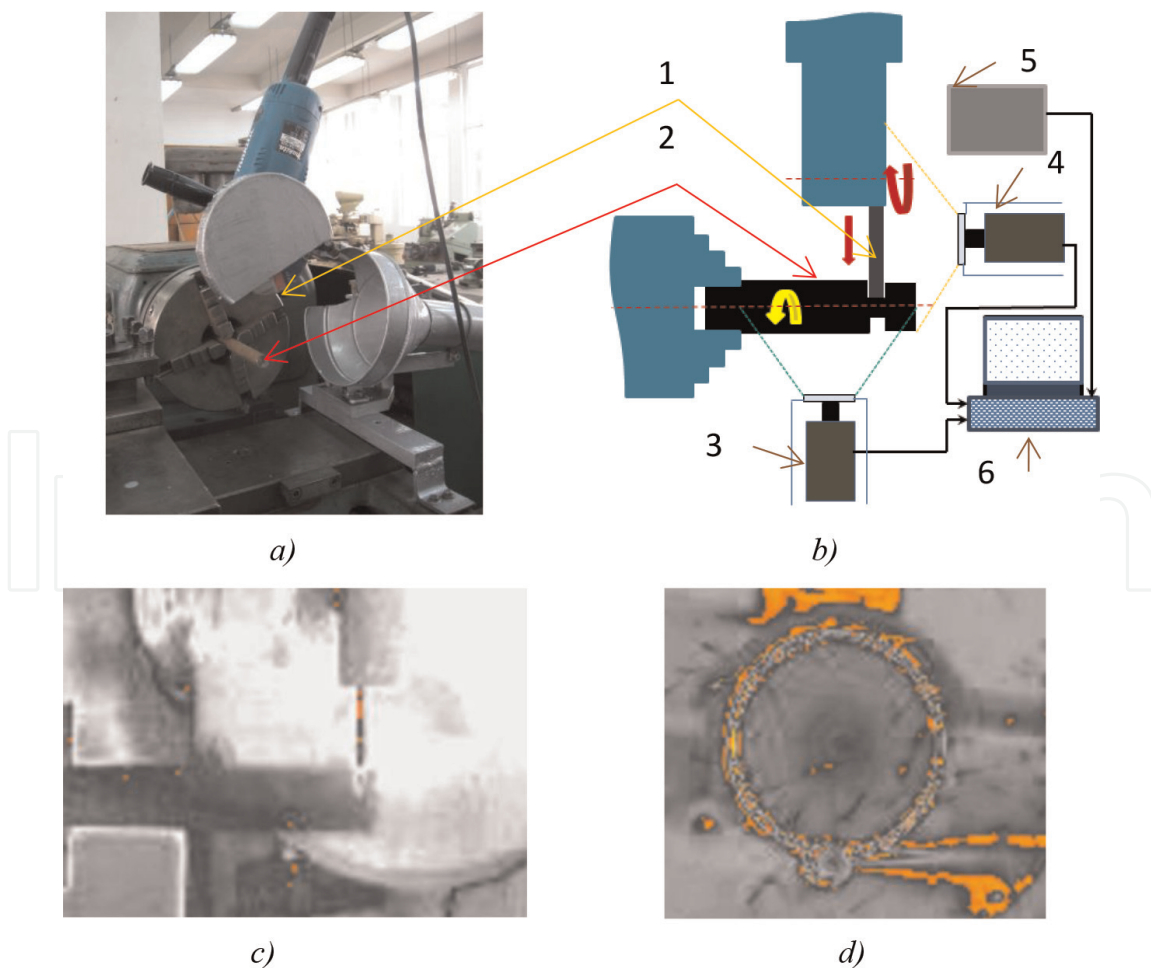


Figure 3. Elements of workstand for elastic abrasive cutting, (a); setup for remote thermal control of cutting process, (b); a thermogram of the abrasive cutting made from the direction to profile of the cut-off wheel, (c); a thermogram of the abrasive cutting made from the direction to full-face of the cut-off wheel, (d).

