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Application of 3D metallic structures for IR emitters with gradient temperature distribution

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Abstract. Comparative evaluation of thermal camera relies mainly on the measurements of standard temperature difference or thermal contrast. The tests are usually performed using expensive IR sources and standard four-bar pattern, which cannot reproduce stepped or gradient temperature distribution required across camera's field of view [1]. The paper presents IR emitters capable of creating such temperature distribution patterns. The emitters are 3D comb-like patterns, manufactured using WEDM (wire electrical discharge machining) method. Radiative properties of such structures depend on the emissivity of base material and geometry of manufactured structure. Presented emitters require less sophisticated temperature control solutions and yet they exhibit better temperature stability. Additionally, they provide metrological features that cannot be achieved using standard test procedures [2].
Keywords: thermal camera, emissivity, electrical discharge machining, surface texture

1. Introduction

Thermal resolution is one of the most important parameters used for evaluation of the properties of a thermal camera. It is equivalent to the minimal temperature difference between two adjacent large area blackbodies that can be resolved by an infrared device. Comparative evaluation of thermal camera relies mainly on the measurements of standard temperature difference or thermal contrast. The tests are usually performed using expensive IR sources and standard four-bar pattern. Sample IR source and four-bar pattern plate (with four different spatial frequencies) are presented in Fig. 1.

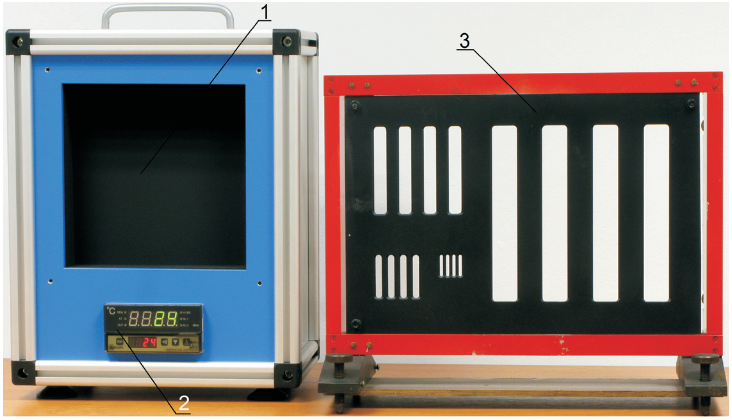

Fig. 1. Elements of test setup: 1 — standard blackbody with precise temperature control (2); 3 — test plate with multiple four-bar tests

Four-bar test measurements are performed in such a way that a metal plate with test pattern is placed in front of extended area IR source. Test pattern consists of four open rectangular gaps spaced in such a way that a distance between them equals the gap's width, thus forming the pattern with desired spatial frequency. The IR source has the radiative properties close to that of a blackbody.

The temperature of the gaps is equal to the temperature of an IR source T_{BB} and it is assumed that the temperature of non-transparent bars (the temperature of a metal plate) T_S is the same as the ambient temperature T_O. In more advanced setup, this temperature is used as a reference value for blackbody temperature controller (element 2 in Fig. 1) which stabilizes the blackbody temperature. The change of blackbody temperature results in a change of thermal contrast between adjacent bars, provided that the temperature of a metal plate remains unchanged. The resulting thermal contrast may be then positive, null or negative and the same differences in radiative power between transparent and opaque bars can be observed. The thermal images of a four-bar test showing positive ($T_S < T_{BB}$) and negative ($T_S > T_{BB}$) thermal contrast are presented in Fig. 2.

