IMPORTANCE OF EXPOSURE TIME ON DIGITAL IMAGE CORRELATION (DIC)

AT EXTREME TEMPERATURES

by

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A thesis submitted in partial fulfillment of the requirements for the degree

of

MASTER OF SCIENCE

in

Mechanical Engineering

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2018
ABSTRACT

Importance of Exposure Time on Digital Image Correlation (DIC)
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Digital Image Correlation (DIC) is a popular method for deformation and strain measurement. At extreme temperatures, it is known that materials emit light in addition to reflecting the light supplied by a light source, and the emitted light can saturate the camera sensor. More recently, a novel method of DIC named ultraviolet (UV) DIC extended the range of temperature further by using a UV bandpass filter to screen out some of the brightest glowing. In principle, the temperature range can be extended further by reducing the camera’s sensitivity to light, and exposure time is an instrumental factor when setting such camera configurations. In this thesis, an investigation was done in order to examine the influence of multiple exposure times on the uncertainty of UV-DIC correlation. Rigid-motion experiments were performed at four different temperatures: room temperature, 1300°C, 1450°C, and 1600°C. At each temperature level, UV images were recorded for DIC at exposure times ranging from 500µs to 61,000µs. The results showed abrupt increases of error at extremely dark or bright exposure times, but at intermediate exposure
times the errors of UV-DIC were basically minimal. It is recommended that cameras should be set at a suitable range of exposure time (between 10,000μs and 40,000μs for the camera used in this thesis) in order to perform meaningful DIC up to 1600°C.

(44 pages)
PUBLIC ABSTRACT

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Thinh Quang Thai

Extreme temperatures have increasingly played an important role in engineering applications, including leading edges during hypersonic flight, spacecraft re-entry, and propulsion systems. In order to design for such thermo-mechanical conditions, materials must be characterized using suitable measurement methods. DIC is a popular and versatile method in full-field measurement. In brief, DIC compares images of a sample between its undeformed and deformed state in order to get displacement and strain field maps. Since the images are acquired from digital cameras, it is important to have high contrast images for meaningful correlation. Exposure time is a pivotal camera setting relating to camera sensitivity. Alteration in exposure time results in variation of image contrast, thereby affecting DIC correlation. Also, it is well known that at extreme temperatures, materials emit light which can saturate DIC camera sensors, but the light can be mitigated using optical bandpass filters. In previous work, many have shown that blue bandpass filters can effectively extend the temperature range of DIC, and our lab has shown that ultraviolet (UV) filters can extend the range further.

In this thesis, four different temperatures: room temperature, 1300°C, 1450°C, and 1600°C were tested by rigid-motion experiments. At each temperature level, UV images were acquired in order to examine the variation of DIC error over the whole range of
exposure time. UV images were acquired at exposure times ranging from 500µs to 61,000µs, which are the minimum and maximum possible values for the cameras used in this thesis. The results showed that there were higher errors of UV-DIC at extremely dark or bright exposure times whereas errors were generally insignificant at intermediate exposure times. In order to perform meaningful DIC up to 1600°C, the exposure time for the camera used in this thesis is suggested to be set between 10,000µs and 40,000µs.
ACKNOWLEDGMENTS

First of all, I would like to express my heartfelt gratitude to my advisor, Dr. Ryan Berke for his fervent support, patience, motivation, and immense insights throughout this thesis. Without his continuous support and guidance, this thesis would not be completed.

My special thanks go to NASA’s Marshall Space Flight Center (award # 80MSFC18M0009) and the Utah State University Office of Research and Graduate Studies for their financial support.

I am grateful to Dr. Barton Smith and Dr. Tadd Truscott for being on my Master’s supervisory committee. I also would like to thank the staff of the MAE department, especially Chris Spall, Karen Zobell and Lindi Brown for helping me with paperwork procedures. Many thanks go to Terry Zollinger for machining specimens.

Next, I would like to thank all of my fellow labmates, especially Robert Hansen for helping with Gleeble heating. I also want to thank Connor Bell, Adam Smith, and Alisa Dabb for accommodating my schedule when using the Gleeble.

A profound gratitude is extended to Air Force Research Laboratory (AFRL) for their idea of how to secure thermocouples when they won’t weld to a sample. This idea marked a turning point in my research.

Last but not least, I would like to thank my beloved family: my parents and my older brother in Vietnam for their mental support and ceaseless encouragement.

