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Pyrometric temperature measurements with a miniature cavity used as a blackbody in the calorimetric method for determining absorbed laser energy

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ABSTRACT

As a result of improvements introduced in the design parameters of detectors, the miniaturization of measuring gauge and software upgrades, today's single band pyrometers are robust devices with innovative solutions developed to enhance their performance. Despite technological advances, entering the correct value of emissivity coefficient of an object in the pyrometric measuring system is still an unsolved problem. One of the possible solutions may be using a blackbody to a greater extent. This study attempts to use a miniature cavity as a blackbody in pyrometric temperature measurements of a metal part, conducted according to the so-called calorimetric (thermometric) method of determining the laser energy transferred to the part. The method helps measure the temperature of a laser-processed material that acts as a calorimeter. Temperatures are normally measured using thermocouples bonded to the laser-treated element, but this technique is not free from limitations. Some of them can be eliminated through pyrometric measurements. The experimental investigations involved simultaneous temperature measurements with the use of a thermocouple fixed to the processed element and a pyrometer for measuring the temperature of the miniature blackbody cavity produced in the material. Comparative study results support the use of a blackbody for calorimetric non-contact temperature measurements of laser energy absorbed in the welded part in laser beam welding.

1. Introduction

As a result of a marked development in the construction of detectors, miniaturization of measuring gauge, and software upgrades, today's single band pyrometers meet the increasing demand for innovative solutions, have fast response time, are often equipped with in-built laser pointers, and allow nearly spot measurements of temperature by recording radiation emitted from an area less than 1 mm in diameter. These features make them suitable for use in laser treatment to accurately measure temperatures of elements processed [1–5].

Numerous innovative solutions developed for single band pyrometers have made measurements easier and more accurate but failed to eliminate the basic problem associated with the influence of the object's surface emissivity on the value of the temperature measured. The temperature measured with a pyrometer depends on the constant value of emissivity coefficient ε of the object, entered (arbitrarily) into the measuring system software. To obtain correct temperature measurements from a single band pyrometer, the real value of the surface emissivity coefficient has to be known, or the incorrect choice may lead to significant measurement errors [6].

Generally, the surface emissivity coefficient changes with

- temperature of an object,
- radiation wavelength,
- material type,
- surface condition – shape, roughness, oxidation,
- phase,
- contamination and the thickness of the deposited coatings,
- observation angle.

Due to the complexity of the relationship between emissivity and the parameters above, setting in the fitting value is difficult or even impossible when, for example, the temperatures of the object or the surface oxidation levels vary during the measurement. The consequence of this variability is that the temperature measurements have a high uncertainty.

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Nomenclature

Bi	Biot number
C_p	the specific heat (J/kg K)
d	blackbody hole diameter (mm)
f_T	thermocouple sampling frequency (1/s)
f_P	pyrometer sampling frequency (1/s)
h	characteristic dimension (m)
H	length of the sample (m)
L	depth of the blackbody (mm)
M	distance between the beginning of laser melting and the end of the blackbody (mm)
m, m_1, m_2	mass of the sample (kg)
P	laser power (W)
Q	absorbed laser energy (J)
R^2	coefficient of correlation
S_1, S_2	surface area (m^2)
t	time (s)
t_{01}, t_{02}	heating initial time or time zero (s)
T	temperature (°C)
T_0	initial temperature (°C)
T_P	temperatures measured with a pyrometer (°C)
T_T	temperatures measured with a thermocouple (°C)
ΔT_1, ΔT_2	differences between the temperatures from the approximation of the temperature drop curve for $t = t_{01}$ or for $t = t_{02}$, respectively, and the initial temperature of the sample subjected to laser melting (°C)
$(\Delta T_1)_P$	temperature difference ΔT_1, calculated for temperatures measured with a pyrometer (°C)
$(\Delta T_1)_T$	temperature difference ΔT_1, calculated for temperatures measured with a thermocouple (°C)
V	laser beam scanning rate (m/min)
x, y, z	variables (m)

