A High-Magnification UV Lens for High-Temperature Optical Strain Measurements

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A HIGH-MAGNIFICATION UV LENS FOR HIGH-TEMPERATURE OPTICAL STRAIN MEASUREMENTS

by

Robert S. Hansen

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

MASTER OF SCIENCE

in

Mechanical Engineering

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ABSTRACT

A High-Magnification UV Lens for High-Temperature Optical Strain Measurements

by

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Utah State University, 2018

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Digital Image Correlation (DIC) is an experimental method used to produce full-field strain maps of specimens undergoing deformation. In this measurement, images of a specimen are taken before and after mechanical and thermal loading, then software is used to track deformation and compute strains. DIC has been recently adapted for high-temperature tests by using ultraviolet (UV) range cameras, lenses, and filters to produce the images.

Application of DIC to small length scales and at high temperatures can be performed with proper equipment. However, for these measurements, there is no commercially available high-magnification lens that will allow images to be taken in the UV range. A custom UV high-magnification lens was recently created by a senior design team at Utah State University, and this project evaluates the potential improvements to high-magnification, high-temperature DIC measurements it offers.
A series of tests was run on a stainless-steel ring specimen (inner diameter of 10 mm with a thickness of 1.2 mm). Two UV cameras and lenses were used to perform simultaneous measurements: one at lower magnification using a commercial lens with a 50 mm focal length, and one with the custom high-magnification UV lens. The low-magnification system captured the entire ring while the high-magnification system focused on a smaller region of interest, capturing just the thickness of the ring. A high-temperature test (900 °C) showed the ability of the custom lens to produce satisfactory images without oversaturation. A tension test was also performed and DIC was used to produce strain maps. In each test, images were taken outside the environmental chamber, necessitating the long working distance. Finally, translations were applied to the ring specimen and DIC software used images of the displacements to produce strain maps. In both the tension test and these rigid body motion tests, these DIC results highlight the advantages that the custom lens offers, in that significantly more data from the image is usable and relevant to a small region of interest. These tests show that the custom lens is suitable for use in high-magnification UV DIC measurements.
A High-Magnification UV Lens for High-Temperature Optical Strain Measurements

Robert S. Hansen

Digital Image Correlation (DIC) is an experimental method used to measure deformation in materials. These measurements, which involve taking images of a sample before and after mechanical and thermal loading, give information about the behavior of the material in extreme temperature and force conditions. With proper equipment, DIC can be adapted for high-temperature tests and small-scale tests. This requires the use of cameras, lenses and filters fitted for use in the UV range and at high magnification. However, there is no commercially-available high-magnification lens that allows images to be taken in the UV range. A custom lens was recently created by a senior design team at Utah State University. This report evaluates the improvements offered by the custom lens on high-magnification, high-temperature DIC measurements.

To demonstrate the differences between the custom lens and a normal magnification lens, both types of lenses were used at the same time to take images during a series of tests. In the high-temperature test, the custom lens successfully prevented oversaturation of the image compared to the normal lens. In both a tension deformation test and a translation test, the custom lens also used the working distance and the field of view to capture more data from the smaller region of interest for use in producing the DIC measurements.
I would like to thank Dr. Ryan Berke for his continued guidance and support in this research, and for always acting in my best interests. His knowledge and advice have been indispensable in several ways. Many thanks to my other teachers and professors throughout the years, who instilled in me a love of science and discovery and a belief that anything is achievable.

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INTRODUCTION

Digital Image Correlation

Digital Image Correlation (DIC) is a non-contact method used to produce full-field strain measurements of a specimen surface. It is a popular strain measurement in a variety of experimental applications because: a) the non-contact nature of the measurement is ideal for in-situ measurements of complicated geometries and test setups, and for when it is not safe to come in contact with the specimen [1], b) it is easily adapted to different length scales of specimens being tested [2], and c) it provides strain data for an entire surface rather than a single point [3]. These advantages make it an ideal candidate for measuring strain in high-temperature and high-magnification situations.

Strain measurements can be produced by comparing images captured before and after a deformation of a material, then using DIC computer software to track the motion of image subsets (collections of pixels). Derivatives of the calculated displacements are then used to find the strains [4].

