A Prefabricated Strain-Slice-Style Speckle Pattern for Digital Image Correlation Method Under Air-Oxidation Condition at High Temperature up to 1000 °C

Qiang Li, Mengjia Xu, Jijin Xu, Junmei Chen, Chun Yu and Hao Lu

Abstract A prefabricated strain-slice-style speckle pattern applied to high-temperature digital image correlation (DIC) method is proposed and studied in this paper. By virtue of spot welding process, this proposed speckle pattern can be prepared directly and easily on specimen surface. A heating experiment was performed to investigate the high-temperature performance of this proposed speckle pattern under air-oxidation condition. Besides, the ability of this proposed speckle for high-temperature DIC method was verified in a thermal expansion experiment, during which thermal deformation and coefficient of thermal expansion (CTE) values were measured and subsequently compared with the reference data. Results show the effectiveness of this prefabricated strain-slice-style speckle pattern for full-field in-plane thermal deformation measurement with high accuracy using DIC method under air-oxidation condition at high temperature up to 1000 °C.

Keywords Strain-slice-style speckle pattern · High temperature DIC · Thermal deformation

1 Introduction

Accurate measurement of deformation is of great importance for characterization of mechanical and thermo-physical properties of various materials used in some extreme environments, especially under high-temperature conditions. In many cases

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involving spacecraft, high-temperature engine and hypersonic flight, it is very essential to make deformation measurement at elevated temperature. Generally, methods for deformation measurement at elevated temperature can be divided into optical methods and electrometric methods. Recently, optical methods have gained more and more attention and application, including moiré interferometry [1, 2], electronic speckle pattern interferometry (ESPI) [3–5] and DIC method [6–8]. Among these optical methods, DIC method is particularly popular and has been widely used because of its obvious advantages such as non-contacting, low requirement for environment and equipment, easy-to-implement yet effective.

In the literature, many research efforts have been devoted to the study of high-temperature DIC method. In general, these works can be concluded to improve the experimental temperature of DIC method for a wider application. Pan et al. [9] measured the CTE of Polyimide composite film in the temperature range of 20–140 °C using DIC method. De Strycker et al. [10] measured the CTE of a tubular specimen made of SS409 ferrite steel up to temperatures of 600 °C. With the raise of temperature, the effects of thermal radiation are becoming more and more obvious and noteworthy. Thermal radiation [11], which can greatly intensify the brightness of speckle images while reducing the image contrast, can result in the failure of images correlation. Grant et al. [12] firstly proposed a method to suppress the effect of thermal radiation using blue light illumination and filters, which enabled the application of DIC method at higher temperature above 600 °C. Pan et al. [13] determined the full-field thermal deformation and CTE of chromium-nickel austenite stainless steel sample which was heated up to 1200 °C using the similar blue illumination system. Recently, a new strategy, with the combination use of ultraviolet lights and various filters such as ultraviolet band-pass filters, neutral density filters and linear polarizing filter, was employed by Guo et al. [14] to measure the stretching deformation of carbon fibers using DIC method at 2600 °C.

Furthermore, many researches [15–19] show that speckle patterns significantly affect the accuracy of image correlation in DIC analysis. Any distinguishable change of speckle patterns can lead to the failure of DIC analysis seriously, such as peeling off, oxidation, color or shape changing. Therefore, an appropriate fabrication technique for stable speckle patterns is critical and high-demanded, especially under high-temperature conditions. In the literature, various speckle patterns [8] have been adopted for high-temperature DIC method including artificial speckle pattern [10, 13, 14, 20–22] and natural texture pattern [23]. Compared with the natural texture pattern, artificial speckle pattern has various advantages such as (1) better anti-oxidative performance at high temperature; (2) carrying more sufficient information of deformation; (3) more flexible for different experimental conditions. Recently, artificial speckle patterns have become the most widely used speckle patterns in DIC method. The most commonly used techniques to prepare macro-scale (from millimeters to meters) speckle patterns used in high-temperature DIC are airbrushing, spray painting and printing [20, 21]. Chen et al. [21] created a simple and repeatable water-transfer-printing (WTP) pattern which was subsequently employed in 3D-DIC method to measure the stretching deformation of carbon steel specimen at room temperature. Mazzoleni et al. [20] proposed a thermo-mechanical toner-transfer-printing pattern which could withstand the high temperature up to 451 °C. Besides, the heat-resistant black and white paints was employed by de Strycker et al. [10] in DIC method to measure the CTE of a tubular specimen made of SS409 ferrite steel up to 600 °C. However, most of heat-resistant paints will burn out and deform above 600 °C. At higher temperature above 600 °C, some ceramic oxides (ZrO_2, $Al2O_3$, SiO_2, etc.) with a high melting point can be good choices for speckling techniques. By blending black CoO_2 powders with a liquid inorganic adhesive, a black liquid mixture was made by Pan et al. [13] and splashed onto specimen surface, forming a stable speckle pattern which was capable to provide full-field thermal deformation measurement of a chromium-nickel austenite stainless steel sample using DIC method at 1200 °C. Using a high-temperature speckle generated by spraying an alumina paint onto specimen surface, Wang et al. [22] measured full-field strain mapping of C/C composite specimen using DIC method at 2000 °C. But this sprayed pattern needed to dry at 200 °C firstly and was used in a strict vacuum environment (less than 5 Pa). By means of a plasma spraying method, a tungsten sprayed speckle was fabricated by Guo et al. [14] which was stable at 2600 °C in a vacuum chamber filled with protective gas. This complicated yet effective speckling technique was utilized successfully in DIC method to measure the stretching de-formation of carbon fibers at 2600 °C.

Throughout these works mentioned above, there is a trend that speckling techniques have become more and more complex, time-consuming, and difficult to implement with the raise of experimental temperature of DIC method. Besides, these speckling techniques for high-temperature DIC more or less require specimens to undergo some specific heat treatment, which may lead to the properties changes of specimens. It can limit the application of high-temperature DIC to a certain degree. It is very necessary to find an easier-to-implement yet effective method of speckle fabrication for high-temperature DIC method.