The aforementioned test method exhibits many limitations. In simple solutions, where the blackbody is stabilized with respect to ambient temperature, the errors are caused by changing temperature of the test plate, mainly due to heat transfer with ambient and blackbody. The same effect is difficult to compensate even in more advanced systems, where the temperature difference between test plate and blackbody is stabilized. Furthermore, any temperature profile other then step one (like gradient

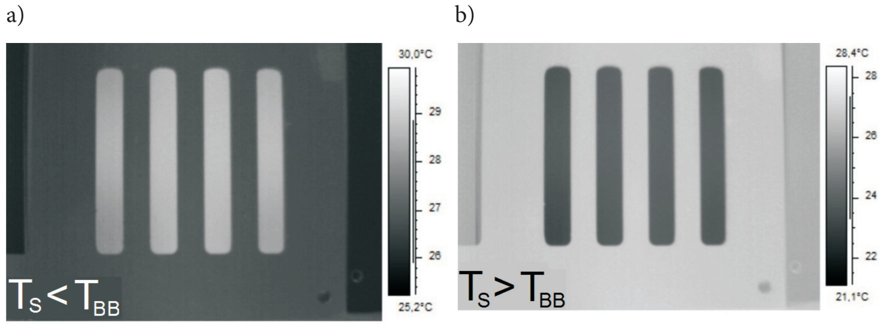

Fig. 2. Four-bar test showing positive (a) and negative (b) thermal contrast

profile, for example) cannot be obtained by cutting out test bars in a metal plate. The possible solution is to create radiative test consisting of the areas with different emissivity and reflectance in one metal block having high thermal conduction. Sample solution showing the areas with the different emissivity coefficients ε_i (reflectance r_i) is presented in Fig. 3.

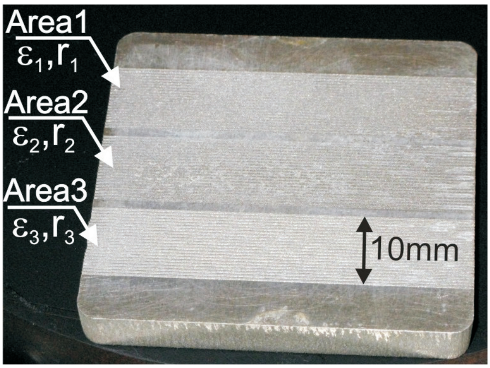

Fig. 3. Test plate with areas of different emissive properties

In most straightforward approach, the separate areas of the test differ in emissivity and as a result their apparent temperatures recorded by thermal imager are also different. Additionally, by adjusting the test temperature with respect to ambient it is possible to change current value of a thermal contrast between particular areas. It is also possible to obtain a desired temperature profile (e.g. linear) by modifying the emissivity value across the test area.

For metallic surfaces, it can be assumed (in the considered spectral range) that they exhibit gray body emissive properties. It means that their spectral emissivity $\varepsilon(\lambda)$ is constant and independent from wavelength. Total power reaching the detector from a given surface is a sum of self emission and reflected components. Self emission depends on the emissivity ε_i and the temperature T_S according to Stefan-Boltzmann law. Reflected component is proportional to reflectance (which in case of non-transparent object is given by 1-ε_i) and the ambient emission. This emission can be approximated using Stefan-Boltzmann law for a blackbody having the temperature equal to the ambient temperature T_O. Finally, the power coming from the *i*-th segment of the proposed test can be written as:

$$P_i = \varepsilon_i \sigma T_S^4 + (1-\varepsilon_i)\,\sigma T_O^4. \tag{1}$$

As a result, the thermal contrast between two given test areas *i*, *j* can be expressed as:

$$\delta_{ij} = P_i - P_j = \sigma\,(\varepsilon_i - \varepsilon_j)\,(T_S^4 - T_O^4)\,. \tag{2}$$

For two given, not identical emissivity values, the thermal contrast can be positive or negative, depending on current test and ambient temperatures, thus the sign of the thermal contrast can be reversed by changing only the test temperature. If the emissivity difference is small, it gives the chance to analyze the response of thermodetecting device to subtle changes in observed apparent temperature. It is also possible (by providing sufficiently high emissivity difference) to obtain very high values of thermal contrast which is difficult to achieve using standard four-bar test because of heat transfer between blackbody and test plate. The presented solution allows for automatic setting of required value of thermal contrast by setting appropriate value of the test temperature T_S with respect to the ambient temperature T_O.

