USING A THERMOVISION METHOD FOR MEASURING TEMPERATURES OF A WORKPIECE DURING ABRASIVE CUT-OFF OPERATION

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Summary

The thermovision method was applied for the determination of temperature of a workpiece during abrasive cut-off operations. Abrasive cutting of steel workpieces with grinding wheels purchased from 3 different manufacturers was conducted under different conditions. The temperature distribution along the grinding wheel circumference and along its radial cross-section was determined. The relative efficiency of a grinding wheel (grinding ratio) *G* was estimated.

Keywords: abrasive cutting, temperature of workpiece, thermovision camera, relative efficiency.

Zastosowanie metody termowizyjnej do pomiaru temperatury przedmiotu obrabianego podczas procesu cięcia ściernicowego

Streszczenie

W artykule przedstawiono zastosowanie termowizyjnego sposobu pomiaru temperatury przedmiotu obrabianego podczas przecinania ściernicowego. Prowadzono badania przecinania stali ściernicami trzech producentów dla różnych warunków tego procesu. Zaprezentowano wyniki badań dotyczące maksymalnej temperatury przekroju przecinanego przedmiotu. W trakcie badań stwierdzono również występowanie wzmożonego zjawiska samoostrzenia ściernic, do oceny którego stosowano dodatkowo wskaźnik wydajności względnej *G*.

Słowa kluczowe: przecinanie ściernicowe, temperatura przedmiotu, kamera termowizyjna, względna wydajność

Nomenclature

A – the cut-off wheel – workpiece interface, mm^2
d_1 , d_2 – the cutting bar diameters, mm
D_{s1} – the diameter of the cut-off wheel before a cutting process, mm
D_{s2} – the diameter of the cut-off wheel after a cutting process, mm
F – the feed force between the cut-off wheel and the workpiece, N
F_1 ,F_2, F_3 – the feed force for cut-off wheels No 1, No 2, and No 3, respectively, N

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F_m	–	the maximum value of the feed force of the cut-off wheel, N
G	–	the relative efficiency of the grinding wheel
t	–	the maximum cutting temperature, °C
v_s	–	the cutting speed, m s^{-1}
φ	–	the density of a heat flux, J mm^{-2}
Φ	–	the heat flux, J
Φ_{ch}	–	the heat flux generated during abrasive cutting that penetrates the chips, J
Φ_p	–	the heat flux that is dissipated to the atmosphere in the form of radiation, J
Φ_s	–	the heat flux generated during abrasive cutting that penetrates the cut-off wheel, J
Φ_w	–	the heat flux generated during abrasive cutting penetrating the workpiece, J
τ	–	the cutting time, s

1. Introduction

An abrasive cut-off method is used for cutting rather than other methods of cutting due to its two fundamental advantages: a very short cutting time and a possibility of cutting hardened materials. This method is mainly used in machining for preliminary operations, so-called material cut-off. However, apart from all the above-mentioned advantages, abrasive cut-off, has also drawbacks resulting from a relatively high temperature occurring in the machining zone. This temperature can cause undesirable and damaging changes in colour in the cutting zone, changes in the microstructure of the material surface layer (up to a depth of several millimeters), and thermal flashes [1]. Additionally, an excessive amount of gases harmful for cutting-tool operators is emitted [2-4].

Apart from machining parameters, the temperature of abrasive cut-off, is affected by characteristic properties of cut-off wheels resulting from their construction, materials used for manufacturing cut-off wheels and the manufacturing technology. Earlier investigations of cut-off wheels from different producers [5] suggest that despite the same technical characteristics of cut-off wheels (according to the information on their labels), their properties differed to a large extent. Thus, we can presume that the temperature generated in the workpiece being machined will be subject to similar changes. Therefore, we have investigated cut-off wheels from different producers. Because of the occurrence of a large number of input variables (paper [2] states that the number of variables is over 200), the precise estimation of influence of all these variables will require a lot of expensive investigations.

