MATEC Web of Conferences **210**, 02018 (2018) https://doi.org/10.1051/matecconf/201821002018
CSCC 2018

Infrared Thermography for Elastic Abrasive Cutting Process Monitoring

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Abstract. This paper presents the features of infrared thermography (IRT) for contactless study of elastic abrasive cutting process of rotating workpieces. IRT monitoring specifics along with the experimental procedures and techniques for data analysis are discussed. IRT measurement results of the influence of workpiece rotational speed, during the processing of various materials, on heat release and heat distribution at the workpiece surface, on the cut-off wheel, the cut piece and the cutting time period are presented. The operational methodology and the results obtained can be used for optimizing the abrasive cutting of rotating workpieces.

1 Introduction

Abrasive cutting is a high efficiency process for rod workpieces manufacturing with rod diameter of up to 60 ÷ 70 mm by cutting disks with diameter of up to 400 mm and slit width up to 4 mm. There are several kinematic patterns for process implementation where the cutting disk performs main forward rotation motion with speed V_s and radial hand-over motion with a speed V_{fp} in reference to fixed or rotating workpiece [1, 2, 4, 5]. The radial hand-over of the tool is performed either cinematically by the cutting machine with V_{fp} = const (solid abrasive cutting) or by keeping constant clamping force of the disc to the workpiece (F = const), where $V_{fp} \neq$ const (elastic abrasive cutting).

Abrasive cutting is associated with large amounts of heat release that is delivered to the workpiece (Φ_{w}), the cutting disk (Φ_{s}), the swarf (Φ_{ch}) and afterwards the heat is dissipated in the environment (Φ_{p}) [3, 5, 6]. Depending on the selected pattern of process implementation, the characteristics of the cut-off wheel and the cutting mode vary in wide range of heat flux Φ components: $\Phi_{\mathrm{w}} = (10\% \div 65\%)\Phi$; $\Phi_{\mathrm{s}} = (3\% \div 20\%)\Phi$; $\Phi_{\mathrm{ch}} = (30\% \div 60\%)\Phi$; $\Phi_{\mathrm{p}} \approx 10\%\Phi$ [5, 7]. This assumes different temperatures of the discs' operational surface and the side surfaces as well as different temperatures of the workpiece and the swarf.

Therefore, the heat dissipated in the process of abrasive cutting is an indicative factor for process optimization in terms of operational mode and efficiency. The excessively high temperature during cutting reduces the operational reliability of the cut-off wheel which leads to increased emissions of environmentally harmful gases, structural changes in the cut cross-section of the (which may require additional processing), residual stresses and material losses.

There are two approaches to process optimization of abrasive cutting of rotating workpiece – modelling, experimental results verification as well as plan-of-experiment by measuring temperature distribution in the workpiece, the cut-off wheel and the cut item in real operating conditions. This paper implements the second approach of the abrasive cutting process study.

Different temperature measurement approaches are applied all of which, depending on their special characteristics, have its advantages and disadvantages [7]. In principle, the measurement is difficult due to the small size of the heated zone (only tenths of mm^2), high temperatures (hundreds of degrees Celsius), large temperature gradient (more than 200 $^{\circ}C/mm^2$), high mechanical load and high speed of heating.

Infrared thermography (IRT) is getting increasingly used as a reliable and effective tool for contactless monitoring and status qualification in real conditions of the cutting process [7, 8].

This paper presents the results of the application of thermography approach to analyze the heat flow distribution and to determine the workpiece temperature and the cutting disk temperature during of abrasive elastic cutting process. The temperature distribution at varied rotation frequency of the workpiece for different processed materials is investigated by an infrared (IR) camera.