Thinh Quang Thai
## CONTENTS

<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>iii</td>
</tr>
<tr>
<td>PUBLIC ABSTRACT</td>
<td>v</td>
</tr>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>ix</td>
</tr>
<tr>
<td>1 INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Motivation</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Thesis statement</td>
<td>3</td>
</tr>
<tr>
<td>1.3 Literature review</td>
<td>4</td>
</tr>
<tr>
<td>1.3.1 Overview of Digital Image Correlation (DIC)</td>
<td>4</td>
</tr>
<tr>
<td>1.3.2 DIC at high temperatures</td>
<td>6</td>
</tr>
<tr>
<td>1.3.3 Error analysis of DIC</td>
<td>7</td>
</tr>
<tr>
<td>1.4 Thesis outline</td>
<td>9</td>
</tr>
<tr>
<td>2 OBJECTIVES</td>
<td>11</td>
</tr>
<tr>
<td>3 METHODS</td>
<td>12</td>
</tr>
<tr>
<td>4 RESULTS</td>
<td>19</td>
</tr>
<tr>
<td>4.1 Room temperature</td>
<td>19</td>
</tr>
<tr>
<td>4.2 Extreme temperatures</td>
<td>21</td>
</tr>
<tr>
<td>5 DISCUSSION</td>
<td>26</td>
</tr>
<tr>
<td>6 CONCLUSIONS</td>
<td>29</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>30</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Schematic of square gauge region test specimen (left), a photo of specimens with speckled gauge region (middle) and a close-up of the speckle pattern (right).</td>
<td>13</td>
</tr>
<tr>
<td>3.2</td>
<td>Gleeble 1500D thermo-mechanical system.</td>
<td>14</td>
</tr>
<tr>
<td>3.3</td>
<td>Schematic of the 2-thermocouple placement (left) and temperature relationship of the two thermocouples (right).</td>
<td>15</td>
</tr>
<tr>
<td>3.4</td>
<td>Photograph of the fixture with experimental setup.</td>
<td>16</td>
</tr>
<tr>
<td>3.5</td>
<td>Transmissivity of UV camera and related optics.</td>
<td>17</td>
</tr>
<tr>
<td>4.1</td>
<td>Mean u displacement at room temperature, compared between case 1 (no applied motion) and case 2 (non-zero rigid motion) with the Gleeble on or off as indicated. Each uncertainty band is the 95% confidence interval.</td>
<td>20</td>
</tr>
<tr>
<td>4.2</td>
<td>Mean strain $\varepsilon_{xx}$ at room temperature, compared between case 1 (no applied motion) and case 2 (non-zero rigid motion) with the Gleeble on or off as indicated. Each uncertainty band is the 95% confidence interval.</td>
<td>21</td>
</tr>
<tr>
<td>4.3</td>
<td>Raw speckle images of specimen surface at different temperatures (increasing from left to right) and exposure times (increasing from top to bottom) respectively, and histograms of the greyscale values corresponding to the images. Images which are too saturated to perform DIC are indicated with a red cross.</td>
<td>22</td>
</tr>
<tr>
<td>4.4</td>
<td>Comparison of $\varepsilon_{xx}$ at Room temperature and (a) 1300ºC, (b) 1450ºC and (c) 1600ºC when there is no applied displacement.</td>
<td>23</td>
</tr>
<tr>
<td>4.5</td>
<td>The $\varepsilon_{xx}$(pixel/pixel) strain map at 1600ºC and an exposure time of 20,000µs, obtained with Vic-2D from two images with no applied strain or displacement.</td>
<td>24</td>
</tr>
<tr>
<td>4.6</td>
<td>Thermal expansion strain at multiple temperatures over the gauge length.</td>
<td>25</td>
</tr>
<tr>
<td>5.1</td>
<td>The temperature map from FLIR IR camera at 1600ºC, data bar shows temperature (ºC) map inside dashed rectangle.</td>
<td>27</td>
</tr>
<tr>
<td>5.2</td>
<td>The thermal strain $\varepsilon_{xx}$(pixel/pixel) strain map at 1600ºC and an exposure time of 20,000µs, obtained with Vic-2D from comparing a reference image at room temperature and a deformed image at 1600ºC.</td>
<td>28</td>
</tr>
</tbody>
</table>
CHAPTER 1
INTRODUCTION

1.1 Motivation

Investigation of material characterization at extreme temperature has increasingly become a hot topic in engineering applications due to its complexity and high demand in various industries. For example, thermo-mechanical experimental testing is conducted to examine material behavior employed in extreme environments including spacecraft reentry [1,2], gas turbine engines [3], hypersonic flight [4,5] and nuclear reactors [6]. In order to design for any of these applications, measurement of deformation and strain during different loading conditions is pivotal to get a better understanding of materials. A technique which is able to collect full field data is more advantageous than point measurements.

