Strain field measurements over 3000 °C using 3D-Digital image correlation

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\textbf{A R T I C L E I N F O}

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\textbf{A B S T R A C T}

With the development of aerospace and fusion engineering, understanding the mechanical behavior of materials under high-temperature conditions has become increasingly important. However, few studies are devoted to the ultra-high temperature range of 2000–3000 °C. In this study, with the aim of developing non-contact measuring techniques of mechanical deformation under ultra-high temperature, a high heat flux (~300 MW) comprehensive experimental platform is established, which includes a vacuum chamber, a three-dimensional digital image correlation (3D-DIC) system, infrared radiation thermometers and an electron beam heating system. Using the electron beam heating technique, the tungsten specimen can be heated to over 3000 °C. Owing to the use of a vacuum chamber, the thermally induced airflow disturbance at high temperature can be completely removed. Tantalum carbide (TaC) powder is chosen as the speckle material and speckle fabrication technology is developed to adapt ultra-high temperatures under vacuum conditions. In order to suppress the blackbody radiation at high temperature, three schemes based on blue light sources, self-radiating light sources and a dual wavelength optical filter technique are designed for three temperature ranges from room temperature to 3067 °C. Afterwards, full-field thermal deformation of the tungsten specimen above 3000 °C was determined based on the above strategies using the 3D-DIC technique. The feasibility and accuracy of the proposed methods are verified by comparing the measurement results with the thermal expansion strain data and model from available databases and literature. The standard deviations in different temperature intervals are 50 με for 25–1200 °C, 100–200 με for 1200–1800 °C and less than 500 με for 1800–3067 °C. The proposed methods and technologies are expected to lay a foundation for further developments in strain field measurements at ultra-high temperature.

1. Introduction

Understanding the mechanical behavior of metals under high temperature conditions is of great significance in many fields, for example, in the aerospace and nuclear industries [1-4]. In fusion engineering, tungsten, the most promising material for the plasma-facing inner wall of future nuclear fusion devices, can work at very high temperatures, owing to ion beam irradiation heating. Full-field strain measurement of a heated tungsten specimen is essential for the determination of its thermal physical properties, and is also important for the proper selection and development of the materials applied in future nuclear industries. Conventionally, high-temperature strain is measured by contact strain gauges and an extensometer. However, for temperatures greater than 1000 °C, strain gauges cannot meet the measurement demands because of the limited operating temperature range. In addition, these two techniques can only provide the average strain of the local area and therefore cannot be applied for full-field thermal deformation measurement. In contrast, non-contact optical measurement techniques based on digital image procession can effectively overcome the shortcomings of contact techniques [5,6] and therefore have gradually become the most effective methods in the field of high temperature experimental mechanics.

Non-contact optical measurement techniques have been widely used in the fields of aerospace, materials, biology and so on because of their advantages, such as simplicity, high measurement accuracy and low requirements of vibration isolation. Digital image correlation (DIC) is a non-contact optical metrology originally proposed by Yamaguchi and Peters et al. in the 1980s [7,8]. In order to meet the urgent need for three-dimensional (3D) shape and deformation measurements, a 3D-DIC technology based on binocular vision was developed [9,10]. In 1996, Lyons et al. fabricated speckles on samples and obtained the thermal expansion coefficient and elastic modulus of chrome-nickel-iron super alloy materials from room temperature to 650 °C using DIC [11]. In 2009, Grant et al. measured the Young's modulus and coefficient of thermal expansion of a nickel-base alloy from ambient temperature to 1000 °C through blue illumination [12]. The accuracy of strain measurements can be enhanced by improving algorithms or using artificial speckle