2 Thermal Effects in the Cutting Zone

The temperature of the working surface of the cutting disk (over 100 °C) depends on the heat flow density

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$\varphi = d\Phi_s / dA$ (*A* is the area of the contact surface of the abrasive disk and the workpiece) and the thermal characteristics of the instrument. In the process of cutting the heat enters the workpiece material through the contact area between the cut-off wheel and the workpiece. The sizes of this area, and therefore the size and power of the heat source, depend on the cutting mode parameters. The shape and dimensions of the heat source are mainly determined by the thickness of the cut-off wheel, the characteristics of the disc and the length of the arc of the contact *L* between the tool and workpiece.

In the cutting process, the workpiece acts as a cooler of the tool by absorbing part of the generated heat, which is afterwards transmitted to the swarf. In this aspect, it is better to increase the contact area ($b_s \times L$), which would lead to an increase in the temperature of the workpiece and to reduction of the temperature of the cut-off wheel. At the same time, the temperature in the cutting zone is affected 1) by the abrasive grains load-up and 2) by the volume of the disjoined processed material by single abrasive grains which are directly dependent on disc characteristics.

Intense heat flows pass through the tool, the cutting swarfs, and the processed material during the process of high-speed abrasive cutting. The mechanical work spent for the cutting consists of deformation work (elastic and plastic) of the processed material, friction work and dispersion work (to form new surfaces). The deformation work W_d done on slipping over the plane of slip is almost entirely converted into heat and it is transmitted to the swarf W_{ch} , and to the workpiece W_w [3, 4, 6].

The heat from the slipping plane depends on the thickness of the cut material layer h_z and the cross-section A_z of the cut material by one abrasive grain. The propagation speed of induced heat depends on the temperature gradient at the slipping plane and the thermal conductivity of the material being processed. When the cutting speed (this is the speed of the cutter grain crossing the heat flux) is small, the heat from the slipping plane freely passes through the workpiece. By increasing the cutting speed the cutting abrasive grain crosses heat flux faster, so that a smaller amount of heat passes through the workpiece and increasing amount of heat remains in the swarfs. The process of cutting by an abrasive cutting is accompanied by the melting of the swarfs (plenty of sparking), which results from the large amount of heat generated in the cutting zone during the burning reaction.

Each material has a given point at which it ignites. Upon reaching a temperature of ignition under the influence of oxygen, the physically and chemically clean surfaces of the processed steel workpieces are oxidized to form iron oxide and slag. During this oxidation significant amount of heat is dissipated producing additional heat to the very small volumes of metal of the swarfs which dissociate by the abrasive grains to the melting temperature.

The presence of carbon in the processed material increases the combustion and increases the temperature in the cutting zone, which is the reason for the differently coloured sparks during abrasive treatment. Under the influence of the high speed of the abrasive cut-off wheel grains the formed slag and iron oxide are removed as glowing sparks. The oxidation of swarf and of the processed material is useful because oxide crust is a fragile component that facilitates the separation of the swarf.

The control of heat flows in the cutting area allows to improve the thermal mode of the cut-off wheel and thus to ensure an increase of its durability. Furthermore, by altering the conditions of the abrasive cutting (cutting pattern and parameters of the cutting mode), it directly determines the thickness of the cut material layer, and as a result the temperature of the tool, swarf, workpiece and the cut piece. This can be also be achieved by selection of particular characteristics of the cutting disc.

Increasing the heat entering the cutting disk increases the wearing of the tool and reduces the cutting intensity as a result of reduction of the relative pressure of the abrasive grains on the target surface (due to softening of the junction of the cutting disc). Heating of the workpiece in the cutting zone leads to changes in the microstructure of the material of the surface layer and occurrence of thermal defects. Blurring of the cutting disc and friction of the lateral surfaces to the facing surfaces of the workpiece are observed in the process of cutting. This leads to tool wreckage and to temperature increase in the zones of contact of the tool and the workpiece. These processes lead to structural changes in the cross section of the cut (whiskers, bumps, deformation of the material) that require further processing. All this shows the crucial role of temperature in the abrasive cutting for the performance of the cutting discs and quality of the treated surfaces and imposes the need for its study and reduction.

