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Deformation measurement of stainless steel in high-temperature environments using DIC for thermal protection system

Xiongjie Che[1]*, Nam Seo Goo*†
Department of Mechanical and Aerospace Engineering, Konkuk University
†*Author to whom correspondence should be addressed. Email: nsgoo@konkuk.ac.kr, Fax number: +822-446-9860*

Abstract

A heat shield called the thermal protection system (TPS) is an important structure in high-speed vehicles as it protects the vehicle from aerodynamic heating. In order to study the TPS, it is particularly important to measure the deformation of structures in high-temperature environments. This study presents an improved method for high-temperature measurement using the digital image correlation (DIC) technique and infrared heater, with a focus on the effects of speckle patterns and mitigation of heat haze effects. The effect of speckle pattern on the DIC measurement has been studied well at room temperature, but high-temperature measurement studies have not reported such effects so far. We also found that the commonly used methods to reduce the heat haze effect could produce incorrect results. So, we studied how to determine the proper size of the speckle pattern under a high-temperature environment. And then we invented the reduction method of the heat haze effect. Finally, we mitigated image saturation using a short-wavelength bandpass filter with blue light illumination to avoid the blackbody radiation from the heated structure, a standard procedure for high-temperature DIC deformation measurement. As proof of our developed experimental method, the deformation of stainless steel 304 specimens was measured from 25 °C to 800 °C successfully, which means this method can be applied to the research and development of thermal protection systems in the aerospace field.

Keywords: *Thermal protection system; High-temperature deformation measurement; Digital image correlation; Speckle pattern; Heat haze effect*

Nomenclature

TPS – Thermal protection system
DIC – Digital image correlation
CTE – Coefficient of thermal expansion
FEM – Finite element method
LVDT – Linear variable differential transformer
T – Temperature
V – Measuring volume
s – Dot size
l – Specific length
r – Camera resolution
h – Planck's constant
c – Speed of light
k – Boltzmann constant
e – Natural logarithm
λ – wavelength
ϵ – Strain
α – Instantaneous CTE
l_0 – Initial length
ϵ_{xx} – Strain in X direction
ϵ_{yy} – Strain in Y direction

1. Introduction

The significance of high-temperature deformation measurements is well-known in the aerospace industry in the high-temperature environments encountered during flight. This includes the internal engine, aerodynamic heat on the aircraft's skin during high-speed flight, and the elevated temperatures

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[1] *Affiliation (Tahoma 10 pt, Italic), Address (Tahoma 10 pt, Italic), E-mail (Tahoma 10 pt, Italic)*

faced upon re-entry into the atmosphere. Understanding and quantifying the behavior and performance of materials under such high-temperature situations is critical [1, 2]. High-temperature deformation measurements can explain important aspects of a material's behavior under extreme thermal conditions. These measurements can derive the coefficient of thermal expansion (CTE), stress-strain relationships, and other pivotal material characteristics. This valuable data is instrumental in material selection, design, and use. It facilitates engineers in identifying materials optimally suited for high-temperature environments, designing components resilient to thermal stress, and making predictive assessments of material behavior in actual flight scenarios [3].

In this study, high-temperature DIC deformation measurement under high-intensity blackbody radiation has been performed with a precise speckle pattern fabrication and a heat haze reduction method. An infrared radiation heater was employed to make an experimental setup, which could heat a specimen to 950 °C. First of all, we mitigated image saturation caused by high-intensity blackbody radiation using a short-wavelength bandpass filter with blue light illumination, a standard procedure for high-temperature DIC deformation measurement. Second, we studied how to determine the proper size of the speckle pattern under a high-temperature environment. Third, we invented the reduction method of the heat haze effect. As proof of our developed experimental method, the deformation of stainless steel 304 specimens was measured from 25 °C to 800 °C successfully, which means this method can be applied to the research and development of thermal protection systems (TPS) in the aerospace field.