In this paper, a novel technique for speckling, generating a prefabricated strain-slice-style speckle pattern, is proposed and studied. In this novel speckling method, specimen's preparation and speckling process are completely separated. All we need to do for speckling is spot welding before DIC experiments. Moreover, this prefabricated strain-slice-style speckle pattern has an obvious potential advantage of being capable of mass production. Besides, the high temperature performance of this prefabricated speckle was investigated by heating experiment under air-oxidation condition. And then thermal expansion tests were directly conducted in the air to measure the thermal deformation and CTE of the DP600 specimens using DIC method at the temperature up to 1000 °C. The results of CTE were compared with the reference data to show a good agreement which indicated that this prefabricated strain-slice-style speckle could be applied to provide practical full-filed in-plane deformation field with high accuracy under air-oxidation condition using DIC method at the temperature up to 1000 °C.

2 Methods

Thermal expansion experiment was performed using DP600 specimen (10 mm × 10 mm × 1 mm) which is shown in Fig. 1. Before the thermal expansion test, another experiment, which was in accordance with standard—"ASTME228-06 Standard Test Method for Linear Thermal Expansion of Solid Materials with a Push-Rod Dilatometer", was conducted for determination of CTE of DP600 material using the equipment called german Linseis L75 platinum series. Table 1 shows the result of CTE of DP600 material within the temperature range from 20 °C up to 700 °C. Subsequently, the result which was considered as the reference data was compared with the experimental results of CTE by high-temperature DIC method described below in this paper, in order to verify the applicability of the aforementioned prefabricated strain-slice-style speckle for high-temperature deformation measurement using DIC method.

2.1 *Prefabricated Strain-Slice-Style Speckle*

Considering the need of anti-oxidative property at high temperature in the air, alumina powder (200–300 mesh numbers, Sinopharm Chemical Reagent Co., Ltd) with a high melting point up to 2054 °C was chosen for speckling in this paper. It would be hard for alumina particle to adhere to the surface of DP600 specimen directly with high bonding strength. Here, a sintering strategy was adopted and a brazing filler material called B-Ni_2 (melting point: 1050 °C) was utilized as the

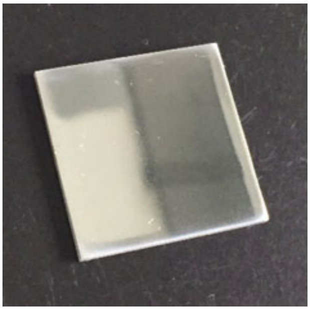

Fig. 1 P600 specimen with a size of 10 mm × 10 mm × 1 mm

Table 1 Reference data of CTE of the material DP600

Temperature(°C)	20	100	200	300	400	500	600	700
CTE(10^{-6}/°C)	12.08	12.15	12.71	14.11	14.93	14.42	15.92	15.59

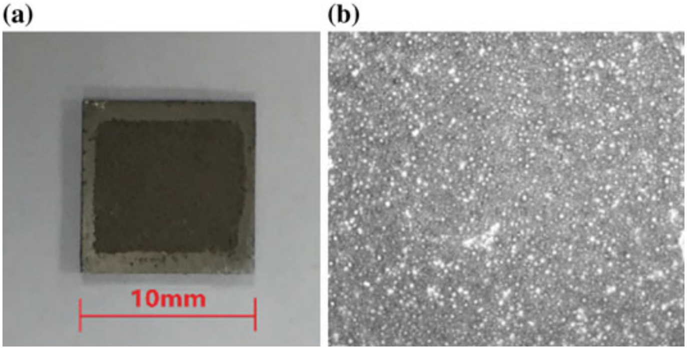

Fig. 2 Photograph of (**a**) specimen 1; **b** the sintering speckle pattern

adhesive between the alumina powder and the specimen surface. Firstly, the surface of DP600 specimen should be polished. And then the B-Ni_2 filler material with a certain liquidity was coated on the specimen surface. The thickness of the filler coating was controlled to 75 μm using a roller coating equipment (SZQ-A2201108, ACIE electronic technology Co., Ltd, Shanghai, China). Afterwards, alumina powder was randomly sprayed onto the coating of B-Ni_2 using an airbrush. Finally, the whole specimen, called as specimen 1 and shown in Fig. 2a, was put into the vacuum furnace to go through heat treatment at the temperature of 1000 °C for 10 min aiming for high bonding strength between the specimen, the B-Ni_2 brazing filler material and the alumina powder. This kind of speckle pattern is called as the sintering speckle pattern in the following and shown in Fig. 2b (8 bitmap). An optimal speckle granule with a size of 3–5 pixels or slightly greater were highly recommended by Reu [24]. In Fig. 2b, white alumina particle with the diameter of 3–10 pixels in the image forms clear and random speckle pattern while the B-Ni_2 filler becomes a dark and gray background. It can be seen that this sintering speckle pattern can provide sufficient variations in contrast to ensure the accurate measurement of deformation using DIC method. Besides, it's very difficult for alumina particle to peel off from the B-Ni_2 filler.

However, the DP600 specimen (specimen 1) also underwent the sintering process of 1000 °C for 10 min which might result in properties changing of specimen. Keeping the organization and structure of specimen's phase in original state is desirable during the speckle preparation. Here, an improved technique for speckle fabrication is proposed based on the sintering approach above. The main improvement is that the B-Ni_2 filler is coated on the surface of NCF600 alloy foil (8 mm × 8 mm × 0.1 mm) instead of the specimen directly with the rest procedure being exactly the same. Thus, a strain-slice-style square foil (8 mm × 8 mm × 0.1 mm) made of NCF600 formed with the sintering speckle pattern already prepared on its surface. By means of spot-welder machine (GW-3C, KYOWA KOGYO Co., Ltd, Japan), the square NCF600 alloy foil was able to be spot welded easily on the original DP600 specimen. The current for spot welding

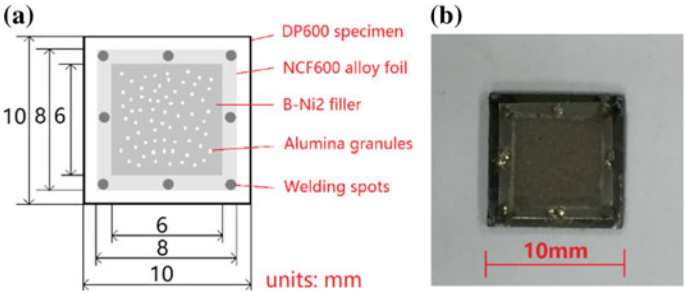

Fig. 3 Photograph of (**a**) schematic diagram of the prefabricated strain-slice-style speckle; **b** specimen 2

was 1A and positions of eight welding spots are given in Fig. 3a, including four vertexes and four middle points of the edges of the square NCF600 alloy foil. For convenience, this process of spot welding is called as eight-point spot welding process in the following. Figure 3b shows the practical photograph of the DP600 specimen (called as specimen 2) welded with the prefabricated strain-slice-style speckle pattern.