In the present paper we have only dealt with the problem of comparison of temperature of a workpiece during a cut-off operation (measured using a thermovision camera), generated by a cut-off wheel type with most frequently used characteristics (41-300x32x3,5 99A 24R BF), manufactured by three different producers.

Temperature measurements during abrasive cut-off operations by means of a thermovision camera have already been carried out before, with respect to the temperature generated in a cut-off wheel [5-6]. A camera PN-290 used in these investigations, however, had a narrow measuring range, from 0°C to 420°C. Considering the significantly higher temperatures expected in a workpiece generated during cut-off operations, we attempted to extend this range by means of a flat mirror suppressing infrared radiation emitted by the workpiece. Unfortunately, these efforts did not yield positive outcomes. For this reason, a new camera of a measurement range of 0-1300°C was used.

2. Heat emission during abrasive cutting

The source of heat during an abrasive cut-off operation, as during a grinding operation, is the work related to elastic and plastic deformations, the removal of chips and friction interaction between abrasive particles and the workpiece. The analysis of heat influence during grinding has already been carried out in many publications: [7-14].

The heat flux (Φ) generated during abrasive cutting penetrates the workpiece (Φ_w), chips (Φ_{ch}), grinding wheel (Φ_s) and is dissipated to the atmosphere (Φ_p) in the form of radiation [5]. The proportions of the aforesaid components of the heat flux are as follows [11]: $\Phi_{ch} \approx 60\%$, $\Phi_s \approx 20\%$, $\Phi_w \approx 10\%$, $\Phi_p \approx 10\%$. We can expect that for abrasive cutting portion of Φ_w flux should be higher on account of the occurrence – in this process – of surface friction of the cut-off wheel and the workpiece. Thus, the value of friction is higher when the cross-section of material being cut-off is higher. The temperature of a grinding wheel depends on the density of heat flux $\varphi = d\Phi_s/dA$ which passes through the cut-off wheel-workpiece, the interface A, and on the thermal characteristics of this grinding wheel. Cutting is usually carried out by means of narrow grinding wheels. The surface of their interaction with the workpiece is relatively small. During a cutting process the cut-off wheel forms a groove from the central zone of which the heat is incapable of escaping into the atmosphere, and totally penetrates the workpiece. As a result, the value of Φ_p component decreases, while that of Φ_w component increases. Despite the fact that the thermal conductivity of most metallic materials is high, a large amount of heat is incapable of escaping from the cutting zone to the atmosphere because of the intensity of an abrasive cut-off process (it generally lasts from a few to dozen or so seconds).

Hence, the above-mentioned factors cause intensive heating of materials during a cut-off operation.

The quantity of the generated heat flux Φ depends mainly on the cutting speed v_s and feed force between the cut-off wheel and the workpiece F.

Because the cutting speed is determined by standards [15-16], the feed value F is the most important factor in this respect. Abrasive cutting is usually carried out by means of manual grinders which are characterized by the lack of precise control of the feed.

3. Experimental studies

3.1. Measurements set-up

The investigations have been carried out on a test-stand used in earlier studies [5-6], one of the basic elements of which was an abrasive cut-off machine, type BS-300, equipped with a 300 mm cut-off wheel, which had a speed of 60 m/s. For cutting investigations, bars of a diameter d_1 = 12 mm and d_2 = 20 mm, made of typical concrete-reinforcement steel, were used. The feed force of a cut-off wheel to cut a bar was effected by the gravitational method using different weights and a simple link system. The temperature was measured using a thermovision camera, type VIGO v.50. It enables temperature of up to 1300^0C to be measured, with a spatial resolution of 0.6 mrad. The accuracy of the thermovision temperature measurement depends, to a large extent, on the emissivity coefficient of the object radiation, for which the measurement is carried out.

