Optics and Lasers in Engineering 111 (2018) 8–18

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

High temperature strain measurement method by combining digital image correlation of laser speckle and improved RANSAC smoothing algorithm

Jinlian Song[a], Jianhong Yang[a,*], Fujia Liu[a], Kefei Lu[b]

[a] School of Mechanical Engineering, University of Science and Technology Beijing, Beijing100083, China
[b] Aerospace Research Institute of Material & Processing Technology, Beijing 100076, China

A R T I C L E I N F O

Keywords:
Digital image correlation (DIC)
Laser speckle
High temperature strain measurement
Improved Random Sample Consensus (IRANSAC)
Smoothing of displacement field

A B S T R A C T

Background radiation and airflow disturbance at high temperature reduce the quality of captured images, resulting in a lot of noises in the displacement field obtained by digital image correlation (DIC) and decreased accuracy of strain measurement. A high temperature strain measurement method (IR-DIC) by combining digital image correlation of laser speckle and Improved Random Sample Consensus (IRANSAC) smoothing algorithm for uniform deformation is proposed. In the IR-DIC method, after obtaining the noisy displacement field by the digital image correlation of laser speckle, the IRANSAC algorithm is used to smooth the noisy displacement field by removing noises with an adaptive noise threshold selection for uniform deformation. Also, when fitting the displacement field, instead of using the minimal data model in the classical RANSAC algorithm, a subset with all the remaining effective data points after removing noises are used in the IRANSAC algorithm. An experiment on tensile test of a C/C composite sample at 2000 °C in the inert atmosphere was carried out. The results showed that, the strain curve calculated by the IR-DIC method is basically consistent with the result simultaneously measured by a high temperature contact extensometer. And compared with the least square algorithm, the mean deviation between the strain curve calculated by the IR-DIC method and the strain curve measured by the contact extensometer is reduced about 13.94%.

1. Introduction

With the development of aerospace engineering, more and more materials need to serve in high temperature environment. In order to accurately characterize the mechanical behavior of materials at high temperatures, a lot of high temperature strain measurement methods have been developed in recent decades, among which digital image correlation (DIC) method [1–3] has attracted more and more research interest due to its advantages of non-contact, high accuracy and low sensitivity to complex environment. In 2011, Liu [4] presented a novel Deformation-Pattern-based Digital Speckle Correlation (DPDSC) method which improved the accuracy and reproducibility of CTE measurement of film at high temperature environment. In 2017, Dong [5] developed an integrated digital image correlation (I-DIC) method to address the difficult problem of the simultaneous and accurate identification of multiple thermo-mechanical parameters of superalloy materials in complicated service condition. However, when DIC is used for high temperature strain measurement, there are still many problems to be solved [6,7], such as the preparation of speckle, the strong background radiation, the airflow disturbance and the strain calculation from displacement field with noises.

Artificial speckle [8] and laser speckle [9,10] are commonly used in DIC. Traditionally, artificial speckle is formed by randomly spraying the specimen surface with black or white paint which can be distinguished from the color of the specimen. In 2017, LePage [11] showed that paint sequence can be important due to fundamental differences in paint pigments, and provided recommendations for optimum painted patterns for digital image correlation. Laser speckle is a phenomenon that is experienced if an optical rough surface is illuminated by a high coherent laser source. In 2000, Lagattu [12] used the laser speckle method for the study of composite and polymer mechanical behavior. In 2000, Anwander [13] presented a laser-based noncontacting strain sensor suitable for temperatures up to 1200 °C, and performed a series of tensile tests with various materials at room temperature and high temperatures to test the applicability of the optical strain sensor. Compared with artificial speckle and laser speckle [14], artificial speckle is easy to prepare at room temperature, but it is more susceptible to human factors. And artificial speckle is more advantageous than laser speckle in large deformation measurement of the specimen. However, in high temperature environment, artificial speckle has some shortcomings, such as speckle falling off, and discoloration. Laser speckle is more suitable for high temperature applications because it does not need to seek special adhesive

* Corresponding author.
E-mail address: yangjianhong@me.ustb.edu.cn (J. Yang).

https://doi.org/10.1016/j.optlaseng.2018.07.012
Received 9 May 2018; Received in revised form 21 June 2018; Accepted 24 July 2018
0143-8166/

or speckle paint resistant to high temperature. But laser speckle pattern will also be influenced by background radiation and airflow disturbance.