Unlike previous studies, thermographic measurement of the surface temperatures is performed simultaneously with two factory-calibrated FLIR SC660 infrared cameras (3) and (4), which work synchronously with the same or different frame rates and are located orthogonally. The cameras have a temperature range from -40°C to $+2000^{\circ}\text{C}$, temperature sensitivity (NETD) $<0.045^{\circ}\text{C}$ and IP-link using FireWire. Matlab, FLIR ResearchIR Max and SDK softwares are used for thermal analysis and supporting cameras communication with the computer (6). The PASCO PS-3209 wireless sensor (5) is used in data collection mode for ambient temperature and relative humidity during thermographic measurements.

LabIR @ thermographic high-temperature applications paint, with high mechanical resistance for long-term uses and high emissivity is sprayed to cover the entire work surface of the workpiece, the cut-off wheel, and exposed metal parts of the equipment. The layer paint thickness is measured by TROTEC BB20. Infrared cameras are located in isolating boxes with IR windows (shown in **Figure 3**). The outside of the boxes is also coated with paint to minimize the reflections from cameras.

A problem in the quantitative thermographic control of elastic abrasive cutting is the identification and suppression of thermal reflections in thermograms. The approach for thermal measurements of the process at an angle from 40 to 60°C was applied. Cold image subtraction and/or background subtraction is used as image processing methods for reflection reduction in thermograms.

After conducting the experiments for thermographic measurement to verify the calculated maximum temperatures of the cut-off wheel, workpiece, and cut piece and derive the corresponding correlation dependencies, the need to use a second infrared camera was eliminated. For the needs of elastic abrasive cutting online thermographic quality monitoring, only one camera is sufficient (camera (3) in **Figure 3b**).

Thermographic measurements were also performed with other approaches, which is not part of the present study. These relate to quantity thermography, such as the use of IR polarizing filters and deep learning to assess the condition of the elastic abrasive cutting process.

IRT used to detect the cut-off wheel wear can help abrasive cutting process automation and dynamically control.

The introduction of an online thermographic inspection system allows continuous monitoring of temperature evolution and thus prevents damage to the workpiece or machine. The following are illustrated possible information criteria for use in such a system.

Figure 4 illustrates the possibility of the IRT system to measure and record the surface temperatures (optional maximum, minimum, average values) in the camera field of vision. Areas (regions of interest—ROI, lines, polygons, etc.) can be selected to identify the temperature distribution and evolution in the process of abrasive cutting in the form of graphs. Such a local inspection of the change in surface temperature significantly increases the visual resolution of the selected area. This visualizes the momentary disturbances from the spark's temperatures. **Figure 4a** shows the temperature curves for the marked lines on the workpiece and the cut piece in a direction transverse to the workpiece axis and close to the cutting area. The temperature profile longitudinally on the axis of the workpiece in the area of the marked line is shown in **Figure 4c**. The temperature profiles for different lines passing through the axis of the cut-off wheel show the change in surface temperature near the cutting area and at the farthest end from this area. **Figure 4d** shows the regions of interest (ROI) for the workpiece, the cut-off wheel, and the cut piece whose maximum temperatures are measured.