2. Technology of manufacturing the monolithic IR emitters

2.1. Choice of manufacturing method

The applied manufacturing method should assure the stability of radiative properties over time, anisotropic spatial characteristics, repeatability of final parameters and broad range of effective emissivity. The latter feature is required to obtain considerable gradient of emitted power between selected areas of the monolithic test plate. Apart from radiative characteristics, the base material should have high thermal conductivity in order to allow temperature control in broad range by means of external cooler/heater units. This requirement narrows the choice of base material to metals and some ceramic compounds. Ceramic materials are resistant to corrosion and offer long-term stability of physical parameters. However, they do not conform to grey body radiative properties as their emissivity varies with wavelength and as a result they cannot be used as a material for broadband IR emitters. Furthermore, they are difficult to process and their surface and shape can hardly be modified after baking. That finally ruled out ceramic materials and only metals and metal alloys were further considered. Finally, aluminum was chosen because of availability and wide range of machining methods available to create final structures. Radiative properties of a metal are determined by its surface layer thus it is possible to create aluminum structures of a desired shape and surface roughness and then cover it with a layer of another metal (e.g. using vacuum deposition). The resulting structures will exhibit the radiative properties determined by the emissivity of outer metallic layer, not the aluminum base.

There are basically three ways of influencing the effective emissivity of particular sectors of proposed monolithic test. First way, by applying coatings with different emissivity values on particular sectors of the test structure. Second method is surface treating, resulting in different roughness. Finally, the emissivity modification is possible by creating 3D structures influencing radiative properties, namely effective emissivity. First method is the least effective because emissivity of a pure metal layer is usually low (from 0.01 for gold to 0.1 for iron) [3] and as a result broad range of emissivity values cannot be obtained that way.

The most effective method is to create 3D structures on the surface in a form of parallel cavities, whose geometrical parameters determine the resulting effective emissivity. Test plates created that way require less complex temperature control systems — they are more thermally stable and offer unique metrological properties. In case of structures created as rectangular cavities it is possible to change the thermal contrast between particular regions by changing the test temperature with respect to ambient. If the width of a single cavity is smaller than spatial resolution of the tested camera, then the image of the whole region consisting of given cavities will be averaged in the output image.

The single region characterized by the specified radiative properties consists of many elementary radiating cavities. The manufacturing method must then allow for creating such cavities smaller than 1 mm in width. The surfaces of such cavities should have anisotropic properties. Standard machining methods like turning or milling leave periodic patterns on treated surfaces which causes directional optical characteristics of such structures. Anisotropic surfaces can be obtained by sanding, grinding, sand polishing or by using WEDM method (Wire Electrical Discharge Machining) [4]. Only the last method can be applied to make rectangular cavities and it was designed for metal working.

2.2. Manufacturing the geometrical structures of an IR emitter using WEDM method

Sample structures were created on the surface of a cuboid block of PA6 aluminum alloy. Two identical blocks were used and the structures S1, S2, S3, and S4 were created on the treated surfaces 1, 2, 3, 4 respectively. The structures were created using wire electro-erosion machine BP-97d, manufactured by ZAP Kutno (Fig. 4a) and the samples are shown in Fig. 4b.

a) b)

Fig. 4. Wire electro-erosion machine BP-97d — (a), samples of PA6 aluminum — (b)

Basic machine settings required to assure stable parameters of the technological process of creating cavity structures on the surface of the samples are given in Table 1 [5]. During the process, two shapes of current pulses were used, named A and B type. The parameters of these pulses are presented in Fig. 5.