3 Experimental Studies

3.1 Equipment, Materials and Methods

For the implementation of the kinematic arrangement of an elastic abrasive cutting with a constant clamping force of the cut-off wheel to the rotating workpiece a special device is created (Fig. 1). It is set on the longitudinal support of an universal lathe, equipped with a device for stepless adjustment of the rotational speed of the workpiece n_w.

The arrangement comprises grinders, which provides constant speed of the cutting disk ($n_s = 8500\,\text{min}^{-1}$), a node to adjust the size of the clamping force *F* of the cutting disc to the workpiece and aspiration system for removal of flying swarfs.

In order to study the distribution of the heat flows in the elastic abrasive cutting and in order to establish any correlations between the temperature of the cutting disc, the temperature of the workpiece and the rotational speed of the workpiece, single-factor experiments are carried out at three rotation speeds: $n_{w_1} = 22\,\text{min}^{-1}$, $n_{w_2} = 80\,\text{min}^{-1}$ and $n_{w_3} = 160\,\text{min}^{-1}$.

Fig. 1. Installation for flexible abrasive cutting

The experimental studies are performed in an oncoming cut by cut-off wheels 41-180x22.2x3.0 A30RBF. The processed material is in the form of cylindrical rods with a diameter of $d_W = 30$ mm of steels C45 and 42Cr4 (Table 1). All studies are done at a constant clamping force $F = 0.8$ daN, to establish the minimum wear of cut-off wheel [2].

Table 1. Setting Word's margins.

Steel, type	**Chemical composition**			σ_B **[MPa]**	**HB**
	C, %	Mn, %	Cr, %		
C45 (1.0503)	0.44	0.5	0.2	750	192
42Cr4 (1.7045)	0.4	0.5	1	1000	205

To investigate the heat flow distribution in the workpiece, in the tool, and in the swarf thermography method is applied. Measurements are carried out by an infrared camera ThermaCam SC640, operating in the spectral range of 7.5 to 13 µm with image resolution 640 x 480 pixels and IP-link using FireWire. It has a temperature range of -40 °C to +2000 °C with thermal sensitivity 60 mK, spatial resolution of 0.65 mrad and accuracy ± 2 % of reading. This camera can acquire images and data at rates of up to 30 Hz with ThermaCAM Researcher Pro 2.9 software package. Real-time processing of thermograms is done by the same software. Further processing of thermograms is performed in MATHLAB. The IR camera was set up and the location of the analysis area was chosen to be on cutting area. Measurements are carried out in two positions: in the direction of cutting and in a direction perpendicular to the direction of cutting.

3.2 Experimental Results

The distribution of surface temperature of the cut-off wheel, the workpiece and the cutting detail in real time by using the resources of ThermaCAM Researcher Pro for analysis as: spot meter, line with cursor, box area, isotherm, scaling, plotting and logging measurement results, temperature profiles, histograms and others, such as emissivity calculation and subtraction of image files are examined. Program screen layout of the software with the results from the processing of the thermograms of the process of the elastic abrasive cutting is shown in Fig. 2. The infrared image, histograms, profiles of selected points, lines or areas, their positions and temperatures, along with values such as minimum, maximum, difference (max-min), mean and mean square deviation and more are displayed on the PC screen.

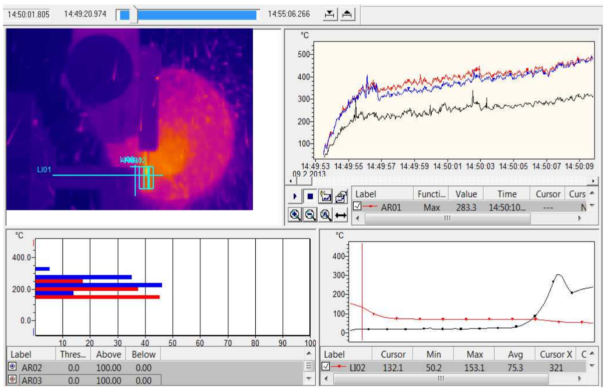

Fig. 2. Screen layout with results of thermographic measurements in real time

Fig. 3 a) and b) show consistent frames of an abrasive cutting process on the side of the cut-off wheel in a direction perpendicular to the direction of cut.