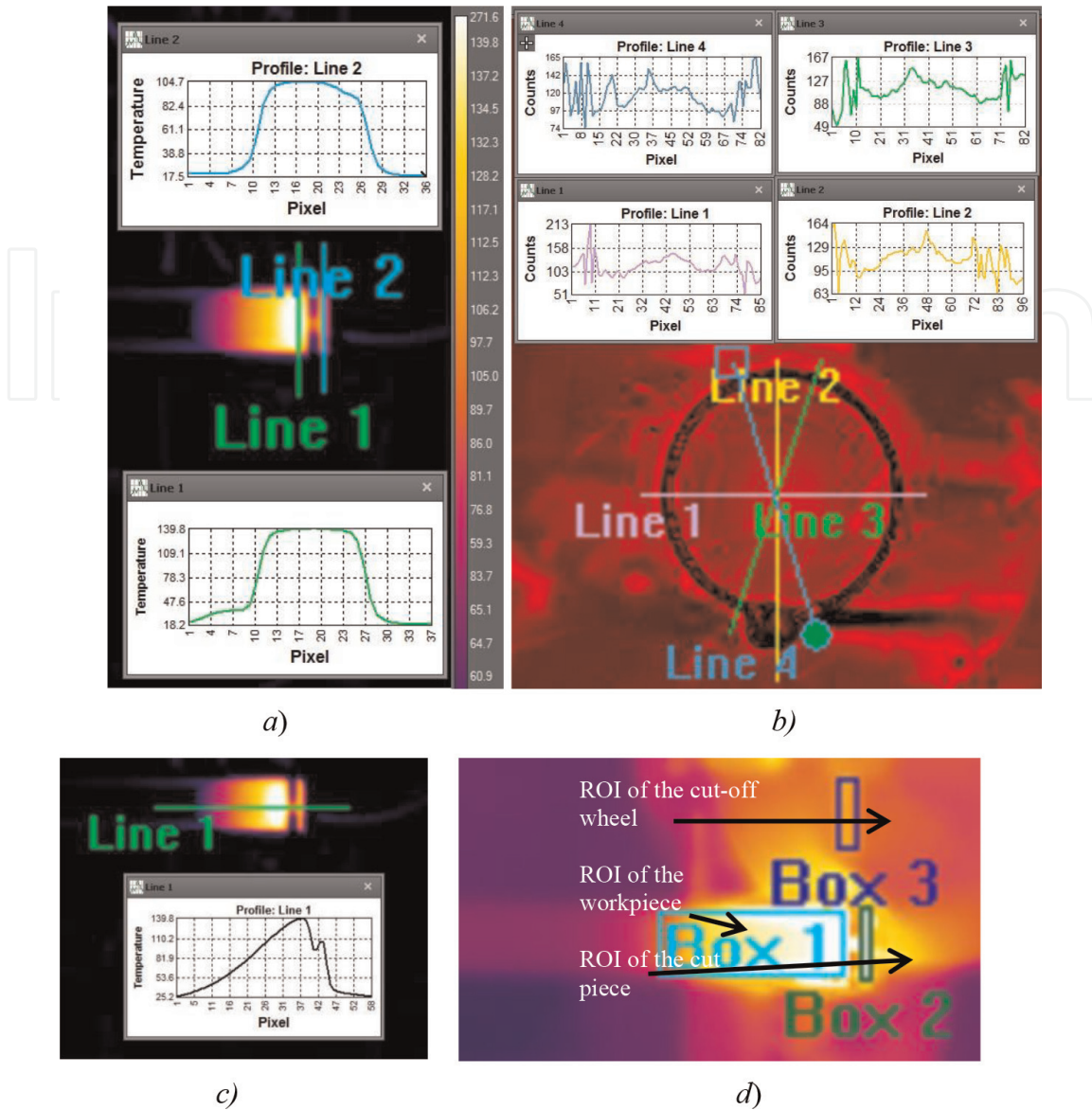


Figure 4. Thermograms image with chosen regions and temperature distribution along with selections. (a) Thermogram from camera (3) (b) thermogram from camera (4). (c) Thermogram from camera (3) (d) thermogram with chosen ROIs.

Due to the lack of a standardized format for reading IR images, software for processing and computer analysis of thermographic images has been developed. So thermal images can be processed regardless of what type of camera they were shot. The wear of the cut-off wheels has been checked. For this purpose, they are divided into four categories: standard (new cut-off wheel, as a reference), slightly worn, critically worn, and worn, which can no longer be used. One or another classification can be prepared on the basis of different criteria for different applications of elastic abrasive cutting. During data processing, areas with elevated temperatures and possible causes of wear are identified. Thus, on the basis of the initial thermal histograms, criteria for diagnosing and evaluating the resources of the cut-off wheels are formed.

The thermal histogram family (according to the camera view of vision) of the entire thermogram or the thermal histogram family of a selected ROI can be used to account for deviations in the quality of the elastic abrasive cutting process relative to a pre-selected optimal process.

