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Determination of emissivity coefficient of heat-resistant super alloys and cemented carbide

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ABSTRACT

This paper presents the analysis of emissivity engineering materials according to temperature. Experiment is concerned on difficult to machine materials, which may be turned with laser assisting. Cylindrical samples made of nickel-based alloys Inconel 625, Inconel 718, Waspaloy and tungsten-carbides based on cobalt matrix were analyzed. The samples' temperature in contact method was compared to the temperature measured by non-contact pyrometers. Based on this relative, the value of the emissivity coefficient was adjusted to the right indication on pyrometers.

Key words: nickel alloys, emissivity coefficient, tungsten carbides

1. INTRODUCTION

Modern construction materials are used in special applications in exacting industries like aerospace, space, marine, mine etc. A significant part of aerospace engine's component is made from nickel-based alloys. It is required that these materials are characterized by high strength, unique features or desirable microstructure. Creep resistance is also very important. Finished parts are art of engineering work, but machining of modern materials causes many technical and economic problems. They are related with very poor machinability of materials such as ceramics, nickel-based alloys, sintered carbides, metal matrix composites etc. [2,6]. Volumetric efficiency of cutting is low and machining takes a lot of time. During the turning process high forces, high temperature and rapid wearing of cutting tool occur, so the tool costs are high [1,4,9]. Application of LAM (Laser Assisted Machining) contributes to changes in the top layer of a workpiece. Radiation derives from laser beam as laser spot falls on the workpiece. A laser spot is characterized by diameter, focal length and power density. Main parameters of a laser action are power and scanning speed (feed rate). Power density is described by the power of the laser beam in the area of the laser spot diameter ratio. These parameters are selected according to process, material and desired results. Additional energy emanated from the laser beam is absorbed by the workpiece. Internal energy of the workpiece increases, which corresponds to the temperature rise. The effects are reduction of the workpiece hardness and its transition to plastic condition. Consequences of this aspect are the improvement of machinability and time reduction of machining. [1,4,5,7,10] Too high temperature on the workpiece's surface can induce deep melting of the surface and the substrate, which is undesirable and makes machining impossible. Excessive heating leads to the deformation of the workpiece, shape defect and reinforcement of residual stress in the surface layer. Accelerated wearing of cutting tool is possible as the effect of intensified diffusion and adhesion between the machined material and cutting insert.

The temperature is measured only by indirect methods in this case, through the conversion of one physics quantity to the other one. Due to the interaction between test object and sensor, two type of measures are distinguished: contact and non-contact. Due to the rotating workpiece in the spindle and the difficulty of sensors connections, the most common are non-contact temperature measurement methods.

The temperature in the heated by a laser beam area is a very important parameter, which should be controlled and analyzed. Measuring temperature in centre of the laser beam is possible by non-contact thermometer, called pyrometer. This method is also used to control cutting temperature in the machining region. The value of infra-red radiation, which is the amount of the substance temperature is measured by pyrometers. Proper working of pyrometers requires the determination of the emissivity coefficient. It affects the correctness of the results. [9]

The emissivity value of a non-black body is always less than a black body's emissivity. The emissivity coefficient is a radiation of the tested body to the black-body radiation ratio at the same temperature (1):

$$\varepsilon = \frac{E}{E_0} \tag{1}$$

where:
ε – emissivity coefficient,
E – radiant intensity of tested body [W/sr],
E_0 – radiant intensity of black body [W/sr].

The ideal black body is characterized by complete absorption of radiation, lack of transparency and lack of reflexivity. The only radiation from this body is a result of its actual temperature. The amount of that is described by Stefan-Boltzmann rule in the formula (2):

$$\Phi = \sigma T^4 \tag{2}$$

where:
Φ– radiant flux of black body [W/m^2],
σ – Stefan-Boltzmann constant,
T – temperature of black body [K].

In the case of non-transparency materials, on which radiation falls, like those analyzed in this research, absorption coefficient and reflection coefficient must be implemented by the equation (3):

$$A + R = 1 \tag{3}$$

where:
A – absorption coefficient,
R – reflection coefficient.