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patterns. Gao et al. proposed a high-efficiency and high-accuracy algorithm for 3D-DIC, known as the IC-GN² algorithm [13]. In 2012, Chen et al. studied the speckle performance of aluminum and zirconia ceramic materials with a monochromatic light source and proposed a way to cure the speckles in advance for the sake of clearly speckle identification [14]. Yang et al. studied the real-time deformation of near-interface regions and the surface of thermal barrier coatings using a micro-DIC method with fabrication of a speckle pattern by spraying a mixture solution of alcohol and high temperature resistant particles [15]. Chen et al. studied the residual stress evolution regularity in thermal barrier ceramic coatings by micro-DIC and micro-Raman spectroscopy [16]. Lin et al. performed thermal shock tests on SiO₂ and Al₂O₃ based on a DIC method [17]. In order to solve the high temperature self-luminescent interference problem, Berke and Lambros proposed a technical route for 3D-DIC measurements with an ultraviolet (UV) light source and UV cameras [18]. Dong et al. measured the in-situ 3D ablation shapes of a blunt cone subjected to arc heating with a temperature range of 1000–1868 °C using a UV stereo-DIC technique [19]. Wang et al. measured full-field strain mappings and a stress–strain curve for a carbon fiber-reinforced carbon (C/C) composite uniaxial tensile specimen at 2000 °C and obtained the Young’s modulus [20]. Guo et al. measured the stretching deformation of carbon fibers at 2600 °C by using plasma spray tungsten powder for speckle preparation and the filters for image acquisition [21]. The authors’ group completed a series of fundamental studies on the DIC technique and measurement precision analysis and developed a general 3D-DIC measurement system (PMLAB 3D-DIC), which has been applied in many fields [22–27].

In summary, according to the addressed DIC technique application cases under high temperature, most of them are under a temperature of less than 2000 °C, with few cases having been extended to an ultra-high temperature range of 2000–20000 °C. In order to measure the strain fields at ultra-high temperature (>2000 °C), there are several problems that need to be solved as listed in the following aspects:

1. Very few speckle materials can be maintained at ultra-high temperature without peeling off or being burned out.
2. Thermal radiation at ultra-high temperature decreases the quality of the images, leading to the failure of strain field calculations. These effects are especially difficult to eliminate in the ultra-high temperature range.
3. The strong airflow disturbance caused by normal environmental atmosphere at high temperature can easily affect the speckle characteristics of images.

Solving the above problems has become an important topic. The key links may lie in three aspects: first, searching for suitable speckle materials for the ultra-high temperature range and improving the fabrication process of speckles onto specimens; second, developing an advanced filtering method to reduce the effects of thermal radiation; third, conducting the experiment in vacuum conditions to remove thermally induced airflow disturbance at high temperature. In this study, a high heat flux comprehensive experimental platform with a vacuum chamber is established and a 3D-DIC measurement system based on blue light sources is used as a strain measurement device. Furthermore, a new kind of speckle material and fabrication technology are developed to adapt ultra-high temperature under vacuum conditions.

This study is organized as follows. Section 2 introduces the sample preparation, including speckle material selection, fabrication and curing of the speckle pattern. In addition, experimental facilities and measurement systems are elaborated, after which three schemes are proposed to suppress the disturbance caused by thermal radiation at ultra-high temperature and a detailed description of the experimental procedures is given. In Section 3, the strain fields of tungsten specimen over 3000 °C are obtained and the measurement results are compared with available database and literature. Moreover, the fluctuation of measurement results are also assessed through analyzing the residual variance. Section 4 draws the conclusions of this work.

![](image)

**Fig. 1.** Pictures of (a) speckle materials, (b) tungsten block with newly-prepared speckle pattern and speckle pattern before (c) and after (d) being cured.