Figure 5 shows (according to the camera's view) a raw thermogram with selected ROI (rectangular area), and the area of the cut-off wheel marked with a black outline. **Figure 6** shows a raw 3D thermogram of the selected ROI. **Figure 7** shows the family of thermal histograms for the same ROI.

There are three density modes of temperature calculation in the histograms:

- High: per each pixel;
- Medium: average temperature using aperture size 3×3 ;
- Low: average temperature using aperture size 5×5 .

Medium and Low approximations automatically exclude any garbage colors detected inside the camera apertures.

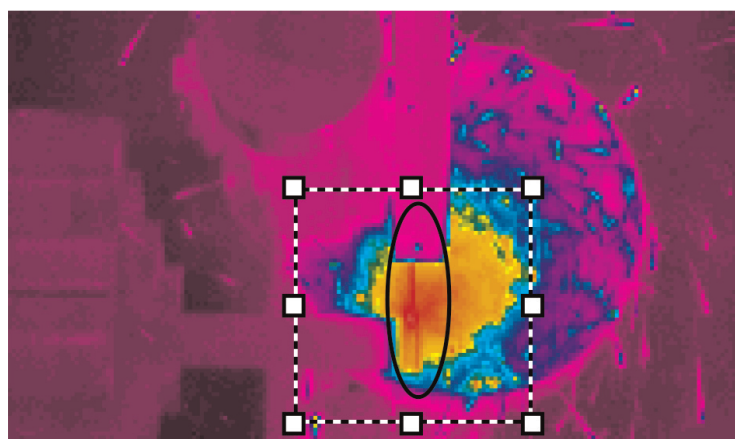


Figure 5.
Infrared image captured with a standard thermal camera.

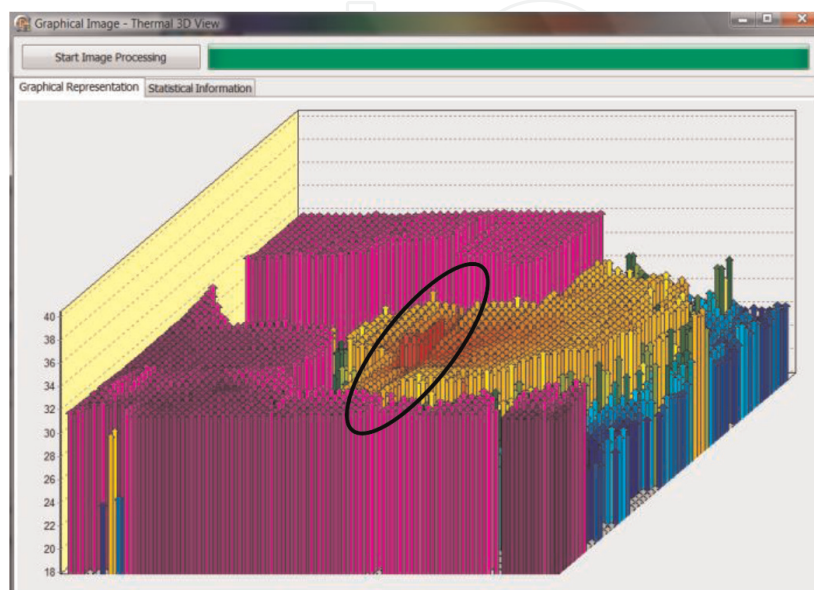


Figure 6.
3D thermogram of the selected ROI in Figure 5.