Reference images must be taken before testing begins. After some displacement of the subsets has occurred, either through deformation of subsets relative to each other or through rigid body motion relative to the camera, more images are recorded. The software will divide a region of interest from the reference image into subsets, then search for each of those subsets in the displaced image using a correlation algorithm to compare each potential subset match to the original reference subset [3]. This can be performed to sub-pixel accuracy, so the displacement measurement resolution is not limited to the size of the pixel. This sub-pixel accuracy can be achieved by interpolating grayscale values between pixels, and has been shown to be fairly reliable [5].
This method first requires that unique patterns be applied on the specimen surface for which the measurement is desired. For the correlation algorithm to capture the motion, the pattern must be unique (non-repeating) and isotropic, so that each subset can be identified and tracked [6]. In some cases, the natural surface can provide this pattern, but often a pattern of speckled paint on a contrasting background is necessary [7].

As the length scale changes, the size of the speckles in the applied pattern must also change to guarantee that the pattern remains distinctive. This ensures that each subset has a unique array of grayscale values and pixel arrangements. If the speckle is too small for the length scale of a test, each subset begins to appear similar in its arrangement of speckles. If it is too large, there is a greater risk of an entire subset being dominated by a single speckle, rendering different subsets indistinguishable. Thus, the subset size used in the correlation depends on the speckle pattern used. A smaller subset will result in more data points for displacement and strain calculations compared with a larger subset, which will provide fewer data, but may provide a more favorable uncertainty for each measurement [8]. Choosing an appropriate subset size has a great impact on the accuracy of the calculated displacements and the proper subset size will depend on the individual speckle pattern [9]. The step size set for the correlation determines the number of pixels between each subset. Thus, for a step size of less than half the subset size, the subsets will overlap and all pixels between the subset centers will be used in at least 2 subsets. A step size of more than half the subset size will cause some pixels to be used in only one of the subsets.
Ultraviolet DIC for High-Temperature Testing

One beneficial application of DIC is its utility in taking strain measurements at elevated temperatures. Several circumstances exist where taking strain measurements of specimens involving high temperatures is desirable, including analysis of material behavior in nuclear components \cite{10,11}, stress corrosion cracking \cite{12}, welding processes \cite{13}, and behavior of heat-resistant aircraft and spacecraft components \cite{14}.

In order to enable the use of DIC in these conditions, light with shorter wavelengths can be utilized in taking the images. Taking images primarily with blue light sources and filters has been shown to effectively raise the temperature at which images can be recorded \cite{15}. That temperature range can be extended further with the use of UV light sources and filters \cite{16}. Without the use of these filters, images produced from visible light become saturated due to the specimen glowing as temperatures increase and as light at longer wavelengths is emitted with higher intensity \cite{17}. This intensity of emission can be described by Planck’s Law in Equation 1, which gives the relationship between the spectral radiance, $B$, at a specific wavelength, $\lambda$, and a specific temperature, $T$. This shows that for a set wavelength, an increase in temperature will also increase the spectral radiance.

\[
B_\lambda(\lambda, T) = \frac{2hc}{\lambda^2} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}
\]
For high-temperature measurements, accommodations must be made to ensure that enough light in the UV range can reach the sensor while preventing the higher-intensity, long-wavelength light from reaching the sensor. In this work, the peak UV wavelength used was 365 nm. To perform these measurements, cameras, lenses and filters must be designed for use in the UV range. The cameras and lenses used must allow sufficient transmission of shorter UV wavelength light. A filter that does not allow transmission of the potentially saturating longer wavelengths while still transmitting shorter wavelengths must be included in the assembly. Finally, additional UV lighting is usually necessary, since ambient light often does not include UV light of a sufficiently high intensity.

**High-Magnification DIC for Small Length Scales**

The increased use of DIC in the field of solid mechanics has led to a need for innovations in its application to micro-scale measurements. DIC can be used on a wide variety of length scales, ranging from large scale to microscale [18] and even nanoscale, with the use of scanning electron microscopes [19]. This can be accomplished for small regions of interest by using macro or zoom lenses, which offer high magnification at relatively large working distances. Macro lenses are often commercially available. These small-scale measurements are especially useful in materials characterization [20], when looking at features such as grains or small platelets and precipitates in a specimen is particularly important [21].