In this prefabricated speckling approach, specimen's preparation and speckling process are completely separated. Besides, this strain-slice-style speckle can be capable of mass production before the DIC test, for which it was called prefabricated speckle pattern. So spot welding is the only work we need do for speckle preparation. Obviously, the strain-slice-style speckling approach becomes more convenient, less time-consuming and easier to implement compared with common speckling methods such as spray painting and printing [20, 21].

2.2 Experimental Setup

The whole experimental setup is shown in Fig. 4 and mainly consists of imaging system, heating system, temperature measurement system.

As mentioned above, thermal radiation is a key problem needed to be solved when temperature rises above 600 °C. Thermal radiation, which can greatly intensify the brightness of the speckle image while reducing the image contrast, can result in the failure of images correlation. In physics, Planck's formula was developed to quantitatively describe the spectral energy emitted in the normal direction from a black body as a function of wavelength and temperature. The Planck's equation is:

$$I(\lambda, T) = \frac{c_1 \cdot \lambda^{-5}}{e^{c_2/\lambda T} - 1} \tag{1}$$

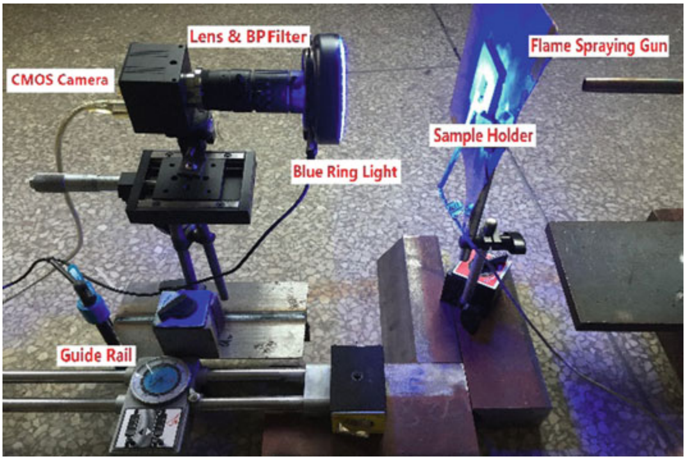

Fig. 4 Photograph of the experimental setup

where I represents the spectral radiation energy as a function of temperature T and wavelength λ, and e is the natural logarithm, c_1 and c_2 are the first and the second radiation constant, respectively. Figure 5 shows the variation curve of thermal radiation energy as a function of wavelength and indicates some important characteristics of the thermal radiation (also called as black body radiation if the heat source can be regarded as black body). As temperature goes up, the amount of radiation energy greatly increases at all optical wavelengths. Meanwhile, the peak wavelength of the radiation curve shifts to a shorter wavelength. In Fig. 6, four variation curves of spectral radiation energy as a function of temperature are plotted for four different optical wavelengths of 400, 500, 600, 700 nm. It can be seen that the radiation energy of the shorter wavelength 400 nm, 500 nm is obviously lower than that of longer wavelengths 600, 700 nm above 700 °C. Based on this similar phenomenon, a strategy of using band-pass filters and blue light illumination was proposed by Grant et al. [12] to suppress the influence of thermal radiation.

In Fig. 4, our experimental system employed a blue ring LED light installed directly in front of the lens (Computar, MACRO ZOOM 1:4.5, CBC Trading Co., Ltd, Shanghai, China). And this LED light was able to provide enough and adjustable blue illumination for speckle imaging. Besides, a commercial CMOS camera (DH-HV3102UC, Daheng Image Co., Ltd, Beijing, China) was used to obtain the digital images (1024 × 768 pixel, 5.89 μm/pixel) of the speckle pattern. The camera was fixed in a slide block of the guide rail with a fine scale of displacement, for which the camera's position could be adjusted freely and preciously in the parallel direction of track. Meanwhile, in order to reduce the bad influence of thermal radiation to the imaging quality, a band-pass filter (NMOT-BP450-D25, Nano Macro Photonics Technology Co., Ltd. Shenzhen, China) was employed, which almost only allow light of the specific wavelength within the range of 430–480 nm to pass through. Figure 7 shows the photograph of this band-pass filter

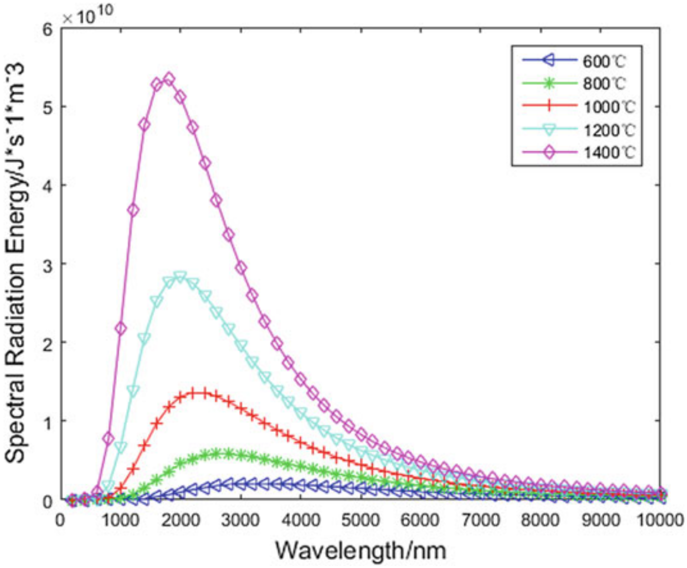

Fig. 5 Spectral radiation energy as a function of wavelength for temperature of 600, 800, 1000, 1200, 1400 °C