Similarly to the emissivity of the black body, it has the absorption coefficient A = 1 (it absorbs external radiation) and the reflection coefficient R = 0. In the case of other bodies, the smaller value of the absorption coefficient, the larger value of the reflection coefficient. Pyrometers receive whole of the radiation from the body, so the radiation measurements are burdened with the deviations, which amount increases with the decrease of temperature [3].

Emissivity is a factor that depends on many features like: kind of the material, condition of a workpiece surface (roughness, cutting marks, reflectivity, color) and actual temperature. Its value is relative to spectral range of radiation, specified for adopted type of pyrometer. Assignation of the emissivity coefficients for various materials is described in this article. For specified conditions, which include: a couple pyrometer-test object and ambient temperature, the term "effective emissivity coefficient" should be used but for simplification the term "emissivity coefficient" is used [4].

2. RANGE, CONDITION AND TECHNIQUE OF RESEARCH

Sintered carbide, Waspaloy, Inconel 625 and Inconel 718 are used as research materials and as cylindrical samples of workpieces (Fig. 1). The thin layer (about 3mm) of tungsten carbide WC based on cobalt Co matrix has been produced by laser cladding method, with additive material in powder form. It consists in 11-13 % of cobalt, 5,2-5,6 % of carbon and the rest is wolfram. The Inconel 625, Inconel 718 and Waspaloy are nickel based alloys with a high content of chromium. All three materials are characterized by corrosion resistance and wide temperature range of applications. Waspaloy's strength and stability ranges are higher than those for widespread Inconel 718.

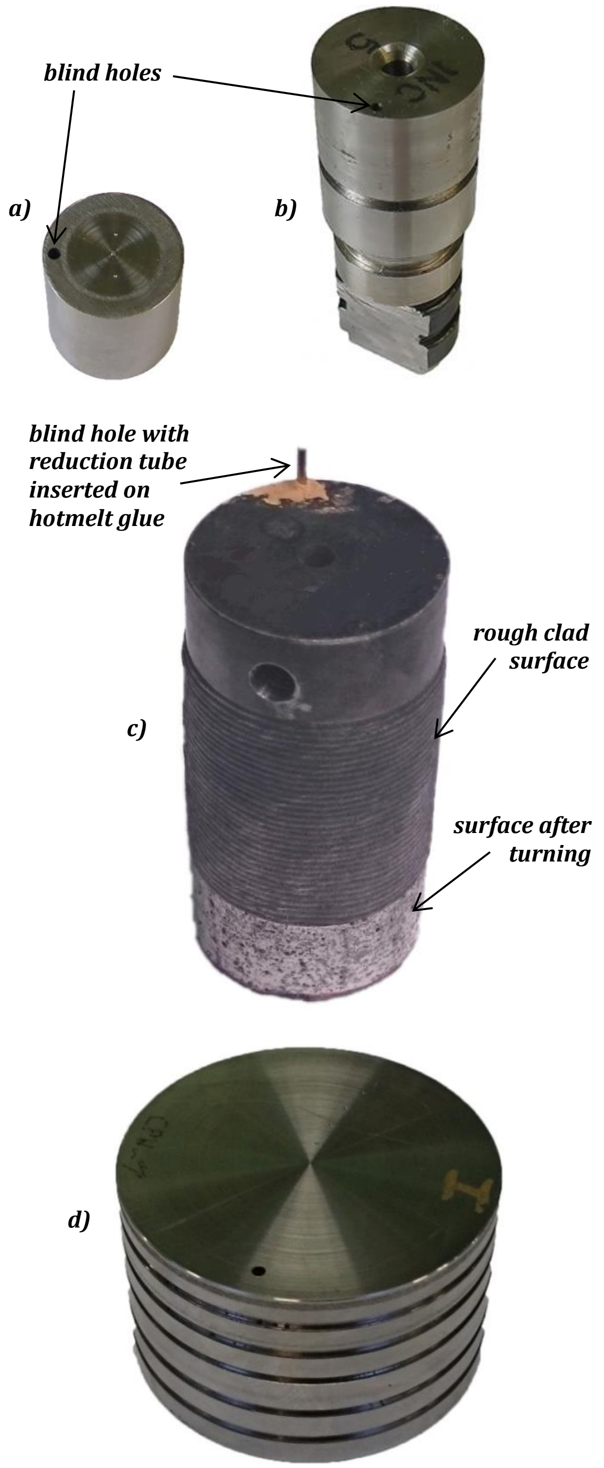

Fig. 1. View of tested samples used in research: a) Inconel 625, b) Inconel 718, c) WC-Co, d) Waspaloy