One of the most popular and versatile methods for obtaining full field strain maps is Digital Image Correlation (DIC) [7,8]. In brief, DIC employs high-resolution cameras to record images of a speckle pattern applied to the sample surface in an undeformed and deformed state, respectively. A computer algorithm is then used to track the deformation of the speckle pattern within a selected region. Strains are calculated by taking derivatives of displacement fields. In comparison with strain gauges [9], DIC has gained popularity since (1) it is able to collect full-field data (as opposed to point-wise or specimen-averaged techniques), (2) it is non-contacting (except for a thin layer of paint), and (3) it can be used at any time or length scale if appropriate cameras and lenses are used. DIC has been
demonstrated at lengths from sub-micrometer [10,11] to tens of meters [12,13] and from room temperature to 2000°C [14].

In order to perform a meaningful DIC analysis, it is essential to have the right amount of light reach the camera sensor when images are acquired [15]. When there is too much light on the camera sensor, the image can become overly saturated. Conversely, the image is underexposed if there is not enough light. There are four main ways that light can be controlled:

1. **Using a brighter light source.** This could be more expensive and can introduce some safety hazards such as those presented by lasers [16] and/or UV lights [17].

2. **Using a wider aperture on the lens.** It is noted that a wider aperture gives a smaller depth of field, but also yields brighter images [18].

3. **Setting the camera to a longer exposure time.** This works well but longer exposure time is more prone to motion blur, especially for vibration and fast loads.

4. **Increasing the gain on the camera amplifier.** This is usually the worst option since it makes images become noisy and grainy.

Theoretically, DIC should work independently of temperature as long as the contrast of speckle pattern is within an acceptable range [19,20]. However, at extreme temperatures, the specimen emits its own light in addition to reflecting the light supplied. This results in the degradation of speckle contrast making the cross correlations weaker [17,21]. It is known that the glow is much brighter at longer wavelengths (i.e. red and infrared) than it is at shorter wavelengths (i.e. blue), and can be mitigated using blue optical bandpass filters [22,23]. More recently, our group introduced a novel method called
ultraviolet digital image correlation [17] (UV-DIC), which uses a UV filter to extend the temperature range of DIC even farther.

In each study where blue or UV filtering was used, different investigators have reported different upper temperature limits for DIC depending on their camera settings. For example, Novak and Zok [24] estimated that the maximum temperature for blue-filtered DIC was around 1500°C. However, Wang et al. [14] reported being able to perform blue-filtered DIC at temperatures as high as 2000°C. Conversely, we showed when comparing blue-filtered DIC against UV-DIC that, under the camera settings used in that study, blue-filtered DIC instead saturated as low as 900°C [17]. Due to these discrepancies, we believe that the limiting factor in performing DIC at extreme temperatures is not only the wavelength of light that images are recorded at, but is the sensitivity of the camera to the light at those wavelengths.

1.2 Thesis statement

This thesis will examine the influence of exposure time on DIC at extreme temperatures. Exposure time is chosen since, of the four ways listed to control light, it is the easiest to manipulate without introducing new error into the measurement (provided that all tests are quasi-static to avoid motion blur). Experiments were performed at four different temperature levels: room temperature, 1300°C, 1450°C and 1600°C. Two sets of measurements were made: (i) isothermal rigid motion experiments, in which DIC was computed from pairs of images taken at fixed temperatures; and (ii) thermal expansion measurements, in which DIC was performed using a reference image at room temperature and deformed images at high temperature. The isothermal measurements were performed
over exposure times ranging from 500µs to 61,000µs in order to assess the error of UV-DIC. The thermal expansion measurements demonstrated the ability for UV-DIC to span a broad temperature range when the emitted light was sufficiently filtered.

1.3 Literature review

The purpose of this section is to give fundamental concepts about methods which are necessary for this research. A basic summary of DIC method is presented, followed by challenges of performing DIC at high temperatures. Finally, error sources of DIC are summarized.