### 2. Methodology

#### 2.1. Sample preparation

The specimen is made of pure tungsten with dimensions of 20 mm × 20 mm × 50 mm. To ensure reliable measurements using the 3D-DIC technique, randomly distributed artificial speckle patterns, serving as a carrier of deformation information, are generally fabricated on the specimen surface. In high temperature deformation measurements, the speckle pattern made by spraying common paints normally burns out or peels off at high temperature. In this work, a simple yet effective speckle pattern fabrication technique was developed for ultra-high temperature deformation measurements, as shown in Fig. 1. Based on a preliminary test verification, TaC powder was chosen as the speckle material due to its high melting point (3880 °C) and low coefficient of thermal expansion. Before fabricating the speckle pattern, the target surface of a tungsten block was prepared by normal degreasing and cleaning. Initially, the target surface was polished using emery papers of #800 to #1500-grit and then cleaned with alcohol. The raw materials for fabricating the speckle pattern were TaC powder with an average particle size of 1 μm and a purity of 99.9% and alcohol. TaC powder and alcohol were mixed in a proper proportion (mass ratio m(TaC):m(alcohol) = 1:2), giving rise to the paste state mixture shown in Fig. 1(a). During the mixing process, the mixture was thoroughly stirred with a glass rod to prevent agglomeration of the TaC powder. After that, each time a small dollop of TaC/alcohol mixture was picked up by a needle tip, and then the dollop was manually deposited to the target surface. Due to the differences of amount of dollop picked up each time as well as the randomness of manual operation, a kind of artificial speckle pattern was fabricated. Then, the prepared specimen was kept in a fume hood for 6–12 h to accelerate the evaporation of alcohol. Finally, the speckle pattern was fabricated, as shown in Fig. 1(b).

Due to the speckle pattern fabricated by the above method being very fragile, we cured the speckle pattern to enhance its adhesion to the tungsten block surface. The tungsten specimen was heated firstly to 400 °C for 5 min and then to 800 °C for 5 min after cooling down to room temperature under vacuum conditions. In addition, low heating rate is more favorable to ensure the quality of speckles during curing. The results show that the speckles could be further strengthened after being cured, as presented in Fig. 1(d).

#### 2.2. Experimental facilities

The experiments are conducted on the high heat flux comprehensive experimental platform, as shown in Fig. 2, which includes five important systems: (1) A vacuum maintaining system; (2) an electron beam...
heating system; ③ a water cooling system; ④ a measurement system; ⑤ a safety protection system. The vacuum maintaining system consists of a vacuum chamber with dimensions of 1540 mm x 1040 mm x 1020 mm, a molecular pump and two mechanical pumps. The vacuum degree can be maintained at 10^{-3} Pa to meet the experimental requirements using the mechanical and molecular pumps, which not only ensures normal operation of the electron gun, but also avoids the thermally induced air-flow disturbance at ultra-high temperature and prevents the specimen from being oxidized [28]. An electron beam heating system (30 kW) is adopted to efficiently heat the tungsten specimen to ultra-high temperature (>3000 °C). Moreover, the strong disturbance of thermal radiation emitted from the heating device can be removed. The water cooling system is employed to cool the vacuum chamber walls and the view windows, so that long-time thermal loading testing can be conducted and the thermal errors induced by the temperature variation of the environment can be removed, ensuring the accuracy of the strain measurements. The measurement system consists of a 3D-DIC system and two measuring temperature instruments. The safety protection system includes a lead room that is employed to protect operators from ionizing radiation and other hazardous events.

The measuring device contains a PMLAB 3D-DIC measurement system, an infrared radiation thermometer (KELLER M.S.R PA 20 AF) with a temperature measurement range of 250–2000 °C and a dual-color infrared thermometer (Fluke E1RH-R07-1.0-0) with a temperature measurement range of 1000–3500 °C, as shown in Fig. 2. Based on our specific experimental platform, the 3D-DIC system was employed to measure the full-field thermal strain of the tungsten block at ultra-high temperature. There are two reasons why 3D-DIC rather than 2D-DIC is employed in this work: first, the 3D-DIC system generally has better measurement performance than 2D-DIC, especially when out-of-plane displacement exists; second, the experimental platform, which includes two observation windows, is designed for 3D-DIC exclusively. The PMLAB 3D-DIC measurement system, consists of two charge coupled device (CCD) cameras with a spatial resolution of six megapixels at 256 G6 levels, blue light sources with a central wavelength of 440 nm, two blue light filters Bi 440 (420–455 nm), image acquisition and processing software. In order to ensure the accuracy of the infrared radiation thermometer, we use K-type armored thermocouples to calibrate the infrared radiation thermometer, as shown in Fig. 3. Fig. 3(a) schematically shows the temperature calibration module, where δ denotes the distance between the calibration point and the thermocouple’s measuring point. We regulated the loading power to maintain that the temperature reported by the thermocouples at the calibration point equal to 300 °C, and then adjusted the parameters of the infrared thermometer to make it display a temperature of 300 °C. Then, the infrared radiation thermometer was also calibrated at 400–900 °C (step size of 100 °C) using the same method discussed above. After that, we comprehensively considered the seven sets of parameters obtained and defined the final calibration parameters. Using the final calibration parameters, we measured the deviation between the infrared radiation thermometer and the thermocouples from 300 to 900 °C (step size of 100 °C). Fig. 3(b) shows the calibration results. Clearly, the deviation between the thermocouple and the infrared radiation thermometer is very small (~1%) in the temperature range of 300–900 °C. When the temperature was above 1000 °C, the temperature was measured by a dual-color thermometer, which can be used directly without the need to calibrate.