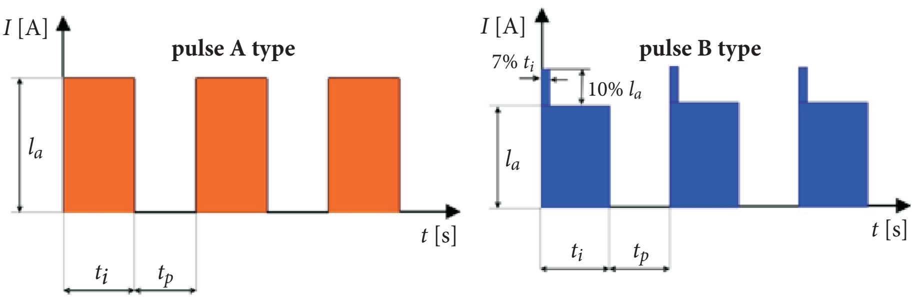

Fig. 5. Current pulses used during WEDM process

Table 1

Parameters of WEDM process

Parameter	Surface			
	S1	**S2**	**S3**	**S4**
Type of current pulse	A	A	B	B
Current I_a [A]	64	80	64	80
Pulse duration t_i [μs]	2	1	2	1
Idle time t_p [μs]	100	100	120	120
Wire speed [mm/min]	950	950	950	950

The surface geometry obtained after WEDM process was measured using contact method and profilometer TOPO 01 Pv3D, which is a part of modular system for the measurements of the surface properties (Fig. 6).

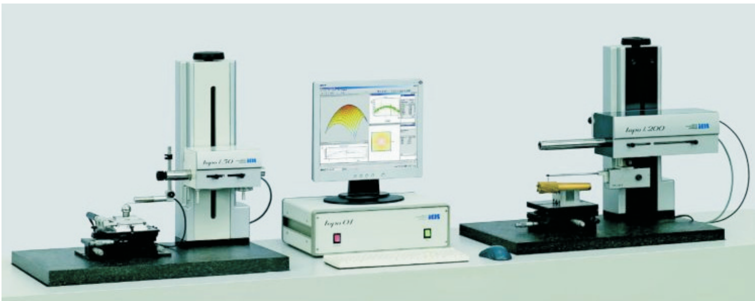

Fig. 6. System TOPO 01 for the measurements of surface properties

The surface measurements were conducted using the system settings gathered in Table 2.

Table 2

Settings used during surface measurements

Speed of measurement head	0.5 mm/s
Measurement path	1.25 mm; sampling distance 0.2 μm
Unitary traverse of measurement table	250 μm
Type of measurement head	G250BS 1003
Number of measurement paths	13
Width of measurement zone	1.2 mm

The scheme of surface measurements, identical for all of the analyzed surfaces *S*1, *S*2, *S*3, *S*4 in TOPO 01 measurement system is presented in Fig. 7.

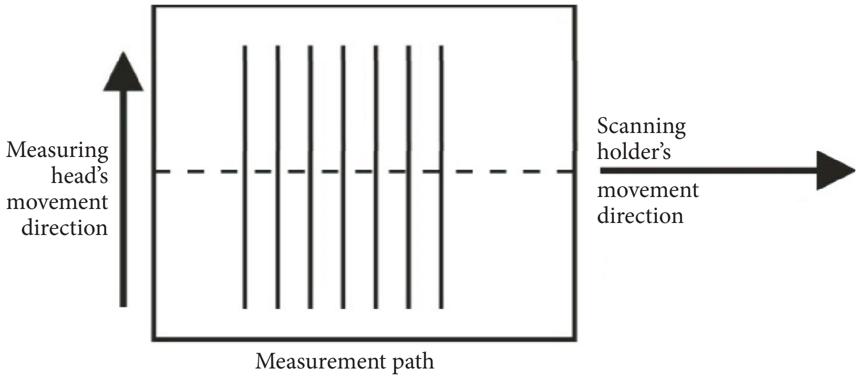

Fig. 7. Diagram of surface measurement paths across *S*1, *S*2, *S*3 and *S*4 surfaces

For each sample 13 measurements were performed along 1.25-mm path. The amplitude roughness parameters R_a, R_z, and R_v were chosen as surface measures because they are commonly used in engineering. Averaged measurement results are shown in Fig. 8. It can be seen that the use of A-type current pulse yielded higher values of R_a than that obtained with B-type pulses, even with higher amplitude of