The test sample WC was divided into two zones: the first, in the raw laser clad condition and the second – after conventional turning. Inconel and Waspaloy samples originate from other experiments, in which they have been turned. In all investigated objects, holes are made for thermocouple (stick temperature sensor). These blind holes (12 mm deep) are drilled closed (about 2 mm) to cylindrical surface and parallel to its axis (Fig. 1a, b, c). Contact measurements on the test samples' surfaces generate false results.

The research includes following problems:

- determination of the influence of the temperature sample on the emissivity coefficient for two pyrometers with various spectral range radiation,
- determination of the emissivity coefficient for four various materials,
- determination of the constant value of the emissivity coefficient for set temperature range with inaccuracy as small as possible.

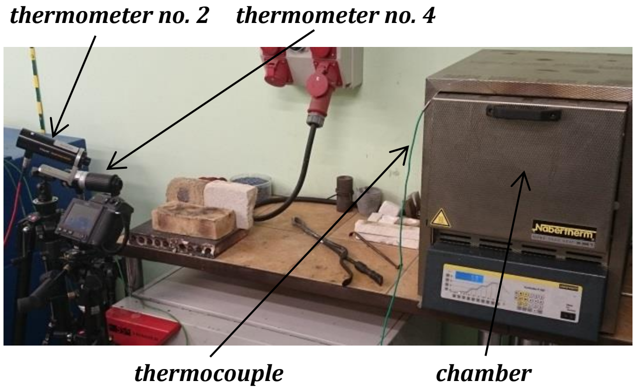

Fig. 2. View of experimental set-up used in research

The 13 kW chamber (Fig. 2) furnace Nabertherm HTC 08/16 (Germany) with SiC heating rods was applied in the research. It is characterized by high heating speed and Tmax = 1600°C. Thermocouple type T produced by CZAH (Poland) is used to control real temperature of the tested sample. It is fixed in a hole by thermo-curing glue. The reduction sleeve is inserted in the hole to adjust the diameter to the size of the thermocouple. The value of the temperature is read on the digital temperature recorder (display step is equal 0,01°C) (Fig. 3).

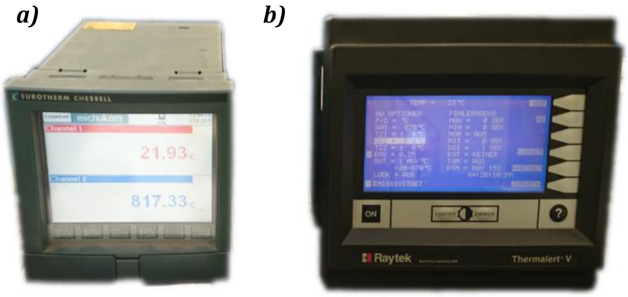

Fig. 3. Measuring apparatus:
a) temperature recorder, b) central unit of pyrometer

The temperature is measured by non-contact method by two pyrometers – no. 4 AHLBORN (Germany) and no. 2 RAYTEK (USA). Operation of both of them is based on the detection of infra-red radiation. Specification of these pyrometers is shown in Table 1. Thermometer no. 2 works with PC and Raytek's Data Temp Multidrop installed software. Thermometer no. 4 works with control unit Raytek Thermalert V (Fig. 3).