2.3. Experimental methods

The specimen in the present investigation is a tungsten block, which is free of constraints and can be heated from room temperature to over 3000 °C using the electron beam in vacuum conditions. It is worth mentioning that the strong thermal radiation is the greatest challenge in the present experiment, because it causes over-saturation of the image and disturbs the observation of the speckle pattern on the surface. In order to measure the thermal expansion deformation of the tungsten specimen under ultra-high temperature, thermal radiation of the specimen at high temperature must be suppressed. Hence, three schemes based on blue light sources, a self-radiating light source and a dual wavelength optical filter technique applied to different temperature ranges are designed and determined by pre-experiment, which are described in detail as follows:

Scheme 1: For the temperature range of 25–1200 °C, a blue-ray light source was used to realize light compensation and the filters Bi 440 (420–455 nm) allow the light wavelength ranging from 420 to 455 nm to pass. The spectral sensitivity graph of the filter is shown in Fig. 4(a). In addition, a pair of polarizers is installed in front of the filters to adjust the brightness of images captured by CCD cameras. It should be noted that when the temperature is elevated over 600 °C, the self-illumination of the tungsten specimen increases obviously. Thus, in order to obtain high-quality images of the speckle pattern, the exposure time needs to be decreased to an appropriate value that can make the cameras capture clear images in the temperature range of room temperature to 1200 °C.

Scheme 2: For the temperature range of 1200–1800 °C, the thermal radiation of the tungsten specimen becomes stronger, resulting in image saturation. In addition, the interference caused by the superposition of strong self-illumination and external light sources results in the decline of quality of the captured images. Therefore, the external blue light sources are removed in scheme 2 to decrease the brightness of the images and to avoid the interference mentioned above, as shown in Fig. 4(a). The blue light of self-illumination is utilized as a lighting source, since distinct speckle images can also be captured in such a state due to different spectral characteristics of radiation for TaC and tungsten. With increasing temperature, the thermal radiation intensity also increases, leading to overexposure of images under a fixed exposure time. Therefore, the exposure time of CCD cameras under different temperature ranges needs to be adjusted, so that clear images in corresponding temperature ranges can be obtained.

Scheme 3: For the temperature range of 1800–3067 °C, the blue light band in self-illumination will be significantly enhanced, so that the filtering method in scheme 2 also loses effectiveness. Here, we found that combining filter Bi 440 (420–455 nm) with filter Bi 420 (405–435 nm) can help us to obtain a narrower band filter of ~15 nm (420–435 nm), as shown in Fig. 4(b). This kind of filtering method greatly reduces the light flux passed the lens through narrowing the band pass of filter Bi 440 while the peak transmittance of the blue light band is also reduced due to
overlapping effects of the filtering band. Using this filtering method, clear speckle pattern images can also be obtained for the target temperature range.