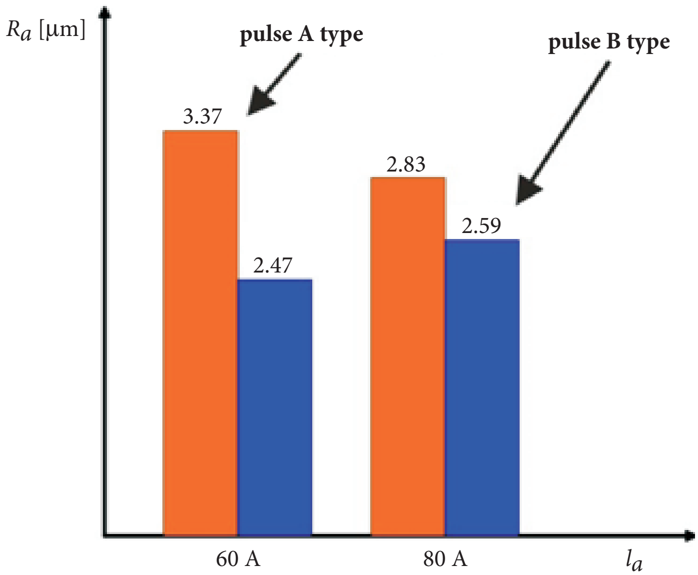

Fig. 8. Values of R_a parameter for both pulse types and peak current values

current. Similar relation can be observed for R_z, R_v, R_p parameters. A-type pulses with peak current value of I_a = 60 A provided the highest values of analyzed parameters which means that the resulting extended surface has the largest area for given nominal dimensions (length and width).

2.3. Emissivity measurements

Analysis of surface geometry by measurements of its roughness and undulation in both 2D and 3D coordinates revealed that the resulting surfaces are random isotropic ones. This can be determined on the basis of exponentially fading autocorrelation functions. It should be mentioned, however, that in each case periodical components of random character could be observed, caused by disturbances in the machining process (non-uniform wire movement, current fluctuations, local non-uniformity of sample material). Other factors proving isotropic properties of the analyzed surface are power density distribution similar to random noise and normal distribution of local profile elevations. The relation between emissivity and surface properties after WEDM machining was investigated and emissivity coefficient of all manufactured sample surfaces was calculated. The calculations were conducted on the basis of apparent sample temperature indicated by ThermaCAM P640 thermal camera and real sample temperature measured by a contact method. The calculations were performed using Researcher software. The sample was viewed by a camera with close-up lens attached to match the size of observed with measured surface roughness data. The whole measurement setup was enclosed in a case, which prevented air convection. The thermal emission from the case itself was constant throughout the measurement session and inside temperature was measured. The emissive properties of the tested sample surfaces were measured as a function of observation angle α. The results in the normal direction are presented in Table 3.

Table 3

Radiative and mechanical properties of tested surfaces after WEDM machining

Surface	S_1	S_2	S_3	S_4
Current [A]	64	80	64	80
Roughness SR_a [μm]	3.37	2.83	2.49	2.59
Emissivity $\alpha = 0°$	0.42	0.37	0.29	0.32

It can be seen that radiative properties of flat surfaces are quite similar, regardless of the pure geometrical characteristics obtained during WEDM process. Thus, in order to achieve wider range of emissivity values, the flat surface must be modified, for example by creating aforementioned cavities, forming periodical, comb-like pattern.

Qualitative comparison of thermal images of test surfaces obtained by mechanical cutting and WEDM method is shown in Fig. 9a. Area marked as 1 was treated by WEDM method, whereas area 2 was mechanically cut. The surface texture after mechanical cutting is clearly visible in Fig. 9b (field 2). The corresponding thermal image shows non-uniform distribution of apparent temperature caused by uneven emissivity across the sample as a result of mechanical machining. The thermal image of area 1 (WEDM machining) represents anisotropic temperature distribution.