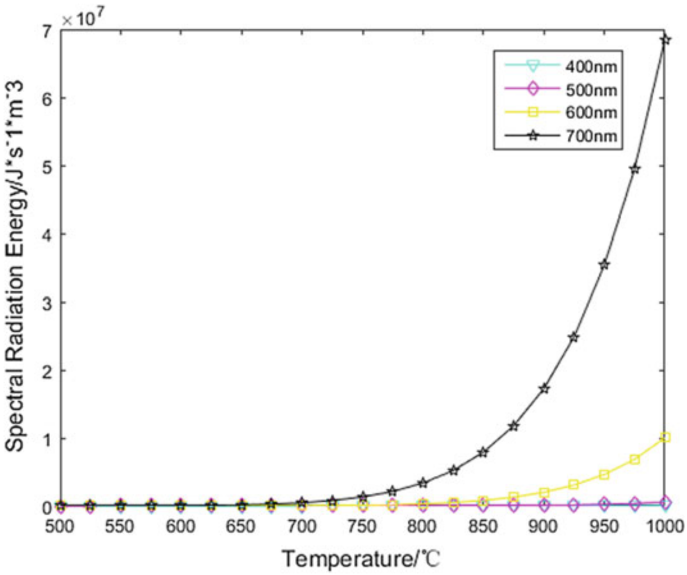

Fig. 6 Spectral radiation energy as a function of temperature for optical wavelength of 400, 500, 600, 700 nm

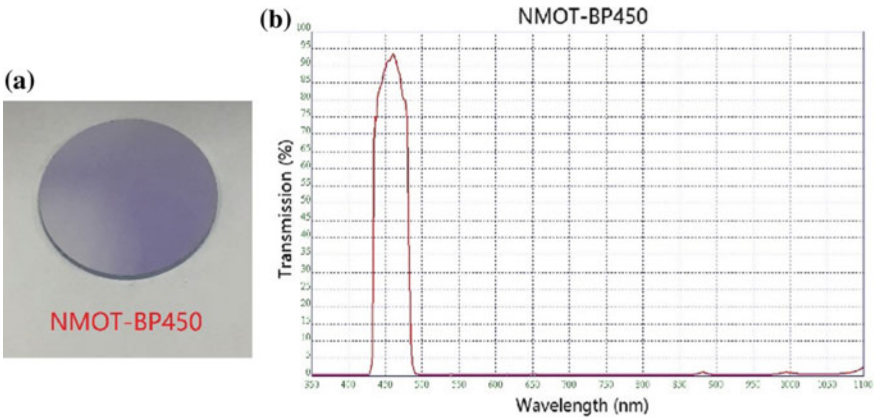

Fig. 7 Detailed information of NMOT-BP450 filter including (**a**) its photograph; **b** the plot of its transmissivity

as well as the plot of its transmissivity. Because of the good matching of diameters between the filter and lens, this band-pass filter was directly installed inside of the lens.

Temperature measurement and heating of specimens during the thermal expansion test are also critical for determination of deformation and CTE. Here, a butane flame spraying gun (shown in Fig. 4) was utilized to heat the specimen on its backside directly in the air. So the speckle described previously needs to withstand both high temperature and air oxidation. It is worth stressing that the square specimen was placed on the sample holder without any fixation so that the specimen could expand freely during the heating process. Also, the direction of the flame was adjusted to be perpendicular to the specimen. Meanwhile, both the center of the flame and square specimen were kept to be consistent.

2.3 *Determination of Thermal Deformation and CTE*

DIC method [6, 7] was developed to provide full-filed deformation and strain measurement by comparing digital images of speckle patterns obtained before and after deformation. Finding the position for a specific pixel in the reference image after deformation becomes the primary job of DIC method. A square reference subset of $(2\ M + 1) \times (2\ M + 1)$ pixels centered the specific pixel in the reference image is chosen to find the corresponding target subset in the deformed image. And a correlation function should be employed for measuring the matching degree between the reference subset and the target subset. A typical correlation function called as zero-mean normalized sum of squared difference (ZNSSD) criterion is

$$
\begin{aligned}
&C\left(u, v, u_x, u_y, v_x, v_y\right) \\
&= \sum_{x=-M}^{M} \sum_{y=-M}^{M} \left[\frac{f(x,y) - f_m}{\sqrt{\sum_{x=-M}^{M} \sum_{y=-M}^{M} \left[f(x,y) - f_m\right]^2}} - \frac{g(x',y') - g_m}{\sqrt{\sum_{x=-M}^{M} \sum_{y=-M}^{M} \left[g(x',y') - g_m\right]^2}} \right]^2
\end{aligned}
\tag{2}
$$

where $f(x,y)$ is the gray value of the pixel at the coordinate (x,y) of the reference image while $g(x',y')$ is the gray value of the pixel at the coordinate (x',y') of the deformed image, and f_m and g_m are the mean gray value of subsets in the reference, deformed image respectively, $\left(u, v, u_x, u_y, v_x, v_y\right)$ is a parameter vector to denote deformation of this reference subset. In fact, the deformation is approximately described with the following equations:

$$x' = x + u + u_x \Delta x + u_y \Delta y \tag{3}$$

$$y' = y + v + v_x \Delta x + v_y \Delta y \tag{4}$$

where u and v are the displacements for the subset center in the x, y direction respectively, Δx and Δy are the distances from the subset center to pixel (x,y), u_x, u_y, v_x, v_y are the first order derivative of displacement (also called as strain) correspondingly.