Based on the above discussion for Scheme 3, we know that the double filter technique is more effective than the single filter Bi 440 in obtaining clear images. In order to clear the principle of reducing the intensity of the light source, the filtering method and the effect of thermal radiation at different temperatures was theoretically analyzed. Superimposing filter Bi 420 to filter Bi 440 can cause the central wavelength of transmitted thermal radiation light shifts to a shorter wavelength, i.e., from 438 to 427 nm, which helps to decrease the intensity of thermal radiation based on Planck’s radiation law. Moreover, the maximum transmittance of band pass is also reduced from 93% to 83%. In addition to this, the most important point is that the combination of filters Bi 440 and Bi 420 leads to a decline in transmission bandwidth from 35 to 15 nm. This will help to reduce the intensity of thermal radiation light through the lens. In short, as the band-pass is narrowed, the maximum transmittance of the blue light band is reduced and the central wavelength of the transmitted self-illumination is decreased. Superimposing two filters can reduce the light flux to about a quarter of the single filter Bi 440, as shown in Fig. 4(b).

Speckle pattern images captured by the three schemes addressed above have different gray features in each measuring interval. Therefore, relative strain fields of the defined area in different temperature ranges must be calculated separately. In order to obtain the continuous strain measurement results from room temperature to over 3000 °C, the strain superposition principle is employed to sum the relative strain of each temperature interval. According to this method, the absolute thermal strain of tungsten material at ultra-high temperature can be obtained.

2.4. Experimental procedures

Fig. 5 schematically shows the corresponding on-site layout of the thermometers, the tungsten specimen and the 3D-DIC measurement device based on the experimental platform. The experimental procedures are briefly described as follows:

1. The cured tungsten specimen was placed on the substrate and a thin layer of TaC powder was put at the bottom of the block in order to
reduce the heat exchange between the tungsten and the substrate, as shown in Fig. 5(b)–(d).

(2) The infrared radiation thermometer and the dual-color infrared thermometer were adjusted to make them focus the strain measuring area at the position of ~5 mm below the top surface of the tungsten specimen. The temperature measuring area is a circle with a diameter of ~5 mm, as presented in Fig. 5(d). In order to calculate the full-filed thermal expansion deformation of the specimen, a rectangular region covering the temperature measuring area, as indicated by the white rectangular shown in Fig. 5(d), was selected as the region of interest (ROI), so the strain fields of the measuring area and its temperature can be linked.

(3) Adjusting the external blue light source to make the distribution of light on the specimen even, so that two CCD cameras can capture high quality images through two observation windows (K9 glass) of the vacuum chamber, as shown in Fig. 5(e). Before experiments, to maximally alleviate the thermal errors in 3D-DIC measurements caused by temperature variations in digital cameras, the two CCD cameras were pre-heated for two hours before image capture [29], then, the extrinsic and intrinsic parameters of cameras were calibrated. After calibration, the position of the two cameras cannot be moved during the experiment.

(4) In order to ensure the synchronization of temperature acquisition and image capture, we have specially written a synchronous acquisition code, so that the thermometers and CCD cameras are connected by a synchronous communication interface. The parameters of 3D-DIC software are then set up, such as exposure time, acquisition frequency, acquisition time, etc., as shown in Table 1. The synchronization signal is employed to synchronize trigger temperature recording and image acquisition, which helps us to establish a functional relationship between the temperature and strain. In this work, images of the tungsten specimen surface were captured by the 3D-DIC system at a frame rate of 10 fps.

(5) The tungsten specimen was heated from the top surface using an electron beam under the vacuum conditions of 10⁻³ Pa. The heating rate was kept as low as possible to generate a near equilibrium temperature field.

(6) For the strain field calculations, after experiment, the captured images of each group are processed using same parameters, some important parameters of image processing can be seen in Table 2.

3. Experiments and results

3.1. Thermal strain of tungsten ranging from 25 to 1200 °C

According to Scheme 1, external blue light sources were adopted to illuminate the speckle pattern for camera imaging. In order to obtain clear images, the exposure time of the cameras was set as 40 ms for 25–600 °C and 25 ms for 600–1200 °C. We captured 696 images and 741 images with an acquisition frequency of 10 Hz corresponding to 25–600 °C and 600–1200 °C, respectively. The relative full-field strain εxx was calculated separately in each temperature interval, as presented in Fig. 6, where Fig. 6(a) is the initial state and Fig. 6(c) is the end state in the temperature range of 25–600 °C, Fig. 6(d) is the initial state and Fig. 6(f) is the end state in the temperature range of 600–1200 °C. The results show that the clear speckle pattern images and strain measurement