This coefficient is among the major parameters set in the camera before the measurement. Therefore, temperature measurements of steel bars being cut were preceded by the determination of the emissivity coefficient of the material of these bars. To this end, a disk cut off the bar, half-covered with soot, the emissivity coefficient of which was assumed to be 0.97 was used. By performing multiple measurements and comparing the temperature of both parts of the disk heated in a chamber furnace, for different emissivity coefficient values set, the value of this coefficient was found to be 0.88.

Due to the fact that it was impossible to make direct measurements of temperature in the machining zone, the temperature of the accessible front surface of the possibly thinnest (of a thickness of 0.5 mm) of the disk being cut was measured. Since the thermal conductivity of steel is high while the cutting time is long, the temperature measured was reproducibly lower by only 9÷10% (the value determined as a result of calibration with a measuring system with a TTP type temperature sensor) than the real temperature occurring in the machining zone. The test results were corrected with the adjusted difference.

The camera was connected with a PC computer equipped with “TERM v.50 2.9.7” software capable of recording thermovision images. A sample thermovision image obtained by the camera used in investigations, with the thermal color palette obtained, is shown in Fig. 1.

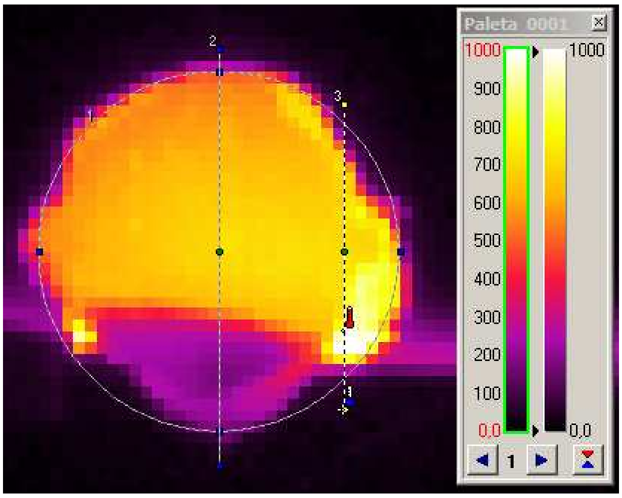

Fig. 1. Sample thermovision image obtained in the final phase of cutting (for: cut-off wheel No 3, $F_3 = 82$ N, $d_2 = 20$ mm)

The camera allows the measuring and recording of maximum, minimum and average temperatures in its entire field of vision. The identification of the recorded temperature (in the form of graphs) can be carried out along freely drawn segments or polyline in a thermovision image. Identification can also be conducted in narrow areas of different shapes in selected and especially interesting places of a thermovision image. The application of narrow areas strongly increases the visual resolution of these places. The area limited by circles was chosen for the identification of temperature of a cut-off bar, which overlapped the bar perimeter. Thereby, it was possible to avoid interferences caused by temperatures of the sparks. A sample temperature curve along the vertical section of the cutting through the bar centre (section 2 visible in Fig. 1) is shown in Fig. 2a, while the curve along the vertical section passing through the hottest point (section 3 visible in Fig. 1) is shown in Fig. 2b.

A thermovision camera also enables the identification of temperature (in form of graph) of the hottest point of the chosen area in time to be made.

In Fig. 1 an elevated temperature of the cut-off wheel perimeter can also be seen. The identification of this temperature was carried out in earlier investigations [5-6].