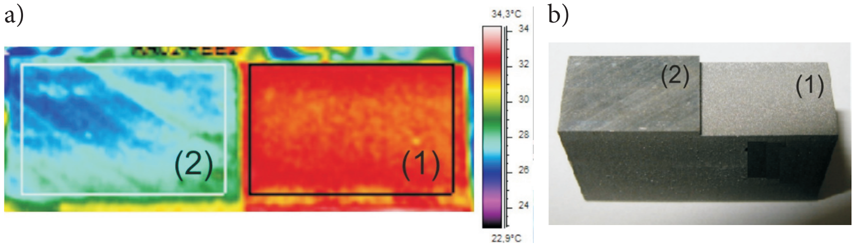

Fig. 9. Comparison of surfaces after WEDM (1) and mechanical (2) cutting: a) thermal images; b) photo of compared surfaces

3. Measurements of effective emissivity of the proposed IR emitters

Measurements of emissivity of comb-like structures were performed on monolithic structures made from *PA6* aluminium. Nine different structure types were made using WEDM method and as a result, nine areas with different comb-like patterns were obtained. In order to unify surface properties, all three structures were covered with a chromium layer, 0.1 μm thick. Sample photos of the comb-like structures are shown in Fig. 10. Experimentally determined effective emissivity of investigated comb–like structures is presented in Fig. 11 as a function of the shape coefficient x, which in turn is the function of the cavity width w and the depth h:

$$x = \frac{h}{w}. \tag{3}$$

Solid line, which is the best fit curve, represents the plot of effective emissivity of a comb-like structures (material emissivity $\varepsilon = 0.3$). Dashed line represents base emissivity of a flat material surface. The points on the plot show the effective emissivity of the tested structures, measured by a thermographic method.

Figure 12 presents the thermal images of the monolithic test surface with comb-like structures. Observation with close-up lens (Fig. 12a.) reveal the discrete apparent temperature distribution across single pattern element, because actual spatial

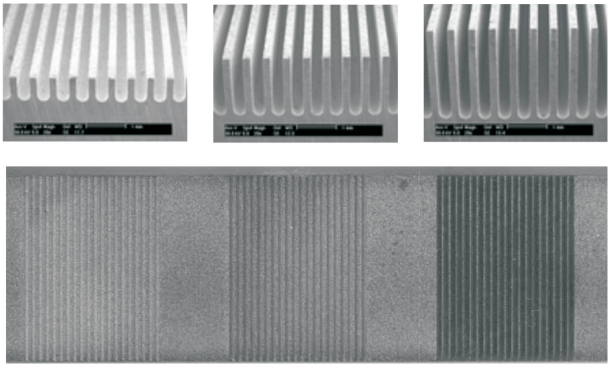

Fig. 10. Comb-like structures with different shape coefficients: from the $x = 2$, $x = 5$, $x = 8$

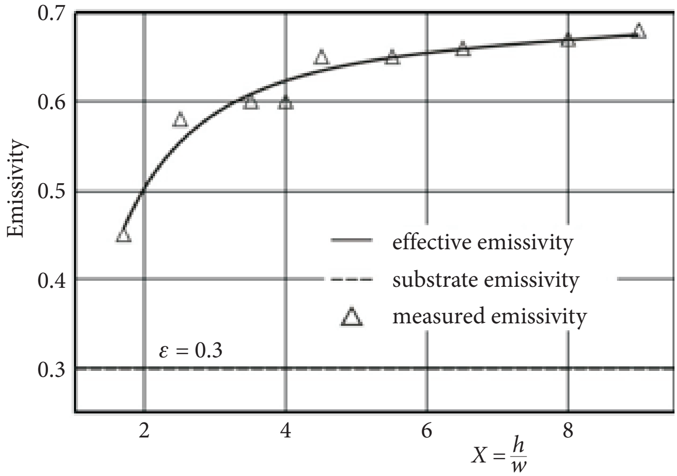

Fig. 11. Effective emissivity for comb-like structures as a function of the shape coefficient x

resolution of a camera is better than the size of single cavity, thus the condition of averaging several pattern elements in a single pixel is not fulfilled.

Second thermal image (Fig. 12b), recorded when the aforementioned condition is met, shows the averaging effect across the test bar elements and their surroundings. Camera visualizes quasi-uniform distribution of apparent temperatures, different in each sector whereas the test temperature measured by contact method is the same for the whole test plate and equals 75°C.