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Table 1

<table>
<thead>
<tr>
<th>Scheme</th>
<th>1</th>
<th>2</th>
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<td>External blue light</td>
<td>Self-illumination</td>
<td>Self-illumination</td>
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<tr>
<td>Filtering</td>
<td>Bi 440</td>
<td>Bi 440 &amp; Bi 420</td>
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<tr>
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</tr>
<tr>
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<td>124</td>
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<td>Averaged f(t)</td>
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<td>Disturbance error</td>
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Fig. 5. Schematic of (a) the experimental setup, (b) heating method, (c) thermal loading area, (d) the white rectangular area is selected as ROI for deformation calculation and (e) measuring system.

Fig. 6. Speckle images of the tested surface and strain calculation exx under the conditions of 25–1200 °C.
results are obtained in each temperature interval. As shown in Fig. 6(c) and (f), the thermal strain distribution is non-uniform. The strains in the upper central regions are larger than that of both sides, because the thermal loading is located at the center of the upper surface of the tungsten specimen. In Fig. 6(d), when the exposure time was changed, the reference image was replaced at the same time, and the current full-field strain values are defined as zero. The solutions are similar in Schemes 2 (Fig. 8(d)) and Scheme 3 (Fig. 10(d) and (g)) when changing the exposure time in the same scheme. Hence, the thermal strain of temperature measuring area ranging from 25 to 1200 °C can be obtained by superimposing the current strains to previous strains based on strain superimposition principle, as shown in Fig. 7. However, the strain measurement results in the temperature range of 25–250 °C was deleted because of the measuring range of the infrared radiation thermometer greater than 250 °C. The reference thermal strain values ranging from 250 to 1200 °C, according to the literature [30], is also plotted as a comparison. It is observed that measurement results are very consistent with the reference, indicating the feasibility and accuracy of the proposed measurement methods.

It is worth noting that in Scheme 1, with increasing temperature up to 1000 °C, we replaced the infrared radiation thermometer (KELLER M.S.R PA 20 AF) with a dual-color infrared thermometer (Fluke E1RH-R07-1-0–0). It should be noted that for images when the temperature reached 1200 °C, a white-gray color is presented, which is caused by self-illumination. Nevertheless, according to the final results of the strain measurements, this kind of interference is tolerable for 3D-DIC strain measurements.

### 3.2. Thermal strain of tungsten ranging from 1200 to 1800 °C

As addressed previously, when the temperature increases to more than 1200 °C, Scheme 2 was used to measure the strain field of the specimen. In order to obtain high quality speckle pattern images, the exposure time is also adjusted for two temperature intervals, one is 60 ms for 1200–1500 °C and the other is 20 ms for 1500–1800 °C. We captured 582 images and 611 images with an acquisition frequency of 10 Hz corresponding to 1200–1500 °C and 1500–1800 °C, respectively.

<table>
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<td>29</td>
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<td>Optimized 4-tap</td>
<td>19</td>
<td>20</td>
<td>0.9 or 0.85</td>
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Fig. 8 shows the original speckle pattern images and the calculated strain $e_{xx}$ of the ROI. As observed, clear speckle pattern images and strain measurement results were obtained for each temperature interval. Obviously, due to the difference of self-illuminating radiation spectra for TaC and tungsten, the images captured under conditions of Scheme 2 (self-illumination light source) have different grayscale distributions from those captured under the conditions of Scheme 1 (external light source). In Scheme 1, the TaC speckles are dark and the tungsten block is bright, while in the case of Scheme 2, TaC speckles are bright and the tungsten block is dark. However, this kind of difference does not influence the relative strain field calculation in the selected temperature intervals, since all images have consistent speckle patterns obtained in the same conditions. The relative strain fields of the ROI were calculated separately in each temperature range based on the initial image of this interval, as presented in Fig. 8. The thermal strain of the measuring area ranging from 1200 to 1800 °C was achieved based on the strain superimposition principle, as shown in Fig. 9. The reference relative thermal strain values ranging from 1200 to 1800 °C, according to the literature [30,31] were also plotted for comparisons. It is observed that the measurement results are also in good agreement with the reference values, indicating the feasibility and accuracy of the proposed measuring method of Scheme 2. It is noted that the strain measurement results from 1200 to 1800 °C have larger burrs compared with those
in Scheme 1. This is likely attributed to some kinds of noise caused by thermal radiation in the case of self-illumination.