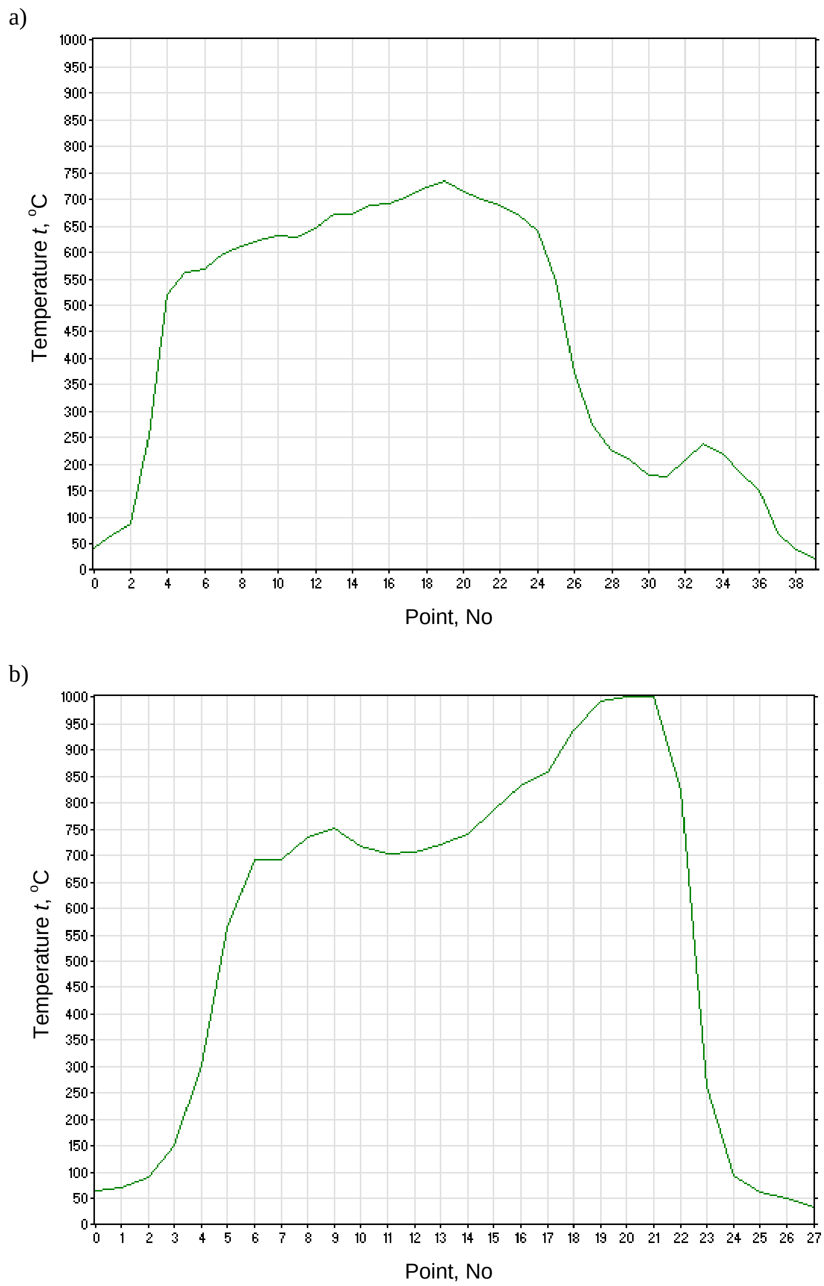

Fig. 2. Typical temperature distribution along sections: a) section 2,
b) section 3. 1 Point = 1 mm

The investigations were conducted in two stages, which were called basic and preliminary. In the stage of basic investigations was singled out initial and essential investigations.

3.2. Results of basic investigations

The maximum temperature generated in a cut-off bar was assumed to be a criterion for studies. To this end, we decided to use a circular area of the camera matched to the cross-section of the cut-off bar. Basic investigations were preceded by preliminary investigations, where the maximum value of feed force of the cut-off wheel F_m in relation to the bar being cut-off was determined. This force amounted to F_m= 82 N. The preliminary investigations also demonstrated that an increase in the feed force was not always accompanied by an increase in the temperature. It was caused by the occurrence of an intensive phenomenon of self-sharpening of the cut-off wheel. This phenomenon was proved by the high wear of the cut-off wheel. Because of this, apart from the maximum cutting temperature t in the preliminary investigations, the relative efficiency of cutting-off defined as G coefficient was also determined (the ratio of the volume of the material removed to the cut-off wheel used for this purpose), which – for abrasive cutting-off – can be reduced to the relationship [5]).

$$G = \frac{d^2}{D_{S1}^2 - D_{S2}^2} \tag{1}$$

where: d – the diameter of the bar being cut off, D_{s1} – the diameter of the cut-off wheel before cutting, D_{s2} – the diameter of the cut-off wheel after cutting.