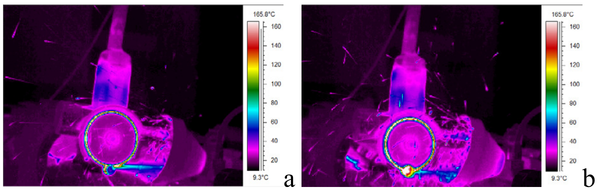

Fig. 3. Consecutive thermograms of the cutting disk in the process of cutting

Fig. 4 a) and b) show two consecutive thermograms of an abrasive cutting process taken in the direction of cut.

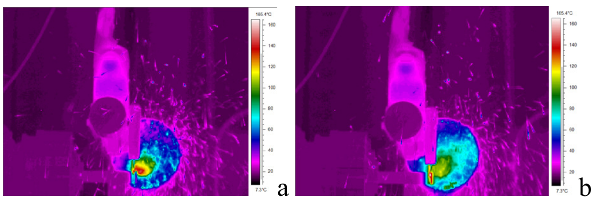

Fig. 4. Successive thermograms of the workpiece during the process of cutting

Experiments with thermocouples and with black paint (with emissivity of 0.95) are performed to determine emissivity at different temperatures of the cutting disk and the used workpieces from both materials. Data obtained from these measurements is used for software emissivity correction of individual objects in the thermogram. During the measurements the atmospheric temperature, relative humidity and reflected temperature, necessary for quantitative evaluation of the heat distribution in the process of abrasive cutting is recorded.

Fig. 5 shows the change of the average surface temperature of the workpiece of C45 material (in red color) and the maximum surface temperature of the cutting disk (blue) at rotation frequency of the workpiece 160 min^{-1}. The cursor (vertical black line) marks the end of the cutting process. When the cut piece is removed the disc surface temperature drops sharply to 50 °C, until the average surface temperature of the workpiece is increased by 5 °C for 0.45 s after the end of cutting due to conductive heat transfer. The nature of relationship that reflects the change of the workpiece temperature is determined by its geometry and thermophysical parameters. The length of the cutting process, which in this case is 0.54 s, can be considered from this temperature profile.

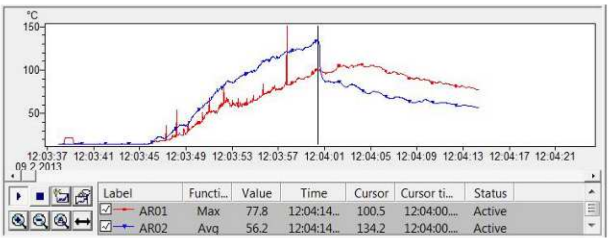

Fig. 5. Change of the average surface temperature of the workpiece and the maximum temperature of the cutting surface of the disk before, during and after completion of the cutting

Fig. 6 shows two possibilities in the examination of the state of the abrasive cutting process. The process of cutting after getting to a certain temperature (C3 area for the curve SP01, representing the change in the maximum temperature of the cutting disk) can be observed in real time and can be ceased, if required. The temperature change of certain points from the workpiece surface in real time may also be observed. The graph shows the temperature profiles for such points (SP02, SP03 and SP04), displaced on the surface of the workpiece away from the cut-off wheel, of 3 mm distance on the horizontal axis one to another. The regular temperature vibration due to the action of the clamping force and the rotational movement is noticeable on the graphics. These thermal vibrations propagate by convection in the workpiece and gradually subside after cutting of the workpiece.