### 3.3. Thermal strain of tungsten ranging from 1800 to 3067 °C

When the temperature is above 1800 °C, Scheme 2 cannot meet the demands of full-field strain measurement due to the thermal radiation being too strong to capture clear images. Scheme 3 was applied, therefore, in which a dual wavelength optical filter method was adopted. In order to obtain high quality speckle pattern images, the exposure time was also adjusted for three temperature intervals: 18 ms for 1800–2300 °C; 7 ms for 2300–2700 °C; 2.8 ms for 2700–3067 °C. We captured 692, 551 and 864 images with an acquisition frequency of 10 Hz corresponding to 1800–2300 °C, 2300–2700 °C and 2700–3067 °C, respectively.

Fig. 10 schematically shows the original speckle pattern images and the calculated strain $\varepsilon_{xx}$ of the ROI. As observed, high quality speckle pattern images and strain fields were obtained at each temperature interval. Obviously, the images captured under conditions of Scheme 3 have similar gray characteristics to those captured under conditions of Scheme 2. The thermal strain of the measuring area ranging from 1800 to 3067 °C were achieved based on the strain superimposition principle, as shown in Fig. 11. It is observed that the measurement results are also consistent with the reference values in the temperature range of 1800–2700 °C. However, some discrepancy occurs in the temperature range of 2700–3067 °C.

In this experimental section, the maximum temperature of the captured pictures reaches 3173 °C. Unfortunately, when the temperature comes to over 3067 °C, the decorrelation effect decreases the accuracy and brings about a failure in correlation analysis, as presented in Fig. 10(b). The experimental results show that the speckle pattern is able to sustain high temperature exceeding 3173 °C without distinguishable change in morphology, as shown in Fig. 10(l). When the temperature exceeds 3067 °C, the failure of correlation analysis is hence ascribed to the sharp reduction in contrast of images caused by increased self-illumination. During this experiment, benefitting from the water cooling system discussed in Section 2.1, the temperature around the 3D-DIC system showed no visible fluctuations, ensuring the accuracy of full-field strain measurement, although the tungsten specimen in the vacuum chamber was heated to 3173 °C. It is worth noting that the thermal errors caused by temperature variation of the environment are unavoidable in all stereovision systems, especially when the specimen is heated to a very high temperature. These errors are usually small enough to be neglected in 3D measurement but should be paid attention to, when a high-accuracy measurement is required [32].

### 3.4. Data reduction and strain fluctuation analysis

According to the principle of strain superposition, the thermal expansion strain of the tungsten block ranging from 250 to 3067 °C was achieved. Fig. 12 shows the comparisons between the measurement results, reference data [30,31] and the theoretical model values taken from the Suzuki model [33]. It can be observed that the measurement results are generally in good agreement with the references in test temperature range. The maximum discrepancy is limited to $\sim7\%$ at 3067 °C, which is acceptable in consideration of the uncertainty of measuring instrument and thermally induced noises. It is noteworthy that the reference data of tungsten thermal expansion strain were obtained mainly based on point measurements with a wire or rod specimen on specially designed instruments, which are very different from our work. For example, the reference data provided by Miller and Cezairilryan [31] were measured on a rod specimen using a transient interferometric technique, while in present work, we measured the thermal expansion strain of tungsten block through the full-field strain measurement technique based on 3D-DIC technique. Obviously, full-field measurement data may provide more insights on mechanical behaviors of structure under ultra-high temperature range in practical applications, such as in aerospace
and nuclear industries. Table 1 summarizes the experimental details of scheme 1–3.