Test samples were gradually heated in chamber furnace, until the set temperature. The test sample was kept in the furnace set temperature for heating the whole volume of it. In this way, heating only the surface is avoided. Actual temperature of the heated sample was read on the digital temperature gauge. Measurements of emissivity were conducted with fixed position of pyrometers and established position of the sample. Angular position of pyrometers was constant. Distance between the sample and the pyrometer no. 4 is equal 600 mm for Inconel 625 and Inconel 718. In the case of sintered carbide and Waspaloy distance it is less and it equals 250 mm for pyrometer no. 4 and 320 mm for pyrometer no. 2.

Table 1
Parameters of used pyrometers

Thermometer model	MA2SC (thermometer no. 2)	S5XLT (thermometer no. 4)
Optical resolution	300:1	32:1
Temp. measuring range [°C]	350÷2000	-20÷870
Spectral radiation range [μm]	1,6	8÷14
Repeatability of measurement	±{0,01% measuring value+0,1°C}	±{0,5% measuring value+0,1°C}
Response time [ms]	1	400
Emissivity range	0,10-1,00	0,10-1,00

Measurements weren't performed with the sample in furnace, because furnace radiation clearly falsified the results. The measurement place was isolated from the ambient heat. The main rule of setting the emissivity coefficient is the adjustment of its value, in the way that the temperature measured by the pyrometer conforms the temperature displayed on the temperature gauge. Right value of the emissivity coefficient was written.

3. RESULTS AND DISCUSSION

The color of alloys changes with the increase of temperature. It is confirmed by this study to both to nickel alloys and cemented carbides. Moreover, increasing temperature causes matting surfaces (oxide), which influences the value of the emissivity coefficient. Noticeable matting surface is visible in case of nickel-base alloys – Inconel 625, Inconel 718 and Waspaloy (Fig. 4). Probably, lack of protective atmosphere induces rising layer of oxides. The color of additional surface changes with the decrease of the temperature. However, the hue of WC-Co sample is the same in wide range temperature to above 600°C.

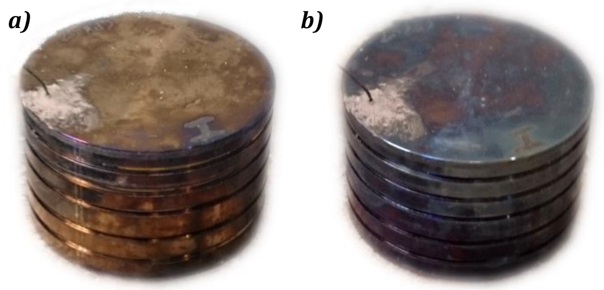

Fig. 4. View of heated sample of Waspaloy with a matt surface in temperature: a) 200˚C b) 300˚C;

The color temperature of Waspaloy surface during heating is shown in Fig. 5 and Fig. 6, above 525˚C when metal alloys radiates visible light. Turning marks presented in Fig. 5 a) disappeared after heating in furnace to above 100˚C and surface became matt. Colors presented in Fig. 6 are similar to the color temperature of steel.

Fig. 5. View of heat colors of Waspaloy in invisible range of light for: a) 20˚C, b) 100˚C, c) 200˚C, d) 300˚C, e) 400˚C;

Fig. 6. Waspaloy heat colors in visible range of light: a) 550˚C, b) 650˚C, c) 750˚C, d) 850˚C, e) 950˚C;

The emissivity coefficient value for Inconel 718 above 600°C is increased by surface condition change (Fig.7). This effect confirms the results included in the research [8]. In temperature range 200°C÷450°C Inconel 718 is characterized by the emissivity coefficient equal to 0,16 and in 800°C value 0,28 is passed (Fig. 7).

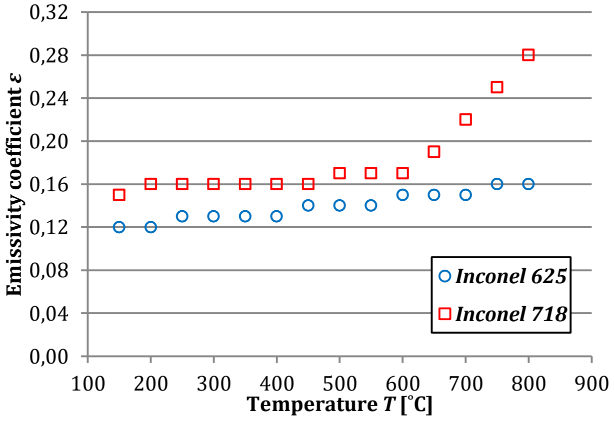

Fig. 7. Emissivity coefficient according to temperature for Inconel 625 and Inconel 718.

