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Measurement of the radiative energy output of flash lamps by means of thermal thin probes

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HIGHLIGHTS

- Simple energy sensor for flash lamps is proposed.
- Thin metal plates can operate as calorimetric sensor.
- 10% Accuracy of energy determination was achieved.
- Conversion efficiency of 11% was estimated for a 6 kJ flash lamp.

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ABSTRACT

Flash lamps are widely used excitation sources in the field of non-destructive testing with active thermography. Though the realized energy density in front of the investigated object is a significant factor with regard to detection sensitivity, only few data concerning this issue have been published so far. It is shown here that local energy densities can be estimated by means of a simple metal plate, which exhibits a certain temperature increase after flash excitation. After discussing the underlying calorimetric principle the sensor concept is reviewed using constant blackbody radiation and short laser pulses, since both kinds of sources generate known energy densities. The relative uncertainty of measurements of the energy density is found to be in the range of 10%. The last part of the present paper describes an application for characterizing the radiation of a usual 6 kJ flash lamp. The energy conversion efficiency was found to be only about 11%.

1. Introduction

Among different nondestructive testing (NDT) methods active thermography (thermal testing TT) became more and more popular during the last two decades. TT is based on the observation of the thermal response of a test object after disturbing the thermal equilibrium between this object and its environment. Mostly, an external energy source has to be applied. The use of flash lamps generating very short pulses simplifies the analysis of thermographic data. Thus, the corresponding method termed *flash thermography* has meanwhile become the most widely used method of TT [1]. However, very little data is available on how much energy reaches the object surface during a flash excitation. This is remarkable considering the fact that flash thermography was developed and is being used for the purpose of quality control and condition monitoring, where high reproducibility is a main issue. Currently, in most publications only the energy consumption of the flash lamps is given (see for example [2,3]), or additional information is provided about distance [4], geometry or type of flash lamp [5,6]. Only few published studies consider how much energy actually reaches the sample [7–9]. These particular papers [7–9] describe the experimental conditions very carefully whereas the majority of publications are incomplete with respect to the real excitation energy. This absence of information might be due to two reasons:

(1) Lack of appropriate energy sensors.
(2) Most data evaluation procedures do not need the energy input explicitly.

However, a considerable percentage of published papers deal with resolution limits in different materials, i.e. which typical defect size could be detected by flash thermography in a certain depth [e.g. 10, 11]. It is evident that the quantity of energy, which is really absorbed by the object, determines the level of arising

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thermal contrasts above defective regions [8]. In order to determine this measurement parameter by default a low cost and easy-to-use energy sensor is needed. The same applies for pulsed thermography, where halogen lamps are used and pulses are much longer than some milliseconds [e.g. 12, 13]. The following study describes experiments and results for establishing a suited energy sensor.

2. Energy distributions of flash lamps

The spatial energy distribution generated by most flash lamps is determined by the geometrically caused $1/r^2$ decay (r is the distance to the source) and the optical performance of the beam-shaping reflector. Due to the super-positioning of both, a simple analytical calculation of energy density in a certain distance is not possible. Furthermore, a direct measurement with usual energy sensors is difficult, as any kind of aperture reduces the incoming energy flow on the sensor area. These energy losses could be corrected if the angular distribution of the radiation was known. However, the real radiation distribution varies over the entire radiated area, thus a calibration would be very complex. This is the main reason why commercially available energy sensors are not suited for this measurement problem. Solar radiometers equipped with fish-eye objectives would be appropriate, but these sensors are definitely too slow to measure an exposure period of only some milliseconds length.

In order to solve the measurement problem Pickering and Almond used the investigated object itself as an energy density probe [9]. The authors calculated the energy absorbed by the test object from the surface temperature decay inside a defect-free area after flash excitation. This procedure is only applicable in case of *thermally thick* samples, where the sample thickness is much larger than the penetration depth of the heat generated at the surface during the measurement period. It should be mentioned that this method requires a detailed knowledge about thermal properties of the investigated material. Energy values obtained in this way are not determined by the flash energy alone, but also by optical properties of the sample surface. A complementary approach was suggested in 2012, where the temperature rise of a metal plate with an area of 1 cm^2 was considered [14]. In that study, the sample thickness was much smaller than the penetration depth of the heat pulse during the measurement period, which is the characteristic of a thermal thin sample. In that configuration the temperature distribution inside the thermally thin sample is uniform and stabilized, which allows an estimation of the energy input generated by a flash.