In order to reduce negative effects on the accuracy of strain measurement, many efforts have been exerted to optimize the process of image acquisition and data processing. One type of efforts mainly focuses on hardware improvement. In 2009, Grant [15] measured the Young's modulus and coefficient of thermal expansion of a nickel-base alloy from ambient to 1000 °C through combining filters and blue illumination. The accuracy of strain measurement was enhanced by improving the quality of speckle pattern through using the natural contrast from the sample. In 2011, Pan [16] employed the band-pass filter to eliminate the influence of black-body radiation of high-temperature objects on the intensity of captured images and obtained high-quality digital images at high temperatures up to 1200 °C. In 2011, Novak [17] obtained accurate measurement of thermal expansion coefficient at temperatures up to 1500 °C by using an air knife to mitigate the effect of heat haze. In 2016, Chen [18] proposed a two-dimensional ultraviolet digital image correlation system to obtain high quality speckle pattern by minimizing the radiation effect and a method using an air controller in combination with image average algorithm to reduce the effect of heat disturbance at different temperatures up to 1200 °C. However, the higher the temperature is, the faster the background radiation increases and the more serious the airflow disturbance will be. It is difficult to completely suppress the influence of background radiation and airflow disturbance by only improving the hardware. It has to seek other solutions to handle with the problem of poor correlation between images before and after deformation, which will result in random noises in displacement field and low accuracy of strain measurement. Thus, another type of efforts has been carried out, aiming at the improvement of the algorithm of strain measurement. In 2015, Su [19] proposed an effective grayscale-average technique to minimize the thermal disturbance effect on strain measurement accuracy under high-temperature atmosphere environment. However, the method of image gray averaging is only suitable for a static thermal process, such as thermal expansion experiment, in which the images collected at the same temperature are considered to have no deformation. In 2010, Pan [20] proposed a solution for local de-correlated regions caused by black-body radiation through combining transient aerodynamic heating simulation device with the reliability-guided digital image correlation and then measured the thermal deformation field of the chromium nickel austenite stainless steel sample from room temperature to 550 °C. In 2013, Pan [21] combined a novel active imaging optical system and a robust reliability-guided displacement tracking algorithm with an automatic reference image updating scheme to extract full-field thermal deformations of a chromium–nickel austenite stainless steel sample which was heated from room temperature to 1300 °C and a woven C/SiC composite at 1550 °C. Although the quality of the image and the correlation between images before and after deformation can be improved, the noises in the displacement field can't be completely eliminated. Therefore, in order to improve the accuracy of strain measurement, the noisy displacement field should be smoothed firstly.

These existing noisy displacement field smoothing methods can be divided into two categories, local smoothing methods and global smoothing methods. The typical local smoothing methods include the least squares method and its improved versions [22–24]. In the local smoothing method, only a small part of the displacement data defined in a calculation window are used for computation by a given fitting function. The widely used global smoothing methods are the thin-plat spline smoothing method [25], the finite element based smoothing method [26] and its improved versions [27,28]. In the global smoothing methods, all the displacement data points are considered and fitted as a whole. In both of the two kinds of smoothing methods, the noisy displacement field is smoothed by fitting. When isolated outliers exist, and especially when abnormal regions which contain many outliers exist, the performance of fitting will be greatly decreased, because the conditional fitting methods regard the abnormal regions as common data and the outliers cannot be effectively removed or suppressed.

The extensively used outliers removing method is the "3-σ" principle. However, the "3-σ" principle is effective only for isolated outliers and ineffective for the abnormal regions. Therefore, in order to smooth the noisy displacement field with isolated outliers and abnormal regions, new methods should be taken into consideration. Random Sample Consensus algorithm (RANSAC) [29–31] is a powerful fitting tool. Unlike other smoothing methods by finding a best fitting among all the data points, RANSAC algorithm removes the outliers and abnormal regions before smoothing. The classical RANSAC algorithm is a resampling technique that generates the optimal minimal data model by using the minimum number of data points [32] randomly selected in an iterative way. If the whole dataset has a large number of points, the instability of the optimal minimal data model will result in poor robustness of the algorithm. This is the case that has to be faced when the classical RANSAC algorithm is used for smoothing the noisy displacement field. In this paper, an Improved Random Sample Consensus (IRANSAC) algorithm is presented. An adaptive noise threshold selection method for uniform deformation is put forward. Also, in order to improve the algorithm robustness, a subset with all the data points after removing the outliers and abnormal regions, instead of the minimal data model which contains the minimum number of data points, is used to fit the displacement field plane.

An experiment on tensile test of a C/C composite sample at 2000 °C in the inert atmosphere was carried out. Laser speckle was used as the characteristic pattern. The DIC method was applied to obtain the displacement field and the IRANSAC algorithm was implemented to remove the noises and smooth the displacement field before strain calculation. Experimental results showed that the strain measured by the proposed method was basically consistent with the result simultaneously measured by a high temperature contact extensometer. Comparative study with the method by DIC and least squared algorithm was also carried out, and the effectiveness of the proposed method was verified.

The rest of this paper is structured as follows. In Section 2, the principle of DIC method is briefly introduced and the proposed IR-DIC method is described with a numerically simulated example. In Section 3, an experiment on room temperature tensile test of stainless steel specimen is introduced. In Section 4, an experiment on high temperature tensile test of a C/C composite sample at 2000 °C in the inert atmosphere is introduced. Finally, the discussions and conclusions are given in Sections 5 and 6.

2. Basic principles

2.1. Laser speckle

When the laser irradiates the surface of an object with optical rough surface (compared with the wavelength of light wave), the surface of the object scatters numerous coherent wavelets, which interfere with each other in the space around the object. If the phase difference of the scattered wavelet satisfies the condition of constructive interference, these scattering wavelets will form a bright spot. On the contrary, if the phase difference satisfies the condition of cancellation interference, the dark spot will be formed. Because the phase of the scattered wavelet is random distribution, a number of bright spots and dark spots formed by the scattered wavelets are randomly distributed around the surface of the object. The bright spots and dark spots are called laser speckle.

2.2. Displacement field measurement by DIC

Digital image correlation uses random intensity distributions on the specimen surface to obtain the full-field displacement by matching subsets of interest before and after deformation. Thus, mechanical properties of the material can be analyzed. The basic principle of DIC is schematically illustrated in Fig. 1. The recorded image before deformation is regarded as "reference image", and the recorded image after deformation is regarded as "deformed image". In the reference image,