The basic experiments were conducted for three different feed forces between the grinding wheel and the bar. These feed forces were as follows: F_1 = 62 N, F_2 = 72 N, and F_3 = 82 N. The diameters of cylindrical bars subjected to cutting were: d_1 = 12 mm and d_2 = 20 mm. The cut-off wheels of type: 41 300x3,5x32 A24 R6 BF from three different producers were chosen for investigations (marked as : No 1, No 2 and No 3). This kind of cut-off wheels is mostly used for the cutting of the concrete-reinforcement bars. Each test was repeated twice in the cutting conditions described above. The conditions and averaged investigation results are presented in Table 1 and their graphic forms as diagrams in Figs. 3 and 4. In these figures the values for the cut-off wheels from different producers are marked with different lining.

Table 1. Conditions and investigation results

No of cut-off wheel	Force *F*, N	Temperature *t*, °C		Coefficient *G*	
		Diameter *d*, mm		Diameter *d*, mm	
		12	20	12	20
1	62	374	541	3.80	4.80
	72	644	810	1.83	8.01
	82	540	851	1.51	2.71
2	62	430	680	4.82	3.35
	72	651	916	1.37	7.80
	82	360	988	1.33	2,61
3	62	607	732	3.65	5.10
	72	620	958	1.70	8.03
	82	537	998	1.38	2.54

a) b)

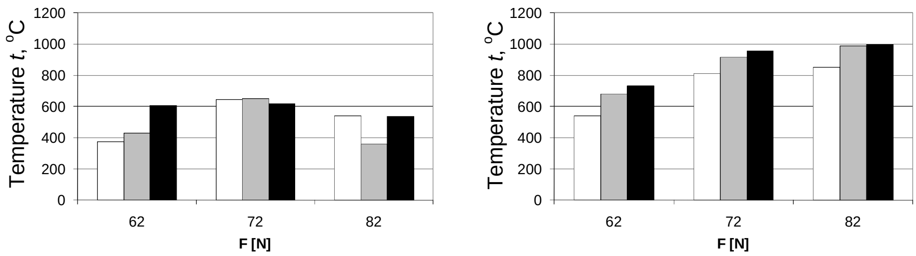

Fig. 3. Maximum temperature values for workpiece during cutting: a) d_1 = 12 mm, b) d_2 = 20 mm

a) b)

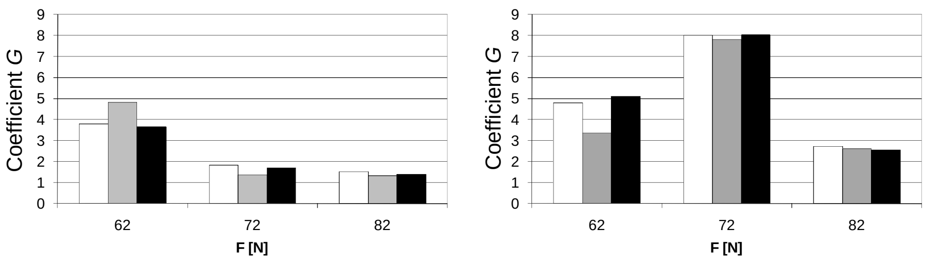

Fig. 4. Coefficient values of relative efficiency *G* of cut-off wheels during cutting: a) d_1 = 12 mm, b) d_2 = 20 mm

3.3. Results of preliminary investigations

The basic investigations were complemented by investigations in which a temperature change in the hottest point of the workpiece being cut off with time was determined. This point obviously changed its position as the cut-off wheel was sinking into the material.