The following paper presents further results of experiments with thermal thin probes consisting of different materials. After introducing the sensor concept, the thermal response of thin metal plates to *artificial flashes*, generated by a laser with known energy density, is studied experimentally. This procedure allows evaluating the accuracy of energy measurements using such thin plates. Limits of the proposed method are discussed. Finally, the application of the method to a typical flash thermography set-up confirms the fact that only a minor part of originally applied electrical energy is available for the intended probe heating [8]. The presented results offer a simple and easy-to-use method for estimating the real energy input during flash thermography investigations.

3. Sensor concept

The main idea is the use of a small but well known metal plate as a calorimetric sensor, which can be read out contactless by means of the already existing infrared (IR) camera [14]. Fig. 1(a) illustrates a possible implementation of the proposed sensor concept realized in a typical experimental set-up in the field of flash thermography. A flash lamp with a reflector and the IR camera are positioned in front of the object under test (OUT). The small plate-shaped sensor (highlighted by the arrow) is located in front of the surface of the OUT, but in a margin region which is not in the region of interest (ROI) and yet in the field of view of the IR camera. The thermal response of the sensor plate is registered during the whole measurement period. Thus, the measured temperature difference ΔT of the plate is used for a determination of the energy density at this position. The proposed sensor concept is related to the calorimetric principle based on known material parameters and geometrical dimensions of the sensor plate, as can be seen in Eq. (1):

$$\Delta Q = m * c * \Delta T \quad (1)$$

Here, ΔQ is the introduced energy in J, m the mass of the plate body in kg and c the specific heat capacity of the material, given in J/(kg K). It must be emphasized that a constant temperature level within the entire probe mass m is essential for the calorimetric principle. This point will be discussed later.

The geometrical dimensions influence the mass term directly. It has to be noted that Eq. (1) applies regardless of the plate area size. This size should meet the following requirements:

- As small as possible to avoid disturbing shadows on the OUT.
- Large enough to cover at least 3×3 pixels of the camera detector (or more depending on pixel crosstalk) to ensure a reliable temperature measurement.

Concerning typical dimensions of a flash thermography set-up, a size of 1 cm $*$ 1 cm was selected fulfilling the requirements.

Knowing the relative lateral energy distribution generated by the flash lamp in the present set-up, the real energy input inside the ROI can be estimated. Following the sensor concept described in [14] the relative lateral distribution has to be determined before a measurement series is carried out. Alternatively, the entire surface of the OUT itself can be used as a relative distribution detector, if the emissivity is uniform and defects which ought to be detected are not too large.

Fig. 1(b) demonstrates the actual sensor setup, where a 1 cm^2 metal plate with blackened surface was glued on a wooden stick at the backside. The plate surface was blackened by means of a camera varnish spray. The mass of this thin layer has been assumed to be very small and has been neglected for all further considerations. During the experiments the wooden stick was fastened by a metal cramp from below, so no disturbing shadow appeared.

Fig. 2(a) explains in principle the temperature evolution at the sensor plate after a short excitation pulse with a length of Δt as described by Eq. (1). The temperature increases monotonically during the excitation pulse (indicated by the solid line) and reaches the maximum after the pulse. Data points were evaluated for the case of an 1 mm thin silver plate with a surface area of 1 cm^2 which was heated up by a power of 246 mW for 1 s according to Eq. (1). This parameter set describes a typical temperature increase of 1 K, which has been observed during various flash excitation experiments. However, a more realistic consideration for the case of optical flash excitation should furthermore include four physical effects:

(1) A large temperature gradient between front and back side directly after the flash. Depending on thermal diffusivity, a temperature balance is only obtained after a certain period of time.
(2) Energy losses due to thermal radiation and convection. These effects increase with increasing energy input as both processes are driven by the temperature gradient to the surrounding.