As further observed in Fig. 12, with increasing temperature, the disturbance of strain measurement increases. In order to analyze the strain fluctuation of measurement results, we use a quadratic function $f(x)$ to fit the measurement results, then calculate the standard deviation $\sigma$ using Eqs. (1)–(3) given below:

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i - \mu)^2}$$  \hspace{1cm} (1)$$

$$x_i = f(t_i) - s_i$$  \hspace{1cm} (2)$$

$$\mu = \frac{1}{N} \sum_i^N (f(x_i) - s_i)$$  \hspace{1cm} (3)$$

where $N$ is the number of experimental data, $f(x)$ is a fitting function of the measurement results, $s_i$ is the measurement result, $x_i$ is the deviation between fitting results and measurement results and $\mu$ is the average value of $x_i$.

The standard deviations for different temperature ranges are presented in Table 1. From the results, it is clear that the standard deviation becomes larger with increasing temperature. In the temperature range of 250–1200 °C, the standard deviation is only $\sim50 \mu$, which is mainly caused by the measurement accuracy of the instruments. In the temperature range of 1200–1800 °C, the standard deviation increases to $\sim100–200 \mu$, which should be attributed to the brightness variation of images induced by the self-luminescence light source, although it had been suppressed to an acceptable range by adjusting exposure time and using filters. In the temperature range of 1800–3067 °C, the standard deviation increases to $\sim500 \mu$, which corresponds to the intensified effects of self-luminescence light source at ultra-high temperature range. Compared with the averaged strain magnitudes in their corresponding temperature range, however, the standard deviation falls in the error range of ±3%, indicating that the adopt techniques are feasible and accurate for strain field measurements.

4. Conclusions

In the present work, with the aim of developing a non-contact measurement technique of mechanical deformation under an ultra-high temperature range, a high heat flux (~300 MW) comprehensive experimental platform was established in combination with an electron beam heating system with a three-dimensional digital image correlation (3D-DIC) measurement system. Based on the vacuum condition on the experimental platform, thermally induced airflow disturbance can be removed. Tantalum carbide powder was chosen as the speckle material and the speckle fabrication technology was developed to adapt ultra-high temperature and vacuum conditions. In order to suppress the thermal radiation at ultra-high temperature, three experimental schemes based on external blue light sources, a self-radiating light source and a dual wavelength optical filter technique were proposed for three temperature ranges. We extend the temperature range of full-field strain measurements with 3D-DIC to over 3000 °C. The feasibility and accuracy of the proposed methods were verified by comparing the measurement results with the data from available databases and literatures. From the results discussed above, the following conclusions are obtained:

1. A high heat flux (~300 MW) comprehensive experimental platform was established to eliminate the thermally induced airflow disturbance, and a water cooling system was introduced to ensure that the observation window can be maintained at room temperature.

2. Tantalum carbide powder is a suitable speckle material in present experimental conditions, which presents high stability and robustness in the temperature range of 25–3173 °C. High-quality images can be obtained from room temperature to 1200 °C based on external blue light sources. When the temperature is higher than 1200 °C, high-quality speckle images can still be obtained based on different self-illuminating radiation characteristics between TaC powder and tungsten block. The speckle fabrication method was demonstrated to be simple and effective for the target material without changing its surface properties.

3. Three schemes were proposed to suppress the thermal radiation at different temperature intervals. The thermal strain fields of tungsten block from room temperature to over 3000 °C were measured successfully, and the thermal expansion curve of tungsten block above 3000 °C was obtained, which is in good agreement with the references, proving that the suggested schemes are feasible and accurate for the full-field strain measurement.

It is noteworthy that the main error source of DIC application in ultra-high temperature range is self-illumination of the target specimen. Although the techniques adopted in this work greatly improve the DIC image quality by narrow band filtering and exposure time adjusting, they are not perfect. Adjusting exposure time based on self-illumination dynamically may completely eliminate the brightness influence on captured images, promoting the accuracy of DIC applications in ultra-high temperature range to a higher level. This work will be undergone in further investigations.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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