The diagram below (Fig. 5) was made using the maximum temperatures of the narrowed thermographic image areas, recorded with a frequency of 2 Hz.

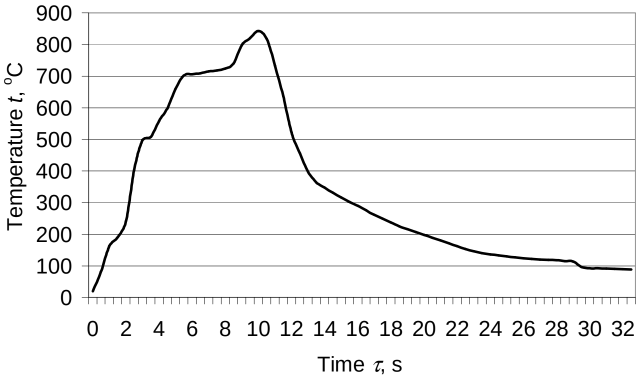

Fig. 5. Temperature profile of the hottest point of cutting-off of the workpiece with time

4. Summary

The maximum values of temperature of the materials being cut off obtained for cut-off wheels having the same characteristics under the same cutting conditions, and provided by different producers, differ from one another by about 30% (Fig. 3). This means that it is very difficult to ensure the identical performance of cut-off wheels manufactured by different producers.

An increase in the diameter of the material being cut off leads to an increase in the temperature of cutting (Fig. 3). This is caused by the increased contact surface between the cut-off wheel and the workpiece despite the resultant lower unit pressure. Moreover, the action time of the heat flux on the material being cut is approximately three times longer for bar of a larger diameter.

An increase in the feed force of the cut-off wheel in the cutting process in the range of 62 N to 72 N is accompanied by an increase in the maximum temperature of the cut-off wheel. However, a further increase in the feed force to 82 N causes a decrease in this temperature (Fig. 3). This decrease can be brought about by the occurrence of a phenomenon of intensive self-sharpening of the cut-off wheel, which is characterized by the penetration of a large number of sharp grains into the machining zone. This phenomenon is intensified in the case of a bar of a smaller diameter (Fig. 3a) due to higher unit pressures occurring in the cutting zone.

The analysis of the investigation results of the relative efficiency of cut-off wheels has shown that along with an increase in the feed force of a cut-off wheel the values of coefficient *G* decreased during the cutting of bars of a smaller diameter (Fig. 4a). Decreased values of the coefficient *G* were also observed during the cutting of bars of higher diameters only for higher feed forces (Fig. 4b). The degradation of the relative efficiency of cut-off wheels demonstrated here can be connected with the intensification of self-sharpening of a cut-off wheel in these cutting conditions.

The temperature of the material being cut is three times as high as the temperature of the cut-off wheel perimeter measured soon after the cut-off wheel is moved away from the object. This is demonstrated by the comparison with the results obtained in previous investigations [8].

The diversified temperature values and the relative efficiency coefficient of the cut-off wheels from different producers obtained in the investigations can be used for the correction of the cut-off wheel manufacturing process.

The analysis of temperature changes occurring with time (Fig. 5) indicates that:

- In the preliminary phase of cutting the temperature of a workpiece changes in a way similar to an increasing exponential curve; such a curve is typical of temperature changes during heating with a constant rate of heat delivery and relatively slow heat removal; this character of heat removal is connected with the short duration of the process (which on average lasts several seconds);
- While the workpiece is “approaching” the maximum temperature, however, the deviation from the characteristic exponential curve is observed, which can be caused by a temporary occurrence of the phenomenon of intensive self-sharpening of the cut-off wheel;
- After the workpiece reaches the maximum temperature corresponding to that of the cut-off workpiece, the continuous decrease in the temperature of the cut-off workpiece, similar to a decreasing exponential curve typical of a cooling-down process, is observed.

A thermovision camera used in the investigations into abrasive cutting allowed the precise and convenient recording of the temperature of the workpiece.

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