In practical implementation of high-temperature DIC of this paper, a subset with the size of 41 × 41 pixels was chosen and the ZNSSD correlation function was employed. Besides, to make DIC analysis less time-consuming, Newton-Rapshon iterative algorithm [25] was used to search for extreme point (x',y') which minimizes the ZNSSD correlation coefficient. It was noteworthy that a square region (512 × 682 pixels) in the center of speckle images (768 × 1024 pixels) was selected as the region of interest (ROI) with the step of 2 pixels for calculation. So totally there were 38,817 (= 171 × 227) pixel points whose strain and displacement value in both x and y direction would be obtained. The uniform thermal expansion can be regarded as uniaxial tensile if only considering one specific direction. For this reason, the mean strain of these 38,817 data was calculated to be the final strain caused by the thermal expansion occurred between the current and room temperature. Afterwards, the CTE α_T of material DP600 at the temperature T can be determined by the following equation:

$$\alpha_T = \frac{\varepsilon(T_0, T)}{T - T_0} \tag{5}$$

where $\varepsilon(T_0, T)$ represents the strain of thermal expansion at the current temperature T, and T_0 is the room temperature.

3 Results and Discussion

3.1 High-Temperature Performance of the Prefabricated Strain-Slice-Style Speckle

To investigate the performance of the prefabricated strain-slice-style speckle described previously, a high-temperature heating experiment was conducted. In this experiment, the original speckle image of specimen 2 was captured as the reference image firstly under the while light illumination. And then, the specimen 2 was heated up to 800 °C at the rate of 25 °C/min using a heating furnace which is shown in Fig. 8. Afterwards, the specimen was kept in heating furnace at 800 °C for three hours, after which the specimen was cooled to the room temperature in the furnace chamber. A new speckle image of the specimen 2 was obtained under the same white light illumination system. Heating up to 800 °C, heat preservation, cooling to room temperature and images acquisition constituted a thermal cycle. By repeating the work of thermal cycle, speckle images of the same ROI of specimen which withstood the air-oxidation condition up to 800 °C for 0, 3, 6, 9 h were able to be acquired and presented in Fig. 9. And the distribution curves of grayscale intensity for these four speckle images are given in Fig. 10.

According to these four speckle images in Fig. 9, this prefabricated speckle remains clear with alumina particles being white and the B-Ni_2 filler being gray after being heated in the furnace chamber at 800 °C for 9 h. Few alumina granules fall off from the specimen surface while the rest keep strong bonding strength with specimen. In summary, there is no distinguishable change in the size and shape of

Fig. 8 Photograph of the heating furnace

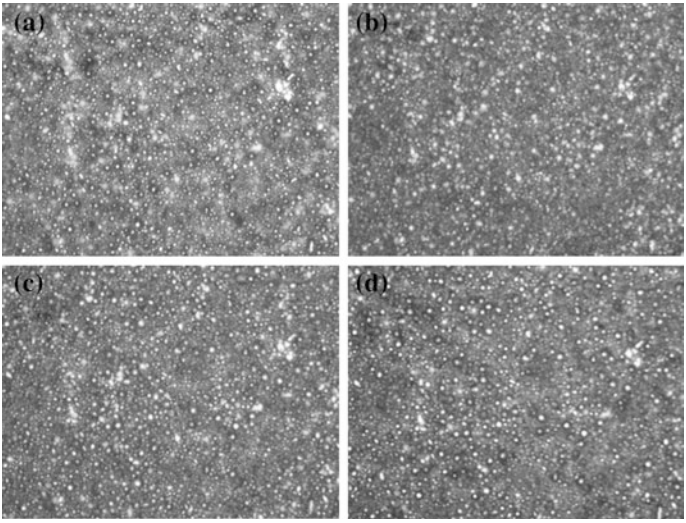

Fig. 9 Images of speckle pattern heating at 800 °C for **a** 0 h; **b** 3 h; **c** 6 h; **d** 9 h respectively

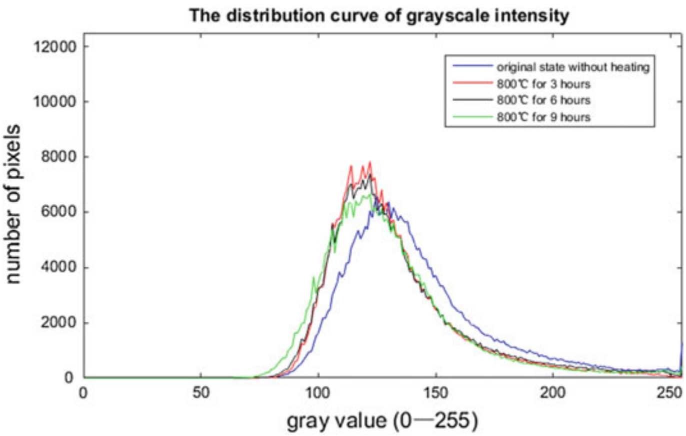

Fig. 10 Grayscale distribution curves of speckle pattern heating at 800 °C for 0, 3, 6, 9 h respectively

alumina granules. In Fig. 10, the grayscale distribution curves of these four speckle images almost keep the same changing characteristics. Compared with the distribution curve of the original speckle without any heat treatment, the rest of three distribution curves all shift to the left relatively with a very short grayscale. This phenomenon can be explained with the primary reason that the color of the B-Ni_2 filler material become slightly grayer after the heat treatment. However, the following DIC analysis indicated that the slight color change of the B-Ni_2 filler material didn't affect high-temperature deformation measurement using DIC method up to 1000 °C. All these results prove that this prefabricated strain-slice-style speckle described in this paper is able to withstand the air-oxidation condition at temperature up to 800 °C at least for 9 h without any obvious reduction of speckle's quality for DIC analysis.

3.2 Thermal Expansion Experiments

In order to verify the validity of this prefabricated strain-slice-style speckle described in this paper for full-field in-plane deformation measurement using DIC method at high temperature, thermal expansion tests were conducted by employing two kinds of speckling methods. As mentioned above, the specimen 1 was prepared by speckling on its surface directly while specimen 2 was speckled by the prefabricated strain-slice-style speckling approach. Both methods for speckling in the following thermal expansion experiment were described systematically and concretely in the methods part of this paper. Out of the consideration that the anti-oxidative performance of this prefabricated sintering speckle for high-temperature DIC method needs to be investigated, the whole experimental setup (shown in Fig. 4) was put in the air. Figure 11 shows the actual photographs of specimen 1 (at 900 °C) and specimen 2 (at 1000 °C). Here, it must be emphasized that specimens were spot-welded on the center of a square NCF600 alloy foil (30 mm × 30 mm × 0.1 mm) with only one welding spot to fit the size of the viewing window of the sample holder. So specimens could expand freely and be photographed conveniently during the thermal expansion experiments. Besides, a point which was 1 mm away from the edge of square specimen on the center line was chosen to be the testing position for temperature measurement by using k-type thermocouple pairs with a high measuring accuracy of ±0.1 °C.