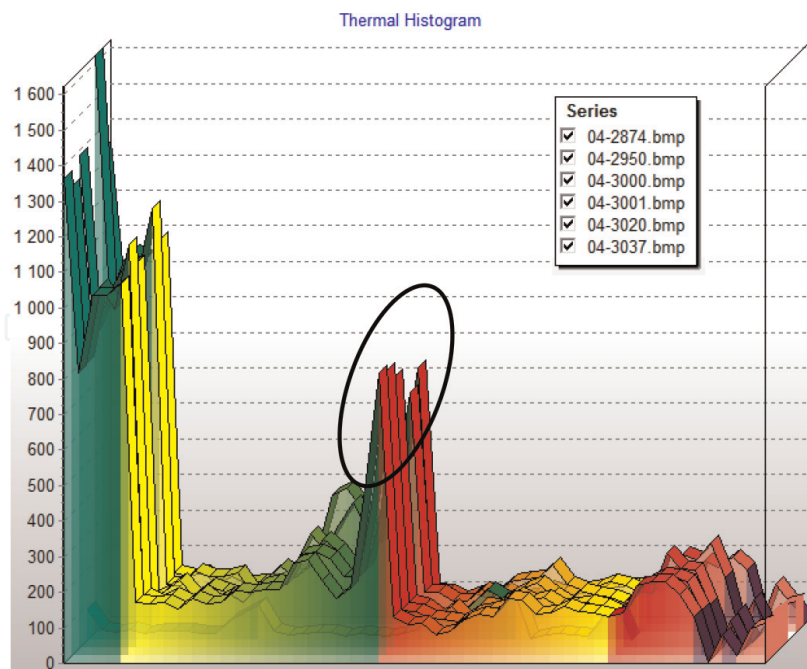


Figure 7. 3D layered thermal histograms (a family) for IR image sequence of the selected ROI with the workpiece, cut-off wheel, and cut piece.

5. Thermal modeling and optimization of elastic abrasive cutting of structural steels

The general form of the models describes the dependency between the workpiece temperature T_w , cut-off wheel temperature T_s and cut piece temperature T_d in elastic abrasive cutting of C45 and 42Cr4 steels, and the operating conditions of the process (cut-off wheel diameter d_s , cut-off wheel compression force F exerted on the workpiece, and workpiece rotational frequency n_w), is as follows:

$$y_g = b_0 + \sum_{i=1}^3 b_i X_i + \sum_{i=1}^3 b_{ii} X_i^2 + \sum_{i < j} \sum b_{ij} X_i X_j \quad (4)$$

where: y_g —studied response variables ($g = 1 - 6$): $y_1 = T_{w,C45}$, $y_2 = T_{s,C45}$, $y_3 = T_{d,C45}$, $y_4 = T_{w,42Cr4}$, $y_5 = T_{s,42Cr4}$, $y_6 = T_{d,42Cr4}$; $X_1 = d_s$, $X_2 = F$, $X_3 = n_w$ —control factors (**Table 1**).

To build the models (4), multi-factor experiments were conducted using an orthogonal central-composite design with a number of trials $N = 2^n + 2n + 1 = 15$

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

Table 1. Factor levels in the experimental design.

($n = 3$ is the number of control factors). Three observations were made for each experiment. The variation levels of the factors, were chosen on the basis of preliminary conducted experimental studies on the cut-off wheel performance [13, 31] and thermal flux distribution in the workpiece, chip, cut-off wheel, and cut piece in elastic abrasive cutting [25, 44], are presented in **Table 1**.

The models (4) were built using the measured values of the workpiece maximum instantaneous temperature, cut-off wheel maximum contact temperature, and cut piece temperature at the end of the cut-off cycle.

After statistical analysis of the experimental results by applying the multi-factor regression analysis method and QstatLab software [48], the following regression models for the workpiece temperature, cut-off wheel temperature, and cut piece temperature were built:

- when machining C45 steels:

$$\begin{aligned} T_{s,42Cr4} &= 89.928 + 3.887d_s + 5F - 0.394n_w - 0.011d_s^2 \\ T_{s,C45} &= 103.865 + 0.447d_s + 8F - 0.201n_w \\ T_{d,C45} &= -88.426 + 3.69d_s + 4.667F - 0.359n_w - 0.011d_s^2 \end{aligned} \quad (5)$$

- when machining 42Cr4 steels:

$$\begin{aligned} T_{w,42Cr4} &= 2965.024 - 21.143d_s - 140.028F + 0.063d_s^2 + 37.403F^2 + 0.006n_w^2; \\ T_{s,42Cr4} &= -89.928 + 3.887d_s + 5F - 0.394n_w - 0.011d_s^2 \\ T_{d,42Cr4} &= -89.928 + 3.887d_s + 5F - 0.394n_w - 0.011d_s^2 \end{aligned} \quad (6)$$

The models built extremely accurately describe the dependency between the variables and control factors. The values of the determination coefficients are $\hat{R}_g^2 = 0.849 - 0.965$ and they were determined at a significance level of $\alpha = 0.05$.