1.3.1 Overview of Digital Image Correlation (DIC)

Digital Image Correlation (DIC) is a popular method due to its simplicity of experimental setup and its capability to perform full-field non-contact measurements. DIC was first presented in 1982 by Peters and Ranson [25]. In their work, they used digital imaging techniques to get displacement and strain components based on tracking of speckle images. Another member of their group, Michael Sutton [26] improved DIC to obtain the full-field planar displacement of a cantilever beam subjected to an end load. Throughout the 1980’s, additional research was published later by their group as improvement of the DIC method [27–30].

Generally, in order to perform a meaningful DIC measurement, there are three fundamental steps, particularly (1) sample preparation, (2) acquiring images during loading and (3) analyzing the images using a correlation algorithm [31].
For the sample preparation step, the minimum requirement is to create a random speckle on the sample surface if it is not naturally speckled itself. In general, a good speckle pattern has features of high contrast, randomness, isotropy and stability [32]. In order to meet these requirements, various assessment methods of speckle pattern quality have been introduced and developed [33–35]. In practice, there are many ways to make a good speckle pattern depending on the desired length scale. Such methods include airbrush spraying [36,37], lithography [38–40], focused ion beam [41–43] and spin coating [44,45].

In terms of image acquisition during loading, in 2D DIC the camera sensor is required to be parallel to the flat surface of a specimen. This alleviates any out of plane displacement. If the sensor is not parallel, it makes magnification non-uniform, resulting in artificial in-plane deformation. Also, geometric distortion should be mitigated, especially in high-resolution imaging systems, because it is likely to interfere with correlation in image matching. In an effort to remove optical distortion, Yoneyama et al. [46] calculated a correction coefficient from displacement distribution in rigid motion test.

In order to track or match the motion of a point in reference image to deformed image, DIC employs a collection of pixel values called a subset. The subset is chosen because it includes a wide distribution of grayscale levels which gives more information in searching for its position in the deformed image. In other words, a subset has a unique signature to differentiate from other subsets in a deformed image. A correlation function is used by computing the sum of squared differences (SSD) of the pixel values as presented in Equation (1) [47]:
\[ C(x, y, u, v) = \sum_{i,j = -n/2}^{n/2} \left( I(x + i, y + j) - I^*(x + u + i, y + v + j) \right)^2 \]  

where \( C \) is the correlation function; \( x, y \) are pixel coordinates in the reference image; \( u, v \) are displacements (disparity); \( n \) is subset size; \( I(x+i, y+j) \) is intensity of pixel at \( (x+i, y+j) \) and \( I^*(x+u+i, y+v+j) \) is intensity of pixel at \( (x+u+i, y+v+j) \). Smaller values of the correlation function give better similarity between the reference subset and deformed subset.

The correlation is accomplished by searching for the position of the deformed subset which has smallest difference coefficient. By using a subset of size > 1 instead of individual pixels, it is able to get sub-pixel accuracy [48]. If not, 1 pixel is the smallest accuracy in displacement due to the nature of discrete integer in digital image pixels.

The strain is obtained by taking derivatives of displacement. In practice, some researchers used Newton-Raphson [49] as numerical differentiation procedure to compute strain.

### 1.3.2 DIC at high temperatures

Theoretically, DIC is able to work at any temperature as long as it still maintains a good speckle with good contrast. However, there are 3 main challenges that need to be tackled in performing a successful DIC [17]:

1. A speckle pattern must be stable and kept consistent contrast during thermal heating. Particularly, the speckle must not flake off and discolor at high temperatures. In order to circumvent this challenge, some solutions were suggested such as refractory
coatings [24], cobalt oxide [21] or sandblasting [22]. In this thesis, a refractory paint which is rated to 1760°C was used.

(2) Any optical distortion due to thermal turbulence and heat haze between camera and specimen need to be minimized. In order to tackle this issue, Novak and Zok [24] suggested using an air knife to blow off the heat haze. In this thesis, specimens were tested in a vacuum chamber, thus removing any warping due to variation of the refraction index of air.

(3) The emitted light from specimen due to black body radiation needs to be suppressed. The intensity of emitted light is more significant at higher temperatures and deteriorates the speckle contrast. The emitted light is also known to be brighter at longer wavelengths. Some researchers suggest using blue light illumination and a blue bandpass filter to screen out the brightest glow [16,20–22,50,51], but eventually the glow in the range of blue wavelengths becomes bright as well. More recently, Berke and Lambros [17] demonstrated that UV optics, which operate at an even shorter wavelength than blue, can potentially extend the temperature range of DIC even further. Their method is potentially the highest-temperature DIC capability, which enables recording more information of heterogeneous material behavior at extreme temperatures. Thus, UV-DIC was used as optical imaging in this thesis.