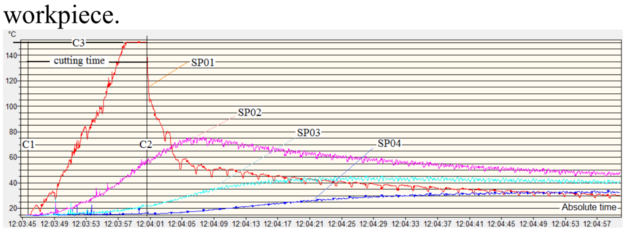

Fig. 6. Distribution of the surface temperature of the cut-off wheel, and individual points on the surface of the workpiece measured along the direction of the cutting (SP01- profile of a point of the cutting disk at 3 mm from the periphery; SP02, SP03 and SP04 - profiles of points on the surface of the workpiece located on the distance of 3 mm to one another).

Fig. 7 illustrates a method of temperature characteristics measurement of individual parameters of the elastic abrasive cutting process of rotating workpieces. The temperature distributions for line LI01 are in red and for line LI02 are in blue – they are shown in the thermogram of Fig. 7. The cursor can be moved and the coordinates of its position, the absolute time (or real-time) and the current temperature can be recorded. By knowing the distance to the subject and used optics the information about the actual location of the cursor in millimetres on the surface of the workpiece or cut-off wheel can be extracted. From the cursors' position on the temperature distribution profile of maximum temperature for lines LI01 and LI02 (LI01 in red is the horizontal line on the diameter of the cut-off wheel and LI02 in blue is the parallel line below it) on the surface of the cut-off wheel it can be read the maximum temperature before the instrument to pass through the cutting zone. From the profile of LI03 (dark purple color) perpendicular to LI01 LI02 it can be observed and quantitatively measured the temperature distribution of truncation detail during the process of cutting.

The dark purple cursor on the temperature profile of LI03 indicates the beginning of the profile of the temperature distribution on the surface of the truncation detail. The next peak to the right, at the larger times, indicates its end. There is an asymmetry in both ends of the temperature distribution of LI01 and LI02, due to the presence and location of an aspiration system. Quantitative data for the size and distribution of the surface temperature, the duration of cutting of the workpiece and the temperature profiles on the cut-off wheel, the workpiece and the truncations detail can be obtained from these temperature profiles in real time of cutting. The shape of the temperature distribution is an indication of the degree of wearing-out of the cut-off wheel as well as the quality of the cut detail. When changing the material and the frequency of the workpiece rotation such profiles change and allow for optimization of the cutting process efficiency. Syncing the frequency of capturing images by the camera with the rotation frequency of the workpiece or with the rotation frequency of the cutting disk, profiles are obtained after each turnover. , can be considered from this temperature profile.

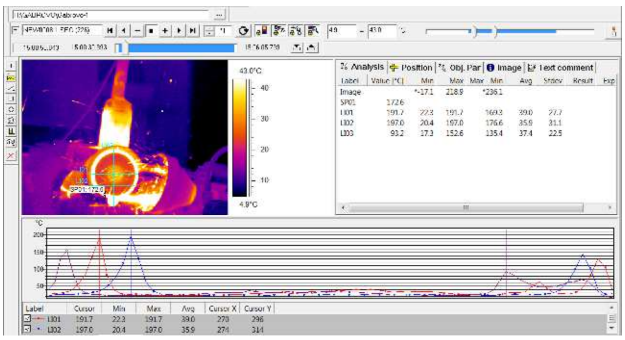

Fig. 7. Illustration of thermographic methodology for investigating the process of abrasive cutting.

The cursor for LI02 is at the periphery of cutting disk and for the lane LI01 is in the upper part of the workpiece, which is cut off, as shown in Fig. 7. Table 2 presents the results of an experimental study of the effect of rotation frequency of the workpiece on the surface temperature during the elastic abrasive cutting of the workpiece by steel C45 and 42Cr4.

Table 2. Temperature at elastic abrasive cutting.

