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Full-field deformation and temperature measurement for CW laser irradiated structures

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ABSTRACT

This paper presented a three dimensional deformation and full-field temperature measurement method for continuous wave laser irradiated structures over a range extending from the room temperature to the melting point. The deformation was measured by the three dimensional digital image correlation technique. The speckle pattern was made on the specimen surface by the high temperature glue with a maximum service temperature of 1700 °C. A bandpass filter and a blue light source were used to eliminate the effect of thermal radiation from the laser irradiated region. The accuracy of present method was validated by the coordinate measurement machine and the laser Doppler vibrometer. According to the relationship between the gray value of images and the temperature, the full-field temperature distribution were measured by the colorimetry temperature measurement method. Finally, parameters that affect the response of laser irradiated thin plates, including laser power, high-speed airflow, plate thickness and material properties are investigated.

1. Introduction

When exposed to continous wave (CW) laser irradiation, the absorbed laser energy by the material surface transforms into the internal heat energy of the target. Then, non-uniform temperature distribution is formed by the conduction of the heat energy from the irradiated region. Previous studies showed that the CW laser induced temperature damaged the target in different forms, according to the laser powers.

The mass loss is one of the main failure mode for the high-power laser irradiated structures, including melt, evaporation, pyrolysis and oxidation of the material [1]. When the laser power decreased, high temperature rise may cause the reduction of the elastic modulus, yield stress, fracture stress and, consequently, the strength of the target [2]. For thin-walled structures, thermal deformation induced by the development of compressive thermal stresses when temperatures of the laser irradiated zone below those that impair the material properties will also reduce the load bearing capability [3]. In addition, the outside environment may also affect the damage threshold of the irradiated structures. The presence of the tangential airflow will enhance the rate of the material removal and the melt-through time, even though the temperature of the target is under the melting point of the material [4]. The airflow may also dissipate part of input energy through convective cooling when the laser intensity varies [5]. Except for the laser induced damage threshold, the thermal deformation of the irradiated target is also strongly affected by the laser power, airflow, geometric and material parameters. However, the measurement of three dimensional (3D) deformation of structures at high temperature is still a challenging problem.

Some contact techniques which are conventionally used in the room temperature, such as displacement sensors, may be invalid in high temperature environments. The high-temperature strain gauge is insufficient to capture the full-field response of the structure and large-scale experiments are not easily carried out due to the high cost of this measurement method. In addition, there are a variety of non-contact optical methods have been proposed for surface deformation measurements of high temperature objects [6–10]. These methods mainly include interferometric techniques, such as strain/displacement gauge and moiré interferometry, and non-interferometric techniques, such as three dimensional digital image correlation (3D-DIC). Wang et al. [11] also proposed the mark shearing method to the thermal deformation of the high-temperature metal alloy at 1000 °C. Although the interferometric for high temperature deformation measurements are able to provide three dimensional deformation of structures, they do have inherent limitations such as low resolution [12].

Peters and Ranson [13] proposed the digital image correlation technique in 1981 by using the computer-based analysis for planar deformation measurements, which is simplified as 2D-DIC. However, 2D-DIC technique is limited to planar specimens that experience no out-of-plane motion. Luo et al. solved this problem by use of two digital cameras ob-

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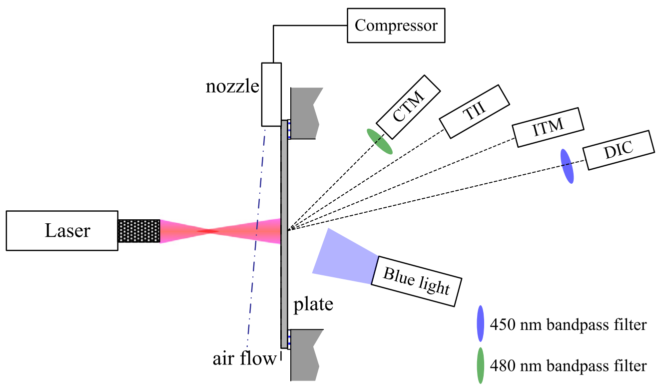

Fig. 1. Schematic of the experimental setup.

serving the surface from two different directions [14]. The 3D-DIC technique have been widely used for the measurement of displacements or strains in different fields [15–19]. In the high temperature environment, Wu et al. [20,21] measured the thermal linear expansion of the ceramic plate and the high temperature failure behaviour thermal barrier coating by using the 3D-DIC system. However, when being used in the high temperature environment, the measurement is restricted by the optical obstacle, and there are a number of issues that have to be considered in order to measure the deformation accuratly and robustly [22]:

(a) Most common coating material will burn or peel off during the test, changing the speckle shape.
(b) Black-body radiation, the light from the surface of heated samples or the heating system, alters the contrast of the images collected by the cameras.
(c) Heat haze, which results from the heating system, can cause local changes in the refractive index, distorting the view of the object.