1.3.3 Error analysis of DIC

The error of DIC comes from many factors happening during experiments. However, it can be classified into two main sources [31]: (1) Experimental setup including quality of speckle pattern, misalignment between camera sensor and specimen surface,
optical distortion due to flaw of lens, and noise; or (2) Correlation matching algorithm including size of subset, correlation criteria, interpolation method and shape function.

When it comes to speckle pattern, Phillip Reu [52,53] presented basic concepts and techniques to meet properties of speckle pattern including speckle size [54], speckle contrast [55], speckle edge sharpness [56] and speckle density [57]. In this thesis, we will examine the influence of exposure time which is a factor contributing to speckle contrast.

Misalignment between camera sensor and specimen surface makes change of magnification of specimen surface during loading resulting in additional in-plane displacement in 2D DIC. Sutton et al. [58] used a telecentric lens system to mitigate the influence of non-parallelism between camera sensor and specimen surface.

Regarding lens distortion, Zhang et al. [59] used an orthogonal cross-grating plate for calibration of lens aberration. Coefficients of warping function were computed by comparing node positions between cross-grating plate and images.

Image noises are inevitable in digital image acquisition. Wang et al. [60] developed a mathematical model to evaluate the error of displacement due to intensity pattern noise.

Selection of subset size is subjective and there is no optimal subset size applied to any tests. Large subset size facilitates in distinguishing from other subsets whereas small subset size gives higher spatial resolution. Pan et al. [61] used Sum of Square of Subset Intensity Gradients (SSSIG) as a criterion to select a suitable subset size.

In terms of correlation criteria, Tong [62] compared four correlation criteria and concluded that zero-normalized sum of squared differences (ZNSSD) and zero-normalized cross-correlation (ZNCC) give the best robustness and reliability.
Schreier et al. [63] recommended using high-order interpolation methods to minimize systematic errors after comparing to other methods such as cubic polynomial, cubic B-spline and quantic B-spline interpolation. Nevertheless, high-order interpolation method is expected to cost long computational time.

The second-order shape function is suggested by Pan et al. [64] since it reduces systematic error in comparison with the linear shape function.

In summary, while there are many ways to control error as shown above, in this thesis, exposure time is chosen to examine its influence on uncertainty of DIC. Exposure time is one of the four main ways to control light in a camera experiment, making it an important factor which controls the quality of a speckle pattern.

1.4 Thesis outline

This thesis has a total of six chapters including this chapter (Introduction). Below are brief descriptions of all chapters.

- Chapter 1 presents an overview of the thesis including motivation, thesis statement, literature review, and this thesis outline.
- In Chapter 2, a list of research objectives is given along with a brief description of the experiments to accomplish them.
- Chapter 3 includes the step-by-step descriptions of the experiments tested in this thesis. The procedure is described in sufficient detail to make sure the reader is able to reproduce it.
• Chapter 4 shows the results obtained from the experiments. The results are divided into two sub-sections which address the room temperature and extreme temperature experiments, respectively.

• Chapter 5 is a discussion of the results presented in Chapter 4.

• Finally, Chapter 6 is the conclusion of this thesis which summarizes the contribution as well as gives a suggestion for users about an optimal range of exposure times when performing DIC up to 1600°C.
CHAPTER 2

OBJECTIVES

The overall goal of this thesis is to examine the influence of exposure time on DIC at extreme temperatures. By completing the following research objectives, the goal will be met:

1. Perform rigid motion experiments at room temperature to get preliminary results about influence of broad range exposure time on the error of UV-DIC.
2. Perform isothermal rigid motion experiments at extreme temperatures. Three different elevated temperature levels are going to be tested at 1300°C, 1450°C and 1600°C, respectively.
3. Combine results at room temperature with extreme temperatures to give an overview about the influence of exposure time on the error of UV-DIC.
4. Calculate thermal expansion by comparing a reference image at room temperature to deformed images at high temperature.
CHAPTER 3