Steel, type	n_w min-1	Maximum temperature, °C		
		of the workpiece	of the cutting disk	of the truncation detail
C45 (1.0503)	22	830	195	220
	80	840	160	210
	160	950	150	170
42Cr4 (1.7045)	22	850	200	235
	80	900	170	220
	160	1000	160	180

The analysis of the results shows that in both processed materials the temperature of the cut detail decreases with the increase of the rotation frequency of the workpiece. This is explained by the increase of the layer thickness of the truncation material and the cross-section of the shearing being cut by one abrasive grain, which improves heat transfer, as well as with the increase of cutting time. Increasing the frequency of rotation of the workpiece on the other hand leads to an increase in the temperature of the workpiece and to a reduction of the cut-off wheel temperature. This is related to the increased area of contact between the cut-off wheel and the workpiece ($b_S \times L$) due to the increase of the length of the contact arc L, and with the fact that in the cutting process, the workpiece acts as a cooler by absorbing a part of the heat, which is then transmitted to the chip.

The use of non-contact methods such as IRT has its disadvantages. The existence of metal parts of the equipment leads to multiple reflections that complicate the measurement of surface temperature. The unknown transmission factor of the measured surfaces varies according to their orientation, the temperature, and the wave length. The measurement of the temperature through thermography does not provide absolute values of the temperature. To obtain these values, a modeling should be applied and a correlation with the temperature change of the surface must be considered. The IRT measurements are indirect measurements in terms of measuring the temperature in the cutting zone.

Although the cutting zone can be side-viewed at any certain position of the camera, the infrared radiation from the cut-off wheel, the workpiece, and the swarfs affect the temperature measurement result of the observed surface. The morphological operators are considered as the most suitable for selective extraction or suppression of certain structures in the images (especially the glowing sparks) [11]. Fig. 8 shows a thermogram after application of morphological processing. It better visualizes the different elements in the process of cutting.

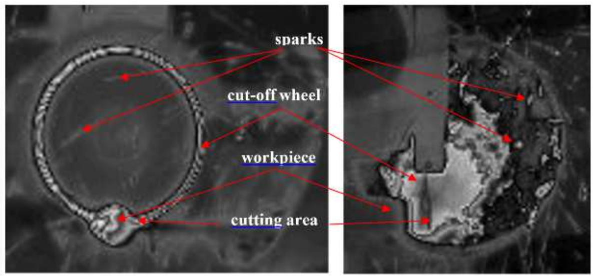

Fig. 8. Thermograms after morphological processing

By implementing appropriate suitable methods of infrared image processing of the abrasive cutting process it can be derived a correlation between the surface temperature of the disc and the workpiece for specific parameters of the process which can be used to control and provide a high efficiency.

4 Conclusion

The heat generated during the process of abrasive cutting influences the tool wearing-out as well as influence on the process output, surface quality, processing accuracy, and other output process parameters. Therefore, the examination and the measurement of the temperature distribution in the workpiece and the cut-off wheel are extremely important for practical applications. Optimum performance, quality, productivity, process economy and stability of the instrument can be determined applying such studies.

This paper is focused on the infrared thermography applications for non-contact and non-invasive study and characterization of the elastic abrasive cutting process as well as the instruments used for flexible abrasive cutting of rotating workpieces. The thermal phenomena of the elastic abrasive cutting process of rotating workpieces are analyzed. The conditions for IRT monitoring of the process, along with the experimental procedures and techniques for data analysis are discussed.

Experimental data from single factor thermography measurements are presented for taking into account the influence of rotational frequency of the workpiece over the cutting time and heat generation and distribution in the workpiece, cutting disc and the swarf during the processing of different materials. The methodology of performing the study and the results obtained might be applied to the process of abrasive cutting of rotating workpieces.

Acknowledgment

The paper is published with the support of the project no. DN 17/16 of the National Science Fund, Bulgaria.

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