This paper gives the full-field temperature and displacement measurement for the laser irradiated structures from room temperature to the melting point. Thermal deformation and temperature are mainly measured by the 3D-DIC technique and colorimetry temperature measurement method (CTM) respectively. The high temperature speckle was made on the specimen surface by using the high temperature glue. The bandpass filter and blue light source were used to eleminate the effect of the thermal radiation. The precision of the present measurement technique is validated by comparing the 3D deformation of the thin plate measured from the present technique with that from the contact measure technique coordinate measure machine (CMM) and the laser Doppler vibrometer (LDV). The accuracy of the CTM is validated by comparison of the spot center temperature on the back-surface measured by the CTM with that from the infrared thermometer (ITM) . The effect of laser power, material properties, geometric parameters and high-speed airflow on the deformation and temperature of thin plates are investigated.

2. Experimental procedure

2.1. Experimental setup

Fig. 1 shows the schematic of the experimental setup. A fiber laser with a maximum power of 2 kW operating at 1.07 µm and a CO_2 laser with a maximum power of 200 W operating at 1064 µm were used to irradiate the thin plates. Three types of samples were considered: aluminium plates with 0.5 mm thickness, SUS304 stainless steel plate with thickness of 0.9–2.7 mm, and GH625 high-temperature alloy plate with thickness of 2.0 mm. The LC4 aluminium plate was irradiated by the CO_2 laser with power of 50–200 W and the SUS304 stainless steel and GH625 high temperature alloy plates were irradiated by the fiber laser with the power of 500–2000 W.

A nozzle was placed at one side of the plate to deliver uniform airflow on the laser irradiated surface. The temperature of the airflow is −103 °C, and the speed is Mach 2. The deformation was measured by the 3D-DIC, which composed of two CCD cameras in two different directions. The full-field temperature distribution was measured by the CTM, thermal infrared imager (TII), and the ITM respectively. The temperature is measured by the TII for aluminium plates with low temperatures and the high-power laser irradiated stainless steel and high-temperature alloy plate are measured by the CTM.

2.2. Measurement of 3D deformation

Several special steps are needed to obtain the 3D deformation of laser irradiated thin plates, due to the high temperature effect. For the 3D-DIC technique, the specimen surface must be coated with some random speckle patterns with appropriately sizes. The speckle used in high temperature must satisfy the following requirements [23].

(a) The speckle must maintain its color and hold the shape during the heating process. Unexpected change in the shape may adversely affect the result of the image correlation.
(b) The speckle must adhere to the surface of the specimen stably and deform simultaneously with the specimen's surface without cracking and peeling off.

To measure the 3D deformation evolution of the high-power laser irradiated stainless steel plate, which has a melting point of about 1400 °C, the specimen was sprayed with a thin layer of white inorganic glue that can withstand temperature of 1730 °C. Then, the high temperature black paint was sprayed on the surface of the inorganic glue to make the high temperature speckle. During the experiment, the light from the thermal radiation of the high temperature region saturates the speckle image brightness and decreases the image contrast dramatically. Then, a serious decorrelation effect occurs among the images to be matched. In addition, there is a significant temperature gradient in the specimen, and the specimen also experience a significant temperature change during laser irradiation. Therefore, as shown in Fig. 2(a), the speckle image cannot be captured clearly over the whole region of the specimen and the whole process of laser irradiation by simply decreasing the illumination of the CCD camera.

As the temperature rises, although the total amount of thermal radiation increases dramatically, the absolute intensity change induced by thermal radiation at short wavelength (e.g., 450 nm) is negligible [24]. Therefore, a bandpass optical filter and a blue illumination light source with associated wavelength were used to eliminate the effect of thermal irradiation. Fig. 2(b) shows the speckle images of 500 W fiber laser-irradiated stainless-steel plate with 0.9 mm thickness measured by the CCD camera with the blue light and the bandpass filter. The failure process of the speckle on the surface of the stainless specimen can be clearly captured by using the present method. So, the present method is more suitable to the measurement of full-field deformation for structures with high non-uniform temperature distribution.

The gray value correlation function used in this paper is the normalized covariance correlation function, which can be written as

$$C(u,v)=\frac{\sum_{x'=0}^{m-1}\sum_{y'=0}^{n-1}\left[I_0(x,y)-\bar{I}_0\right]\left[I(x'+x,y'+y)-\bar{I}\right]}{\sqrt{\sum_{x'=0}^{m-1}\sum_{y'=0}^{n-1}\left[I_0(x,y)-\bar{I}_0\right]^2}\sqrt{\sum_{x=0}^{m-1}\sum_{y=0}^{n-1}\left[I(x'+x,y'+y)-\bar{I}\right]^2}} \tag{1}$$

Where x and y are the coordinates of the original image, and x' and y' are the coordinates of the target image. x_0 and y_0 are the coordinates of the template center. u and v are displacements at x and y directions. m and n are the size of the compute template, $I_0(x, y)$ is the gray value of the point (x, y) on the source image and $I(x', y')$ is the gray value of the point (x', y') on the target image. $\bar{I}_0$ and $\bar{I}$ are the average gray value of compute template on the source and target image respectively.