METHODS

Experiments were performed using graphite rods purchased from GraphiteStore.com. The graphite has a melting point of 3000°C in vacuum but oxidizes aggressively in air, and thus all high temperature tests were performed in vacuum. Specimens were machined from graphite rods with a length of 6in and diameter of 0.5in by using a manual knee mill. The gauge region was a square cross section of 0.3in in order to provide a flat, planar surface on which to perform DIC. Figure 3.1 shows a schematic and photograph of the machined specimens. The graphite, which is naturally dark, provides the dark background on which to create a speckle pattern for DIC. A white speckle was then applied directly on the surface of square gauge region using a splattering method. This was accomplished by flicking the bristles of a toothbrush dipped in paint to splash paint onto the flat surface of the specimen. The speckle size created by this method is not small enough to examine under a microscope. However, for the scale of millimeters used in this work, it is a saving-time and straightforward method and offers sufficient accuracy to perform DIC. The paint is Pyro-Paint 634-AL from Aremco Products Inc. (Valley Cottage, NY, USA) which has melting point of 1760°C. The paint was dried at room temperature for 2 hours and then cured for 2 hours in a box furnace at 200°F, per the manufacturer’s instructions.
Figure 3.1 Schematic of square gauge region test specimen (left), a photo of specimens with speckled gauge region (middle) and a close-up of the speckle pattern (right).

The specimen was then tested in a Gleeble 1500D thermo-mechanical system as shown in Figure 3.2 which consists of a load cell inside of a vacuum chamber, and which can heat a specimen up to 3000°C. This is accomplished by running a high voltage through the electrically-conducting specimen.
In order to heat the specimen in the Gleeble, a K-type thermocouple is required as a feedback control. The highest temperature level tested in this thesis is 1600°C occurring in the middle of specimen. However, a K-type thermocouple is only rated to 1250°C [65]. Therefore, a new method was devised to extend the range of available testing temperatures beyond the K-type thermocouple range. Two K-type thermocouples (called TC1 and TC2) recorded temperatures at two different locations 35 mm apart, as shown in Figure 3.3. A thermal gradient was then applied along the length of the specimen, resulting in the temperature recorded by TC1 in the middle always being higher than temperature recorded by TC2 towards one end. The temperature relationship between TC1 and TC2 is also shown.
in Figure 3.3. In subsequent tests, TC1 was removed so as not to block the view of the speckle pattern from the cameras. TC2 was then used to provide temperature control by assigning temperatures which corresponded to the desired temperature in the middle.

![Schematic of the 2-thermocouple placement (left) and temperature relationship of the two thermocouples (right).](image)

A fixture was designed using aluminum T-slot framing to mount the UV camera, UV lights and UV filter. The experimental camera setup is shown in Figure 3.4. The specimen was monitored through a borosilicate glass window, which transmits both UV and visible light. The camera model was a CM-140GE-UV camera manufactured by JAI, which also detects both visible and ultraviolet light. The camera was equipped with a UV lens from Universe Kogaku Inc. with a focal length of 50mm. The camera was fitted with
an XNite 330C M58 ultraviolet bandpass filter from LDP LLC. The UV lights were purchased from CCS Inc. which emits at a peak wavelength of 365nm. Figure 3.5 shows the transmissivity of the UV camera and related optics.

Figure 3.4 Photograph of the fixture with experimental setup.
Figure 3.5 Transmissivity of UV camera and related optics.

The specimen was heated to temperatures corresponding to room temperature (RT) and multiple extreme temperatures (1300°C, 1450°C and 1600°C) at the middle of the specimen. The loading condition is purely static. Since the goal of this work is to examine the influence of exposure times, any other factors contributing to camera sensitivity (i.e. UV light intensity, aperture, and gain) were kept fixed. Specifically, the aperture of the lens was set to an f-number of 4 and the gain was set to 0. Images were taken at multiple exposure times from the shortest time the camera is capable of (500µs) to the longest time (61,000µs).

Due to unexpected relative motion between the camera (outside the vacuum chamber) and the specimen (inside the chamber), an investigation was done to confirm that the relative motion was caused by the vacuum pump. At room temperature, the two following cases was tested, and at extreme temperatures, only Case 1 was tested:
- **Case 1**: No motion applied to the specimen. For each value of exposure time, two consecutive images at the same state were taken.

- **Case 2**: An actual rigid motion was applied. The camera was moved a little bit out of the reference state in mostly the horizontal direction, producing a relative motion in the recorded images. A third image was then recorded at each exposure time.