2. Theory

2.1. Blackbody radiation

Image saturation is caused by thermal radiation emitted from the specimen at high temperatures. Thermal radiation, an electromagnetic emission from all objects above absolute zero, encompassed a broad spectrum, from infrared to ultraviolet wavelengths, behaving consistent with the principle of blackbody radiation. With increasing temperature, the peak of the emitted radiation moves to shorter wavelengths and its intensity amplifies. This behavior has a significant impact on image capturing, such as DIC, since the CCD cameras used in this study are particularly sensitive to certain radiation wavelengths. Thus, understanding and solving the effects of high-intensity blackbody radiation is critical in ensuring accurate high-temperature DIC measurements.

2.2. Speckle pattern

Typically, a speckle pattern is devised using black and white paint, one serving as the background and the other as randomly distributed dots. The size of the random dots in the speckle pattern is a critical requirement, and according to Eq. (1), the dimension of the random dots should be 5~7 times the spatial resolution [4]. Where s is the dot size, V is the measuring volume, and r is the camera resolution. These parameters can be defined by calibration parameters. However, this approach has been applied in normal temperature DIC measurements, without any existing research or utilization in the field of high-temperature DIC analysis. Based on the above, we have created a high-contrast speckle pattern of suitable size, suitable for high-temperature DIC measurements.

$$s = \frac{V}{r} \times (5\sim 7) \tag{1}$$

2.3. Heat haze effect

The final challenge is the heat haze effect. In high-temperature experiments, the heating apparatus not only elevates the specimen's temperature but also impacts the surrounding air, leading to air turbulence [5]. This interference induces variations in the air's refractive index, distorting light propagation called the 'heat haze effect'. This effect can significantly compromise the accuracy of imaging results, presenting a substantial challenge in high-temperature DIC measurements. Established solutions for mitigating this issue include the use of pneumatic devices [6], air knives [7], and electric fans [8]. However, these methods can alter the airflow around the specimen, causing a decrease in the surrounding temperature. This discrepancy can lead to an underestimation of the specimen's actual temperature during measurements. Hence, we developed a novel approach to mitigate the heat haze effect by integrating a thick layer of thermal insulation in front of the experimental fixture.

2.4. Experimental set-up

As shown in Fig. 1, an infrared radiation heater including ten 220V, 1000W quartz lamp tubes heat the specimen, with a maximum temperature of 950 °C. The specimen is placed vertically in the clamp on the S45C panel. Temperature data is gathered by a K-type thermocouple welded to the specimen. The insulation was added in front of the S45C panel. Two CCD cameras located roughly 0.9m from the specimen and equipped with bandpass filters and blue light illumination, capture image data. The heating process progresses at a rate of 100 °C/min. This study utilized a stainless steel 304 specimen, measuring 100 mm × 100 mm × 2 mm, to verify the accuracy of high-temperature DIC measurements. Stainless steel 304, owing to its superior corrosion resistance, remarkable strength at low temperatures, high melting point, and beneficial cost-effectiveness, has found extensive applications in the aerospace industry. In this study, for safety considerations, the specimen was heated up to 800 °C, and it is noted that 800 °C is enough temperature to show the black body radiation.