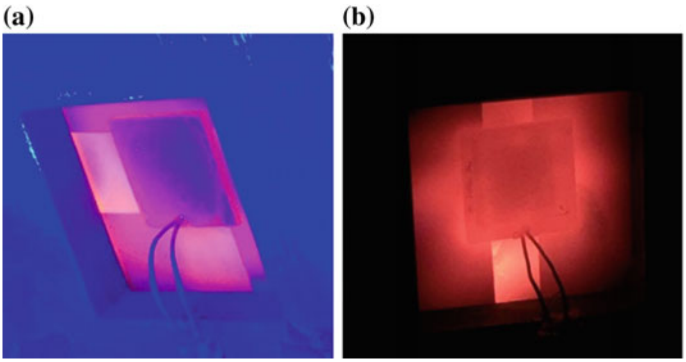

Fig. 11 Photographs of (**a**) specimen 1 at 900 °C; **b** specimen 2 at 1000 °C

There was a concern that the temperature of this testing point and the speckling region (6 mm × 6mm) may differ sharply. So a test for temperature measurement of the specimen's surface was performed before the thermal expansion experiment, aiming for verifying the homogeneity of temperature field of the specimen surface. Five points on the center line of the specimen were chosen, and the distances between these 5 points and the edge of specimen were about 1, 3, 5, 7, 9 mm respectively. Figure 12 shows the photograph of these five points for temperature measurement. Here, an original DP600 specimen (10 mm × 10 mm × 1 mm) without speckling was heated to reach the nominal temperature from 100 to 900 °C at the interval of 100 °C in turn. Once the nominal temperature was reached, 10 min was given to make the specimen's temperature reach stable state firstly, and afterwards temperature of these five points were measured. Table 2 shows the actual record of these five points' temperature. The temperature difference between these 5 points at each nominal temperature is less than 9.4 °C, which reasonably presents a good homogeneity of the specimen's temperature field.

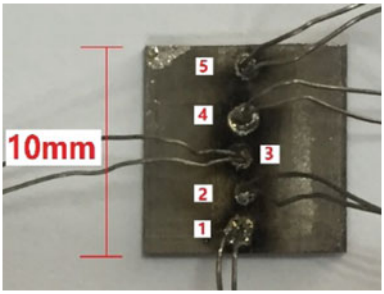

Fig. 12 Five points for temperature measurement test

Table 2 Records of temperature measurement of these 5 points (°C)

Nominal temperature	Point 1 (1 mm)	Point 2 (3 mm)	Point 3 (5 mm)	Point 4 (7 mm)	Point 5 (9 mm)	Maximum difference
RT	28.6	28.4	28.2	28.6	28.4	0.4
100	100.3	94.3	100.1	92.5	91.2	9.1
200	195.7	199.7	200.2	195.4	193.3	6.9
300	299.1	300.5	300.4	303.8	301.8	4.7
400	406.1	402.3	406.2	398.5	398.2	8.0
500	503.6	496.3	501.3	501.3	494.2	9.4
600	601.4	600.5	604.2	597.5	599.4	6.7
700	700.3	697.4	702.5	693.2	695.9	9.3
800	800.3	802.0	802.2	797.9	793.0	9.2
900	899.0	902.7	901.3	894.9	897.2	7.8

Back to the thermal expansion experiments, the speckle images of specimens were obtained at the room temperature (28.5 °C) as reference images with the use of blue illumination and band-pass filter. By exactly the same heating procedure used in the test mentioned above, specimen 1 and specimen 2 were heated up to the nominal temperature from 100 to 1000 °C at the interval of 100 °C in turn. At each nominal temperature, the actual temperature of the specimen was measured and recorded and then speckle images (1024 × 768) of the same region of specimens were acquired as current images.

Figure 13 presents the reference images and the current images of both specimens. For some unknown technical reasons, the specimen 1 was eventually heated up to 900 °C instead of 1000 °C. According to Fig. 13, no matter which approach was adopted for speckling, the speckle still remained high quality and stability without discernible change of its color, size and shape at high temperature. The success of subsequent DIC analysis also verified the ability of both kinds of speckles for full-field in-plane deformation measurement using DIC method under air-oxidation condition at least 1000 °C.

By the DIC method mentioned above, the full-field displacement and thermal strain field of specimens in the horizontal (x) and vertical (y) direction at every nominal temperature were obtained finally. Figures 14 and 15 show the displacement and strain field of specimen 1 and specimen 2. According to Fig. 14, the equally spaced contour lines, being nearly parallel to the vertical, horizontal direction correspondingly, indicate that the displacement field presents a similar characteristic of uniaxial tensile in both directions of x and y. The phenomenon of slightly slant can be explained by the slightly rigid-body rotation of both specimens in a counterclockwise direction which will not introduce extra strain field.