Gentle differences in results between [8] and this thesis, may arise in other measuring conditions, for example: distance between the test sample and the pyrometer. For Inconel 625 (Fig. 7), emissivity change isn't so important and adopts nearly constant values (0,12÷0,16).

The emissivity coefficient for Waspaloy (Fig. 8) using low temperature pyrometer (no. 4) is similar to Inconel's 625 (0,11÷0,16) and practically doesn't depend on temperature but for measures with high temperature pyrometer it is very variable from 0,24 for 400˚C to 0,94 in 950˚C. This value is very close to the black body value, which is equal to 1,00. Registered upsurge value of the emissivity coefficient between 600˚C and 650˚C is from 0,4 to 0,74.

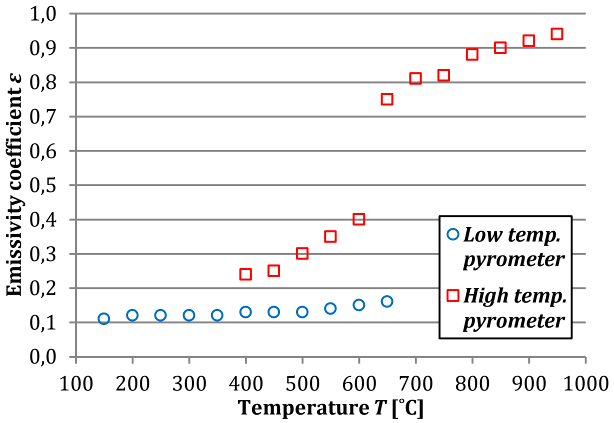

Fig. 8. Emissivity coefficient according to temperature for Waspaloy using different pyrometers.

Fig. 9 presents the results of measured rough surface made from WC-Co by laser cladding. It is characterized by high roughness and porosity. Surface condition doesn't change significantly. This surface is originally matt and the temperature doesn't affect this. For high temperature pyrometer the emissivity coefficient is stable near 0,7÷0,83 and using value is equal to average 0,77. For the second pyrometer, changes are more visible – from 0,63 for 150˚C÷400˚C to about 0,89 above 600˚C.

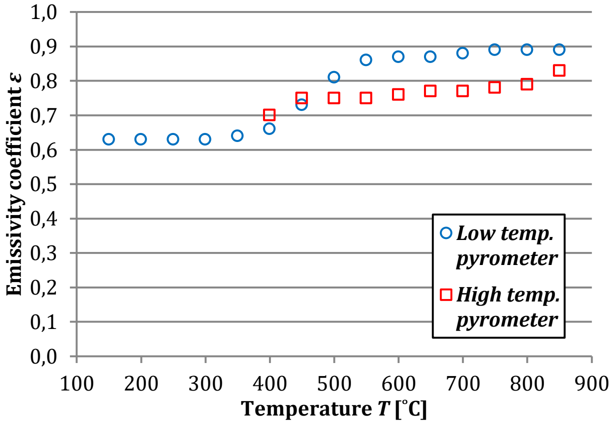

Fig. 9. Emissivity coefficient according to temperature for WCCo's rough surface using different pyrometers.

Last analyzed graph is Fig. 10 which presents the results of research on the turned surface of WC-Co. Survey with the application of high temperature thermometer showed constancy of emissivity coefficient above 600˚C and is equal to about 0,6. In this temperature the surface is very matted and oxidised. In case of low temperature pyrometer the emissivity is stable up to 350˚C (ε = 0,25) and intensely increased up to 750˚C, when it stabilizes reaching the value of 0,89. This value is similar to rough surface of WC-Co.