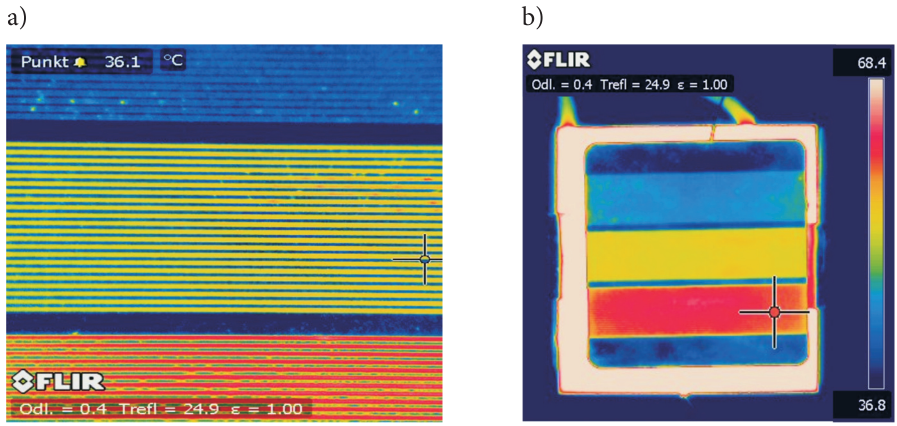

Fig. 12. Thermal images of a test plate: a) microscopic observation of structure details; b) typical thermal image of the test plate

4. Conclusions

Shaping geometrical structures by wire cutting in a WEDM process allows us to create monolithic structures that can be used as radiative tests targets.

Analysis of geometrical properties of the surface (their roughness and undulation) in 2D and 3D coordinate systems revealed that the resulting surfaces obtained by WEDM method can be treated as isotropic ones with nearly ideal diffusive properties.

However, measurements of effective emissivity of flat, WEDM-machined surfaces show little influence of surface (and WEDM process) parameters on final emissivity value. Thus, the surface development must be applied in order to obtain greater and precisely defined values of emissivity. This can be achieved, for example, by creation of comb-like cavity patterns described here, which allows for nearly unitary emissivity values.

Presented emissivity measurements (by a thermal imaging method) for comb-like structures show that it is possible to obtain the precisely determined value of effective emissivity just by choosing the groove depth for such structures during WEDM manufacturing process. This parameter can be easily controlled and changed in a wide range, yielding desired emissivity values.

Knowledge of experimentally verified relations makes it possible to design the monolithic IR emitter perfectly suited for testing infrared cameras. Such emitter can consists of several rectangular areas exhibiting the desired emissivity values, optimal for a given testing method. Apart from the fixed steps of emissivity changes (as presented in this paper) it is also possible to obtain emissivity profile across the test plate described by a simple arithmetic function, for example sinusoidal one.

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Zastosowanie struktur przestrzennych emiterów metalicznych do wytwarzania gradientowych promienników podczerwieni

Streszczenie. Badania porównawcze kamer termowizyjnych, służących do obserwacji sceny termalnej, sprowadzają się zwykle do obserwacji wzorcowych różnic temperatury lub wzorcowego kontrastu termicznego. Standardowe badania wykonuje się zwykle przy wykorzystaniu drogich wzorcowych źródeł promieniowania, które tworzą wraz z dodatkowymi elementami powszechnie stosowany test czteropaskowy. W pracy przedstawiono sposoby wykonania metodami WEDM promienników podczerwieni spełniających rolę płytek testowych, w postaci metalowej grzebieniowej struktury przestrzennej. Właściwości promienne takiego promiennika zależą od współczynnika emisyjności, charakterystycznego dla powierzchni płaskiej materiału wyjściowego oraz parametrów geometrycznych struktury grzebieniowej. Płytki tego typu promienników wymagają mniej złożonych systemów kontroli temperatury, są bardziej stabilne w czasie oraz zapewniają dodatkowe możliwości metrologiczne, niemożliwe do uzyskania innymi metodami.

Słowa kluczowe: kamera termowizyjna, emisyjność, obróbka elektroerozyjna, struktura geometryczna powierzchni