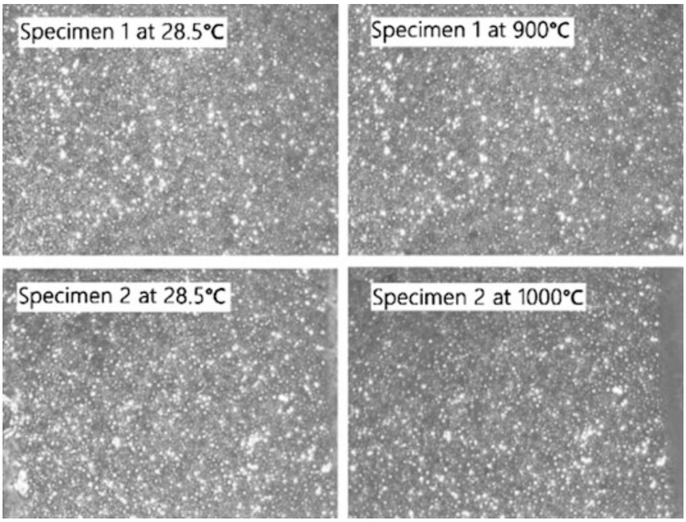

Fig. 13 Speckle images of DP600 specimens obtained under blue illumination system

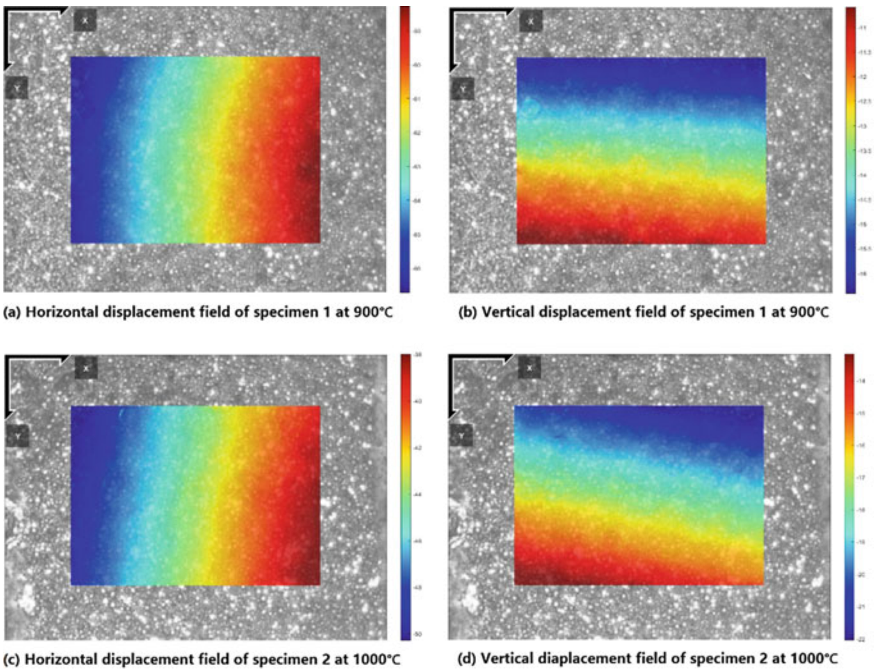

Fig. 14 The displacement field of both specimens

In Fig. 15, the full-field strain field at the corresponding highest temperature were measured for both specimens.

As mentioned above, there were totally 38,817 (= 171 × 227) pixel points whose strain and displacement value in both x and y direction would be obtained. Table 3 lists some statistical data of the strain fields for both specimens. With standard deviations being small enough (less than 9.1971E-04), all strain fields of specimen 1 (at 900 °C) and specimen 2 (at 1000 °C) show a good uniformity. Furthermore, because of the lower temperature to reach, three kinds of statistical data (the mean value, the maximum value, the minimum value) of the strain field of the specimen 1 (at 900 °C) is smaller than those of the specimen 2 (at 1000 °C).

It is worth noting that the speckling approaches of these two specimens are different. As for specimen 1, the speckle prepared directly on specimen surface is able to deform with the surface of DP600 specimen, for which the strain field of the speckle is considered to be exactly the same with that of the specimen surface. However, as for specimen 2, the deformation of specimen surface below is transferred to the strain-slice-style speckle above through the shearing force of eight welding spots. Therefore, the strain field of the strain-slice-style speckle above is merely an approximation of that of the specimen surface below. Here, the similarity between these two surfaces is determined by various factors including the number and positions of welding spots, the spot welding process, etc. In the eight-point spot

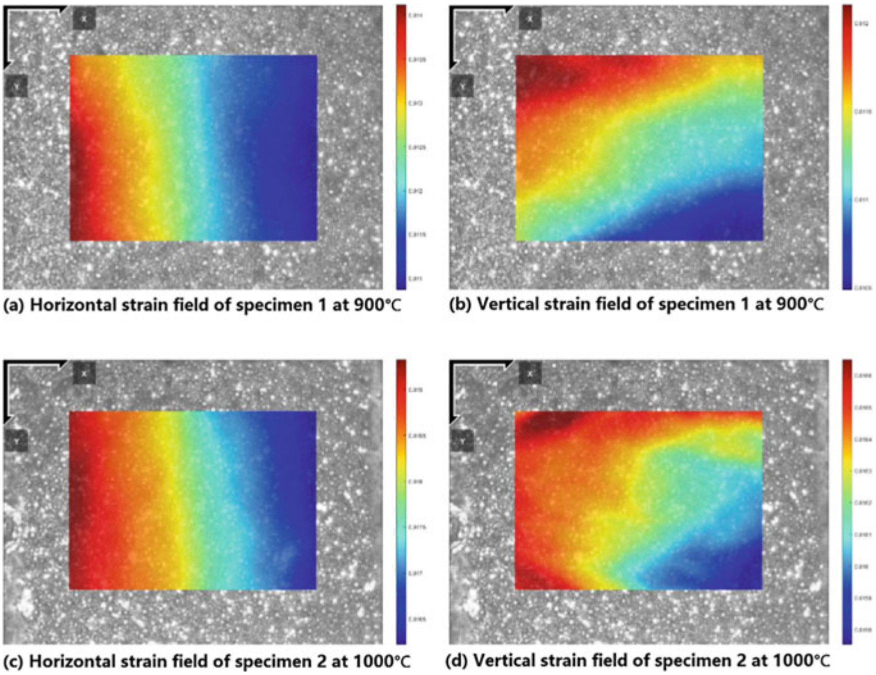

Fig. 15 The strain field of both specimens

Table 3 Some statistical data of the strain field for both specimens

Sample number	Direction	Mean value	Maximum value	Minimum value	Standard deviation
Specimen 1 (900 °C)	Horizontal	0.012290	0.014270	0.010725	9.1971E-04
	Vertical	0.011336	0.012190	0.010463	3.9952E-04
Specimen 2 (1000 °C)	Horizontal	0.017828	0.019392	0.016015	8.9676E-04
	Vertical	0.016283	0.016680	0.015702	2.1099E-04

welding process mentioned previously, these eight points formed a square region which is small enough (8 mm × 8 mm approximately) to provide a high similarity of the deformation field between the speckle above and the specimen surface below. Therefore, the strain-slice-style speckle pattern proposed in this paper can be as equally effective to provide a highly similar thermal strain field as the speckle directly prepared on specimen does. For example, in Fig. 15a, c, by the dye strategy where different colors represent different strain values, both specimens' strain field in the x direction show a same characteristic that the strain values decrease slowly along the *x* direction. Besides, according to Fig. 15b, d, the similar decreasing feature of the strain field also exists along the direction from top left to bottom right of ROI region. Figure 16 is the two-dimensional vector diagram of the