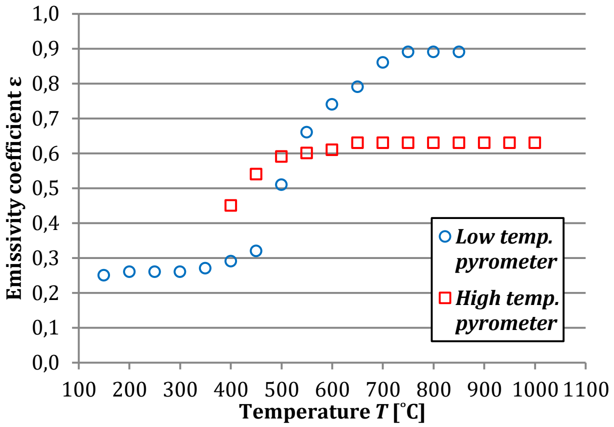

Fig. 10. Emissivity coefficient according to temperature for WC-Co's turned surface using different pyrometers.

4. SUMMARY AND CONCLUSION

Pyrometers are widely used in industry to control the process of temperature. Continuous development of modern materials and their temperatures research on emissivity coefficient, without correct measures are impossible.

In general, for investigated materials in this thesis, the emissivity coefficient increased with the increase of the temperature. For the expected temperature of the test object in non-contact measures, the emissivity coefficient should be set, according to graphs. Accuracy of the setting value isn't so important, because radiation measures in real conditions are burdened with appreciable uncertainty.

Adopted thermometer no. 2 responds to the wavelength λ=1,6 μm. This value is close to the spectral range of visible light, therefore this pyrometer is more responsive to the change of color of sample above 500˚C than thermometer no. 4.

In the range of temperature above 700˚C, surface condition of WC-Co is not important.

This recognition in which effective emissivity coefficients were set provides a basis for non-contact measurements of temperature of nickel-based alloys and sintered carbides. Obtained results in this thesis should be applied in other research only in similar circumstances (material, pyrometer and measurement conditions).

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REFERENCES

[1] **Ajit Joshi, Neel Kansara, Subhankar Das, P. Kuppan, K. Venkatesan,** A Study of Temperature Distribution for Laser Assisted Machining of Ti-6Al-4V Alloy, Procedia Engineering 97 (2014) 1466 – 1473.

[2] **Kieruj P., Przestacki D.,** Polycrystalline diamond tool's wear during machining of cemented carbides produced by laser cladding, Advances in Manufacturing Science and Technology, Vol. 38, No. 4, 2014, p.61-70

[3] **Madura Henryk**, Pomiary termowizyjne w praktyce, Agenda Wydawnicza PAKu, 2004.

[4] **Mark Anderson, Rahul Patwa, Yung C. Shin,** Laser-assisted machining of Inconel 718 with an economic analysis, International Journal of Machine Tools & Manufacture 46 (2006) 1879–1891.

[5] **Przestacki D., Jankowiak M.,** Surface roughness analysis after laser assisted machining of hard to cut materials. Journal of Physics: Conference Series Volume 483 (2014) 012019, Published online: 28 March 2014

[6] **Przestacki D., Sieniawski J., Stambolov G., Lisiak P**., An overview of selective laser sintering strategies, Archives of Mechanical Technology and Automation Vol. 35, 2015, s. 1-10

[7] **Przestacki D.,** Conventional and laser assisted machining of composite A359/20SiCp, Procedia CIRP Vol. 14, 2014, pp. 229 – 233

[8] **Przestacki Damian, Marian Jankowiak Marian, Piotr Mazur Piotr,** Wzorcowanie termometrów bezkontaktowych, Zeszyty Naukowe Politechniki Poznańskiej, nr 1, 2006.

[9] **Venkatesan K., Ramanujam R., Kuppan P.,** Parametric modeling and optimization of laser scanning parameters during laser assisted machining of Inconel 718, Optics & Laser Technology 78 (2016) 10–18.

[10] **Virginia García Navas, Iban Arriola, Oscar Gonzalo, Josu Leunda,** Mechanisms involved in the improvement of Inconel 718 machinability by laser assisted machining (LAM), International Journal of Machine Tools & Manufacture 74 (2013) 19–28.