A commercial DIC software from Correlated Solutions Inc. named VIC-2D was employed to compute displacement and strain distributions over the gauge length region. The subset size was 61x61 pixels, the step size was 25 pixels, and the strain window was 15 subsets. The calculation was performed separately for each temperature and exposure time, such that each use of the software involved only three images at room temperature (Case 1 and Case 2 with the same reference image) or two images at high temperatures (Case 1 only). The same images were later used to compute thermal expansion strains by assigning a reference image at room temperature and deformed images at the elevated temperatures.

After all data was collected, the data was post-processed using MATLAB to find the mean and 95% confidence interval. The 95% confidence interval was computed by sorting the data in ascending order and it was between value 2.5% and the value 97.5% of the data.
CHAPTER 4
RESULTS

4.1 Room temperature

The mean displacement and axial normal strain are presented in Figure 4.1 and Figure 4.2, respectively, with uncertainty bands showing the 95% confidence intervals. Since displacements were mostly applied in the horizontal direction, only the horizontal components are included. Each figure contains three datasets: case 1 (no applied motion) with the Gleeble turned off, case 1 with the Gleeble turned on, and case 2 (applied rigid motion) with the Gleeble turned on. For clarity, the first and last dataset have been staggered horizontally slightly by adding ±500µs to exposure time in order to avoid excessive overlapping of the uncertainty bands. Each dataset also features a horizontal line to indicate the combined mean of all points in the set, which should be nominally zero (for case 1 displacements and all strains) and non-zero (for case 2 displacements). The left y-axis is referred to Case 1 including Gleeble turned off and Gleeble turned on whereas the right one is used for Case 2.

As can be seen in Figure 4.1, when the Gleeble is on, it imposes a small relative motion between the cameras and specimens according to the mean line. However, when comparing to Figure 4.2, strains are all consistently around zero over the whole range of exposure time. This justifies that the relative motion is purely rigid-body motion. Accordingly, at high temperatures only the strains (not the displacements) will be reported in later figures.
Figure 4.1 Mean $u$ displacement at room temperature, compared between case 1 (no applied motion) and case 2 (non-zero rigid motion) with the Gleeble on or off as indicated. Each uncertainty band is the 95% confidence interval.
Figure 4.2 Mean strain $\varepsilon_{xx}$ at room temperature, compared between case 1 (no applied motion) and case 2 (non-zero rigid motion) with the Gleeble on or off as indicated. Each uncertainty band is the 95% confidence interval.

4.2 Extreme temperatures

A series of images showing the speckled surface of the specimen are arranged in Figure 4.3 at different temperatures (room temperature, 1300°C, 1450°C and 1600°C) and different exposure times (30,000µs, 45,000µs, 58,000µs and 61,000µs) along with histograms of the corresponding greyscale values. As both temperature and exposure time increase, the images become visibly brighter. Eventually, some images became so saturated that VIC-2D could no longer perform a correlation. The speckle images where VIC-2D was unable to correlate are marked with red crosses.
Figure 4.3 Raw speckle images of specimen surface at different temperatures (increasing from left to right) and exposure times (increasing from top to bottom) respectively, and histograms of the greyscale values corresponding to the images. Images which are too saturated to perform DIC are indicated with a red cross.
Figure 4.4 shows comparisons of ε_{xx} at room temperature (RT) vs 1300°C (a), 1450°C (b) and 1600°C (c) respectively when there are no applied displacements (i.e. Case 1). At the highest temperatures and longest exposure times (including the cases indicated by red crosses in Figure 4.3, data is unavailable because the images were too saturated for VIC-2D to perform its correlation.

Figure 4.4 Comparison of ε_{xx} at Room temperature and (a) 1300°C, (b) 1450°C and (c) 1600°C when there is no applied displacement.

Figure 4.5 presents the ε_{xx} strain contour at 1600°C when there is no applied displacement. Exposure time is 20,000µs since generally it gives a small uncertainty band at high temperatures. The data is overall centered around zero which is in good agreement with condition of no applied displacement.
Figure 4.5 The $\epsilon_{xx}$ (pixel/pixel) strain map at 1600°C and an exposure time of 20,000µs, obtained with Vic-2D from two images with no applied strain or displacement.