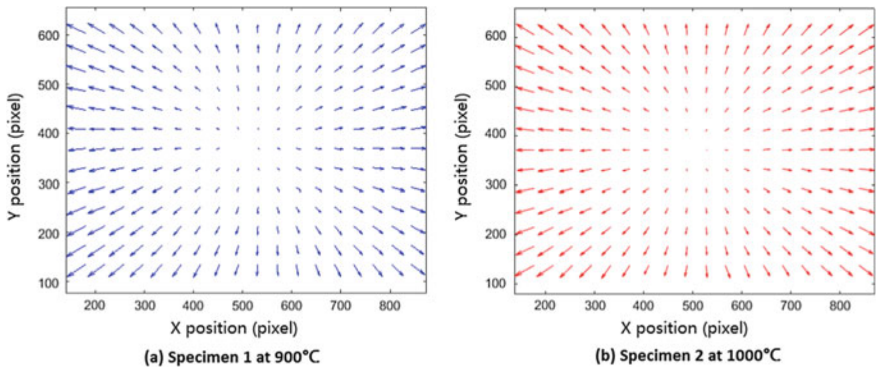

Fig. 16 Two-dimensional vector diagrams of the displacement fields

displacement field of the thermal deformation and both present a typical thermal expansion with a nice homogeneity evidently. These high similarities between specimen 1 and specimen 2 in the strain field indicate a good effectiveness of the strain-slice-style speckle pattern for thermal deformation measurement using DIC method under air-oxidation condition at the temperature up to 1000 °C.

3.3 Determination of CTE

As mentioned above, the CTE can be determined by computing the mean strain of 38,817 pixel points in ROI region of each image and dividing by the temperature difference between the current and room temperature. Considering two directions and two speckling approaches, four different CTE values at each nominal temperature were obtained and given in Fig. 17. Besides, Fig. 17 includes the reference data of CTE which is also given in Table 1.

According to Fig. 17, the variation tendency of these five different CTE values as a function of temperature reaches a good agreement. As the temperature goes up, foremost the CTE increases and then decreases slowly with 600 °C as the turning point. Here, it is noteworthy that four CTE values of DP600 specimens determined by DIC method differ a little bit sharply at 100 °C with the maximum relative difference percentage being 21.3% relative to the reference data. To make specimen reach the lower nominal temperature 100 °C, the flame spraying gun is kept further away from the specimen relatively compared with that in conditions at higher nominal temperature, which results in a slightly unstable and swaying flame to heat the specimen. For this reason, the temperature field of the specimen at 100 °C is not uniform enough to form a stable deformation field and to provide an accurate CTE values furthermore. However, at higher temperature from 200 to 900 °C, two different speckling approaches result in nearly the same values of CTE in both *x*, *y* directions with the maximum relative difference percentage being 9.4% relative to

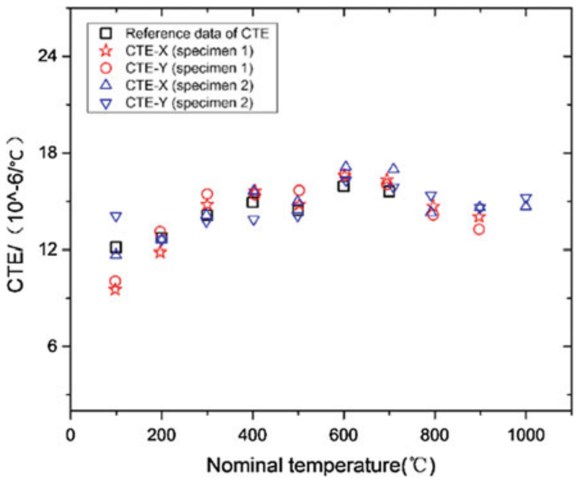

Fig. 17 Mean CTE of DP600 material as a function of temperature

the reference data. Moreover, no matter which speckling approach is chosen, the CTE values in both directions (*x* and *y*) determined by the subsequent DIC analysis are almost identical with the maximum difference being 1.2×10^{-6}/°C at various nominal temperature (except for 100 °C). It can be concluded that the DP600 material used in this study is an isotropic material with the same CTE in the *x* and *y* directions. All these close agreements prove the ability of both speckle patterns used in DIC method for full-field in-plane thermal deformation measurement with an acceptable high accuracy under air-oxidation condition at high temperature up to 1000 °C.

4 Conclusion

An easy-to-implement yet effective speckle pattern called as prefabricated strain-slice-style speckle pattern, which is fabricated only by virtue of the eight-point spot welding process, is proposed in this paper. A heating experiment was conducted to prove the anti-oxidative and stable performance of this prefabricated speckle pattern at temperature up to 800 °C at least for 9 h without any obvious reduction of speckle's quality. Besides, the strain and displacement field of DP600 specimens at various temperature were measured using DIC method, and subsequently the values of CTE were determined and compared with the reference data, confirming the effectiveness of this prefabricated strain-slice-style speckle pattern proposed in this paper for thermal deformation measurement with an acceptable high accuracy under air-oxidation condition at high temperature up to 1000 °C. It's also noteworthy that this strain-slice-style speckle pattern may be able to withstand air-oxidation condition at higher temperature for wider applications of DIC method if the brazing filler material with a higher melting point is chosen.

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