In **Figure 8** and **Figure 9** the bar diagrams of measured and calculated maximum temperatures are presented, at different parameters of the abrasive cutting process for both materials with the same workpiece diameter. The maximum temperatures are the averages of five measurements for the cut-off wheel, the workpiece, and the cut piece. The error of the calculated values does not exceed 2% (under 20°C) in the worst case.

The analysis of the models built makes possible the evaluation of the effect of the operating conditions on the temperatures of the workpiece, cut-off wheel, and cut piece:

- Among all factors under study, the workpiece rotational frequency has the highest effect on temperature in elastic abrasive cutting. As n_w increases within the range being studied, cut piece temperature and cut-off wheel temperature decrease (respectively by up to 29% and 19%) whereas workpiece temperature increases by up to 12%. The nature of this change is linked to the enhanced heat removal as a result of: the thicker layer being cut, the increased cross-section of the chip being cut off by one abrasive grain, the increased time per cut, and the increased contact zone between the cut-off wheel and workpiece resulting from the longer contact arc.

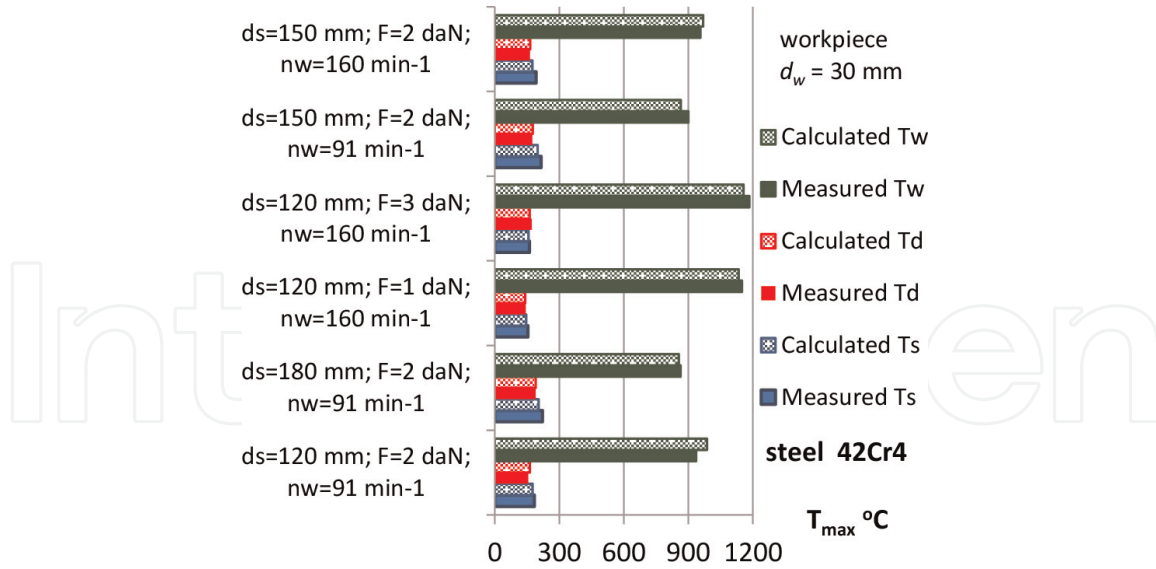


Figure 8.
 Temperature bar diagrams for different parameters of the elastic abrasive cutting of 42Cr4.