Greek symbols

α	thermal diffusivity (m^2/s)
β	laser energy transfer efficiency
δ	relative temperature difference, $\delta = (\lvert(\Delta T_1)_P - (\Delta T_1)_T\rvert / (\Delta T_1)_T)\cdot 100$ (%)
ε	emissivity coefficient
ε_w	emissivity coefficient of the blackbody walls
ε_{ef}	emissivity coefficient of the blackbody
λ	conductivity coefficient (W/m K)
τ	interaction time : melt length (equal to 55 mm) divided by the laser beam scanning rate V) (s)

Moreover, when the fitting coefficient is to be taken from the literature, an experimental investigation has to be conducted prior to the actual pyrometric measurements. This leads to higher costs and more time used. Hoffman in [7] described the method of determining absorption coefficients of laser radiation for irradiated metal samples using preliminary experimental study to find the emissivity coefficient. The results of the measurements made with thermocouples were used as reference temperatures for the pyrometric measurements.

It is, therefore, advisable and desirable to search for the solution that might eliminate the difficulties encountered with non-contact temperature measurements and lead to an extension of the pyrometer application areas.

This paper presents the results of the experimental evaluation of the possible use of a blackbody for limiting the effects of potential differences between the actual emissivity and that set in the pyrometer on temperature measurement performed calorimetrically (thermometrically) to find the absorbed energy of deep penetration laser welding. The main reason for the use of a blackbody in this study is the possibility to increase the value of the surface emissivity coefficient in the precise and controllable manner. High emission coefficients make the object easily measurable and allow eliminating the effect of the radiation from the surroundings (e.g. CO_2 laser radiation) reflected from the object's surface. To make the study simpler, laser welding was replaced with laser melting of a uniform material. Temperatures were determined simultaneously using a thermocouple installed on the element and a pyrometer measuring the temperature of the miniature blackbody cavity produced in the material. Comparative analysis confirmed that the blackbody could be used for non-contact temperature measurements conducted according to the calorimetric method of determining the absorbed laser energy in laser beam welding.

2. Calorimetric method of determining absorbed laser energy

Two calorimetric methods of measuring the absorbed laser energy are used: water calorimetry [8–11] and the method called thermometric method, which uses a welded sample as a calorimeter [7,12–14]. Water calorimetry is an accurate method but time-consuming and costly. The other method is less accurate but simple and relatively less expensive. In this method, a small, slim metal sample, separated thermally from the base, is heated with a laser beam. During the heating and some time after the treatment is stopped, the temperature of the heat cycle in the element is recorded using a thermocouple [12–14] or a pyrometer [7]. Typical temperature traces are obtained as a result of the lighting (Fig. 1), with a fast rise from the initial temperature of the sample T_0 to the peak temperature, and then slow decrease associated with the cooling of the sample in air, in accordance with Newton's law [15].

Temperature differences ΔT_1 or ΔT_2 are the quantities necessary to calculate the absorbed energy. They represent temperature changes that would occur if the laser heating of the metal element was infinitely fast. At "zero" heating time, heat transfer to the surroundings equals zero. Difference ΔT_1, corresponding to the beginning of t_{01} of heating the element, or to the ending moment of laser beam operation, is used in less accurate calculations [9,12–14]. Temperature difference ΔT_2 determined for t_{02} for which equal surface areas of S_1 and S_2 are obtained, is used to accurately calculate the absorbed energy [8,11]. The temperature curve fraction that corresponds to the gradual cooling of the material plays an

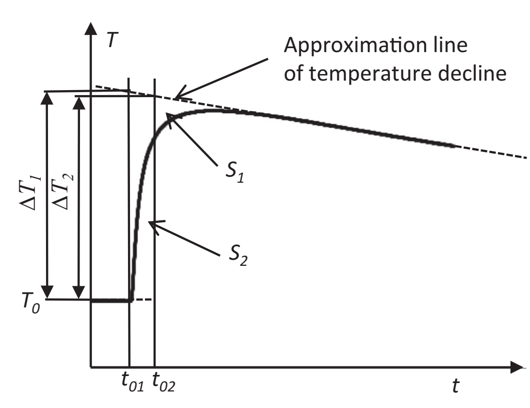

Fig. 1. Temperatures used to calculate the laser energy absorbed.