Figure 4.6 shows thermal strains at 1300°C, 1450°C and 1600°C as a function of position along the gauge length. Unlike the strains in the previous figures, the thermal strain was computed by correlating between a reference image at room temperature and corresponding deformed images at high temperature. The exposure time was set to 20,000µs. As can be seen in Figure 4.6, thermal strain gets bigger at higher temperature. Particularly, mean thermal strain (horizontal lines in Figure 4.6) is 0.0034, 0.0055 and 0.0063 at 1300°C, 1450°C and 1600°C, respectively, which correspond to mean coefficients of thermal expansion of $2.6020 \times 10^{-6}$ K$^{-1}$, $3.8087 \times 10^{-6}$ K$^{-1}$ and $3.9362 \times 10^{-6}$ K$^{-1}$ respectively. For temperature of 1600°C, the standard deviation of CTE is 0.1367 ($10^{-6}$K$^{-1}$) which is insignificant when comparing to its own CTE (around 5%). The
Coefficient of thermal expansion (CTE) from the manufacturer is $2 \times 10^{-6}\text{K}^{-1}$ [66]. Although it is unknown which temperature the manufacturer measured CTE, our results are generally of the same order of magnitude as the specifications of the manufacturer.

Figure 4.6 Thermal expansion strain at multiple temperatures over the gauge length.
CHAPTER 5
DISCUSSION

In general, results at room temperatures from Figure 4.1 and Figure 4.2 showed that the uncertainty bands are much wider in case 2 compared to case 1. Error caused by the vibration of the Gleeble (difference between two grand mean in Case 1) is well within the precision of the system (uncertainty band of Case 2). Therefore, the influence of Gleeble vibration is insignificant in a real experiment with non-zero motion. Another observation is that the uncertainty bands are wider at extreme exposure times and narrower at moderate exposure times. This is reasonable since the contrast of images at extreme exposure times is degraded, resulting in deteriorating the correlation.

The upper temperature limit of DIC depends on the light sensitivity of the camera system. As can be seen in Figure 4.3, when an exposure time of 61,000µs was used, the upper temperature limit of UV-DIC was 1300°C, whereas when it was reduced to 58,000µs, the limit was 1450°C and by using 45,000µs and below it was able to reach 1600°C. In other words, the variation of exposure time alters the contrast of image resulting in change of upper temperature limit.

For a given exposure time, the uncertainty bands are wider at extreme temperatures compared to room temperature as shown in Figure 4.4. This is reasonable since images get brighter at higher temperatures resulting in weaker correlation. Additionally, as temperature increases, images tend to saturate at lower exposure times, resulting in dropped data points (at the very highest exposure times) and larger uncertainty bands (at less high exposure times).
In order to justify the validity of 2-thermocouple method as presented in Methods chapter and illustrate the thermal gradient as well, Figure 5.1 shows a temperature map captured from a FLIR A6751sc IR camera. The temperature varies linearly in the X direction and is hottest in the middle of specimen.

![Temperature Map from FLIR IR Camera](image)

Figure 5.1 The temperature map from FLIR IR camera at 1600°C, data bar shows temperature (°C) map inside dashed rectangle.

Figure 5.2 is also an illustration of non-uniform strain distribution over the gauge length due to the thermal gradient. In Figure 5.2, the thermal strain contour at 1600°C over the gauge length is computed by comparing a reference image at room temperature and a
deformed image at 1600°C. Note that the data in Figure 5.2 is thermal strain at 1600°C while data in Figure 4.5 is nominally zero-strain at 1600°C when there is no applied loading or displacement.

Figure 5.2 The thermal strain $\varepsilon_{xx}$ (pixel/pixel) strain map at 1600°C and an exposure time of 20,000µs, obtained with Vic-2D from comparing a reference image at room temperature and a deformed image at 1600°C.

As temperature increases, thermal strains over the gauge length become less consistent around the mean line due to thermal gradient as shown in Figure 4.6.
CHAPTER 6

CONCLUSIONS

In summary, the influence of exposure time on DIC at extreme temperatures was investigated thoroughly in this thesis. Since the uncertainty bands are wider at extreme exposure times, it is recommended to avoid setting the exposure time too short (below 5,000µs for the camera settings used in this thesis) at all temperatures. Additionally, at high temperatures, it is advised to use short exposure times to avoid overexposing the images. For the example used in this study, exposure times of between 10,000µs to 40,000µs are a good range for this camera system to test from room temperature up to 1600°C. Most importantly, the upper temperature limit of DIC depends on the light sensitivity of the camera system which depends on multiple factors – including exposure time – and can be effectively extended by reducing the sensitivity of the system.
REFERENCES