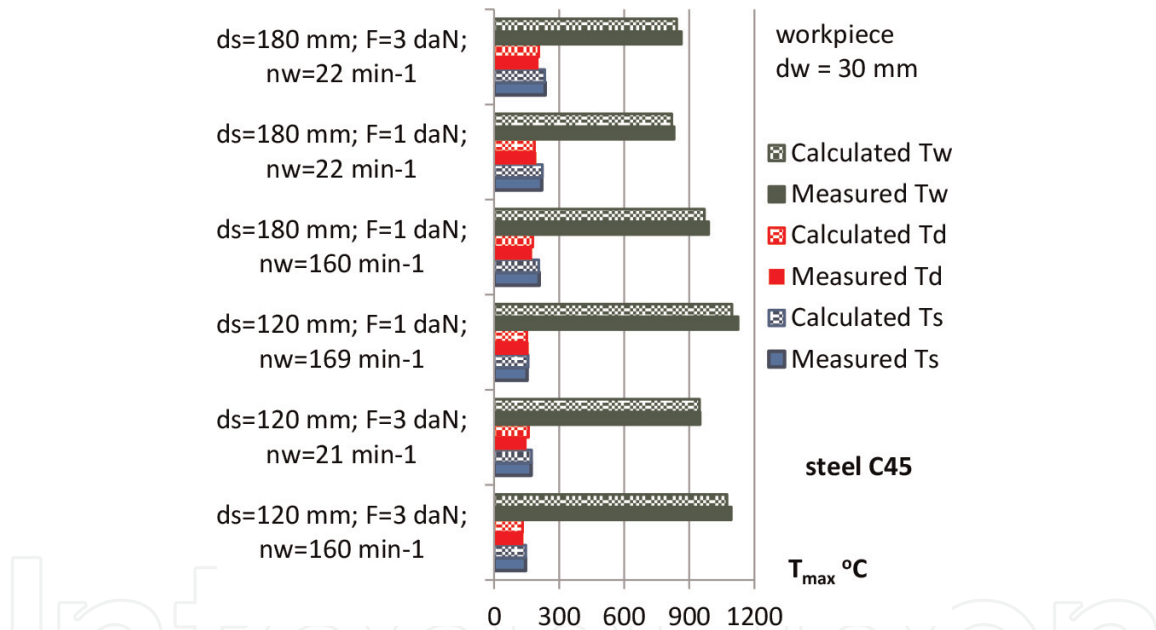


Figure 9.
 Temperature bar diagrams for different parameters of the elastic abrasive cutting of C45.

- As the cut-off wheel diameter d_s decreases within the range under study, cut piece temperature and cut-off wheel temperature decrease whereas the workpiece temperature increases as the change is within the range from 11 to 17%. That is related to the thicker layer being cut and the increased cross-section of the chip being cut off by one abrasive grain, which enhances heat removal as abrasive cut-off time increases and cutting speed decreases.
- The compression force has the least effect on temperature. As it increases, the temperatures of the cut piece, cut-off wheel, and workpiece increase by 5–11%. The minimum effect of the compression force is related to the fact that when F increases, the elastic abrasive time per cut decreases, and on the other hand, the length of contact arc and the depth of cut increase.

- The nature of influence of workpiece rotational frequency, cut-off wheel diameter and compression force on the temperature in elastic abrasive cutting are equal for the two materials under study (C45 and 42Cr4 steels). Nevertheless, the temperatures of cut-off wheel, workpiece, and cut piece are higher when machining 42Cr4 steel (by 4–7%), which is related to the higher hardness and strength of this material.

Each studied temperature parameter of the elastic abrasive cutting process has a specific meaning yet is insufficient for its optimum control. The optimum values of the temperatures of the cut piece, cut-off wheel, and workpiece for each material being machined will be obtained at different combinations of values of control factors (cut-off wheel diameter, compression force, and workpiece rotational frequency). Therefore, optimization by one parameter is irrelevant. Multi-objective optimization provides much more information so as to make a justified decision on the selection of optimum elastic abrasive cutting conditions. There are various algorithms for its implementation, which differ in the type and number of target parameters, as well as in the method for determining the optimal solution [45, 49]. To determine the optimum elastic abrasive cutting conditions, multi-purpose optimization was implemented as the area where the temperature parameters under study obtain minimum values were determined. The optimization problem is reduced to solving the following system of inequalities:

$$\begin{cases}
 d_{s,l} \leq d_s \leq d_{s,u} \\
 F_l \leq F \leq F_u \\
 n_{w,l} \leq n_w \leq n_{w,u} \\
 T_d = f(d_s, F, n_w) \rightarrow \min \\
 T_s = f(d_s, F, n_w) \rightarrow \min \\
 T_w = f(d_s, F, n_w) \rightarrow \min
 \end{cases} \quad (7)$$

where $d_{s,l}$, $d_{s,u}$, F_l , F_u , $n_{w,l}$, $n_{w,u}$ are respectively the top and bottom levels 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)—**Table 1**.

Functions $T_d = f(d_s, F, n_w)$, $T_s = f(d_s, F, n_w)$ and $T_w = f(d_s, F, n_w)$ reflecting the correlation dependencies of the temperatures of workpiece, cut-off wheel, and cut

Steel, type	Optimization method	Control factors			Response variables		
		d_s (mm)	F (daN)	n_w (min ⁻¹)	T_w (°C)	T_s (°C)	T_d (°C)
C45	Genetic algorithm	150	2	91	863.15	168.53	199.2
	Random search method with increasing density	120	0.96	159.48	1057.03	133.02	133.02
42Cr4	Genetic algorithm	150	2	91	864.56	176.67	212.20
	Random search method with increasing density	120	0.8	159.99	1034.02	140.97	146.35

Table 2. Optimum conditions of elastic abrasive cutting.

piece on the control factors of elastic abrasive cutting process are described by Eqs. (5) and (6) for the two materials being machined—C45 and 42Cr4 steels.

The optimum conditions of elastic abrasive cutting, providing the best combination of minimum values of the temperatures of workpiece, cut-off wheel, and cut piece, were determined by applying two methods—genetic algorithm and random search method with increasing density. The optimization problem was solved upon machining of C45 and 42Cr4 steels by using QStatLab software [48].

The defined optimum conditions of the elastic abrasive cutting process are presented in **Table 2**.

6. Conclusions

This chapter considers the specifics of implementing the process of elastic abrasive cutting and analyzes the conditions for stabilizing the dynamic thermal phenomena accompanying it. The processes of heat generation and heat removal in abrasive cutting are generally analyzed, as well as the methods and tools applied to investigate temperature and thermal fluxes. An innovative approach to non-destructive thermal measurement and control of elastic abrasive cutting experimented for two types of structural steels by applying the methodology of planned experiment and multi-objective optimization has been proposed.

Latest trends show that there is a need to apply an automatic smart system for controlling thermal fluxes in the cutting zone so as to ensure a higher quality of machined surfaces and longer cutting tool life. This is also linked to the design of a new approach to non-destructive thermal control of abrasive cutting when developing a smart thermographic system.

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Nomenclature

a	cutting depth, mm
b_s	thickness of the cut-off wheel, mm
d_s	diameter of the cut-off wheel, mm
d_w	diameter of the workpiece, mm
F	cut-off wheel compression force, N
h	thickness of the layer being cut, mm
L	length of the contact arc, mm
n_s	rotational frequency of the cut-off wheel, min^{-1}
n_w	rotational frequency of the workpiece, min^{-1}
T_d	temperature of the cut piece, °C
Q	heat generated in cutting per unit time
Q_{ch}	heat transferred to the chip
Q_d	heat generated as a result of deformation
Q_f	heat transformed from friction force

Q_p heat transferred into environment
 Q_s heat transferred to the cut-off wheel
 Q_w heat transferred to the workpiece

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Author details


Anna Stoynova^{1*}, Irina Aleksandrova² and Anatoliy Aleksandrov²

1 Technical University of Sofia, Sofia, Bulgaria

2 Technical University of Gabrovo, Gabrovo, Bulgaria

*Address all correspondence to: ava@ecad.tu-sofia.bg

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