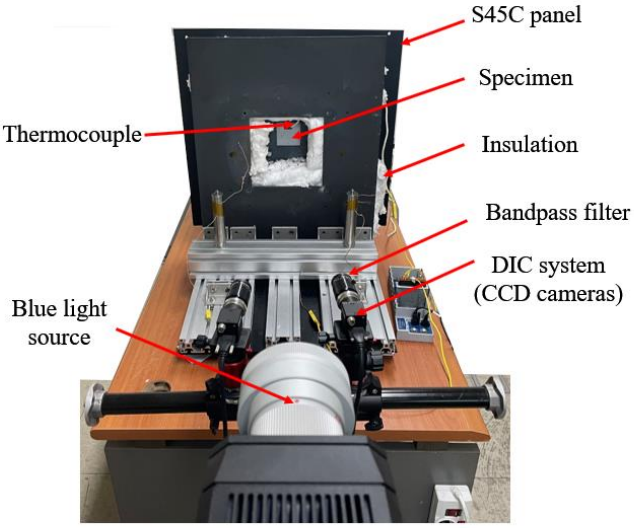


Fig 1. Experimental set-up

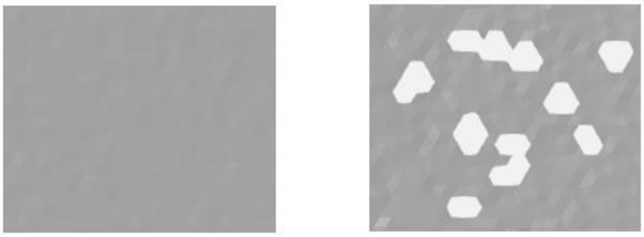
3. Results and discussion

3.1. Image saturation phenomenon

The sharp increase in thermal radiation intensity not only leads to image saturation but also significantly diminishes its contrast, making it impossible for DIC measurements. Thus, overcoming image saturation induced by intensified thermal radiation becomes one of the key issues in high-temperature DIC measurements. By using the bandpass filter and blue light illumination mentioned in the reference [9], the image saturation phenomenon caused by high-intensity blackbody radiation is well solved.

3.2. Proper speckle pattern fabrication

In DIC analysis, if the speckle pattern’s dot size is appropriate, the 3D measuring view of the object in ARAMIS® software appears smooth and flat. However, if the dot size is inappropriate, it leads to insufficient contrast, resulting in an incomplete 3D measuring view. Consequently, the missing area lacks measurable data, thereby affecting the accuracy of the analysis. Fig. 2(a) shows the 3D measuring view of a speckle pattern with an appropriately sized dot in an 800 °C environment, exhibiting a smooth and flat view. In contrast, Fig. 2(b) presents the view for a pattern with undersized points in the same environment and displays an incomplete 3D measuring view with insufficient data.



(a) Proper size (b) Improper size

Fig 2. 3D measuring view in ARAMIS® software

3.3. Heat haze effect

In this study, to account for the heat haze effect, two experimental setups were employed and compared: using an electric fan and using insulation. The existence temperature fluctuations when using an electric fan, and it is difficult to reach the set temperature. So, we lowered the environmental temperature and mitigated the heat haze effect by using a new panel in front of the existing S45C panel and a thick layer of Saffil insulation between the two panels.

3.4. Deformation of a stainless steel 304 specimen

To prove the accuracy and effectiveness of the proposed method, the stainless steel 304 specimen was heated to temperatures ranging from 25 to 800 °C. And measured its thermal strain, CTE, and thermal deformation field and compared the measured data with FEM and reference data.

The mean CTE was computed by linearizing the measured strain across the temperature range of 25 to 800 °C. The mean CTE for the specimen was 19.3 ppm/°C. Furthermore, to facilitate understanding of CTE in the ranges of 25 to 500 °C, 25 to 600 °C, and 25 to 700 °C. When compared with established handbook data and extant data, these results demonstrated substantial agreement, confirming the reliability of the measurements (Table 1) [10,11].

Table 1. Comparison of reference CTE and experimental CTE in various temperature ranges

Temperature range	**25 to 500 ℃**	**25 to 600 ℃**	**25 to 700 ℃**	**25 to 800 ℃**
Reference CTE (ppm/℃)	17.9	18.3	18.8	19.2
Experimental CTE (ppm/℃)	17.6	18.3	18.8	19.3

4. Conclusion

This study presents an improved method for high-temperature measurement using the DIC technique under high-intensity blackbody radiation, with a focus on the effects of speckle patterns and mitigation of heat haze effects. Initially, a designed precise speckle pattern was developed, ensuring high contrast and accurate measurements under extreme thermal conditions. Additionally, we integrated a thermal insulation layer into the experimental setup using a new approach, which significantly reduced the heat haze effect. Simultaneously, we employed the standard method of short-wavelength bandpass filters and blue light illumination to mitigate image saturation caused by high-intensity blackbody radiation. To validate the method, we heated a stainless steel 304 specimen from 25°C to 800°C using an infrared radiation heater. The thermal deformation distribution was measured and compared with finite element analysis, demonstrating good agreement. Further validation was obtained through the calculation of the CTE from the measured strain, with comparisons to handbook data and existing literature data. The validated reliability and precision of the proposed method suggest its applicability to the research and development of thermal protection systems in the aerospace domain.

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