DIC can be applied to small-scale measurements using images taken with equipment which rely on traditional light sources, or with equipment such as scanning
electron microscopes or atomic force measurement techniques [22]. Often, DIC on smaller length scales involves images captured with a microscope and therefore it is more difficult to record images while the deformation is being applied. As a result, these measurements are often ex-situ, although more recent advances have enabled in-situ measurements [23, 24].

**Custom High-Magnification UV Lens**

Advances in UV-DIC and high-magnification DIC have paved the way for future work where the two methods can be combined. However, if measurements are to be made on small-scale specimens where magnification is needed, commercially available magnification lenses are not capable of transmitting a sufficient amount of light in the UV range. Thus, a UV-capable, custom high-magnification lens is necessary to extend the upper end of temperature capability for high-magnification images to be used in DIC measurements. A senior design team at USU designed and assembled such a lens. The subsequent information in this subsection is based on their development of the lens, and the final report presented at the conclusion of their project. It primarily describes the function of each subassembly of the lens, and how it is designed to interface with the rest of a high-magnification UV DIC setup.

The custom UV lens assembly was designed to be paired with a JAI CM-140GE-UV camera with a C-mount type threading. Previous demonstrations have used this camera to perform UV-DIC [16]. The camera features a 1/2" sensor with a 1392 x 1040 resolution and a pixel size of 4.65 um. The assembly was also designed to be paired with a UV band-pass filter from LDP LLC and a pair of external UV light sources with a peak
wavelength of 365 nm, which were also previously demonstrated to perform UV-DIC in the same studies as the camera.

The lens was designed with the commercial software package OpticStudio, developed by Zemax LLC (Kirkland, WA, USA) for designing and characterizing optical assemblies. A schematic of the ray diagram used in the design is shown in Figure 1. The entire assembly was built using off-the-shelf components, which were bought primarily from Edmund Optics (Barrington, NJ, USA) and ThorLabs Inc (Newton, NJ, USA) using 13 singlet lenses. These lenses can be separated into three functional groups: a translating focus group, a stationary magnification group, and a stationary master group, seen in the cross section of the assembly, Figure 2:

![Figure 1: Ray diagram of the 13 lenses used in the assembly, with the 3 lens groups indicated](image)

![Figure 2: Cross-sectional view of the custom UV lens assembly and group subassemblies](image)
The focus group consists of a lens triplet, which collects light as it enters the assembly and columnates it to be used by the magnification group. It is infinity-corrected, and is mounted in an adjustable housing which allows fine focal adjustments to be made after a camera is placed at an appropriate working distance.

The magnification group receives the light from the focus group and extends its focal point to the master group, magnifying the image by a factor of 3.2X. It is in a static housing resulting in a fixed magnification power. An adjustable iris is capable of changing the effective f-number of the system. The f-number affects the diffraction limit, spot size, and depth of field. The diameter of this iris ranges from 5-20 mm.

The purpose of the master group is to receive light from the magnification group, to use a series of lenses to correct aberrations, then to transmit the image to the camera sensor. It is designed to be a telephoto-lens system, shortening the effective focal length of the light. This allows closer placement of the camera sensor to the lenses. The unadjusted effective focal length would be so long that the camera would need to be placed nearly a meter away from the rest of the assembly. The master group is in another static housing and features a C-mount adapter to connect the overall assembly to the camera.

In order to reduce chromatic aberrations, the lenses alternate between calcium fluoride and fused silica, both of which are known to be good transmitters of UV light, with a transmittance between 0.7 and 0.9 through most of the ultraviolet range [25]. The assembly is fully color-corrected for wavelengths between 270 to 400 nm. Due to the
relatively large number of lenses in the assembly, the overall transmissivity is 58% at the 365nm wavelength, which corresponds to the peak wavelength of the external light sources.

The entire assembly has an overall working distance of 254 mm, allowing the camera and lens to be placed safely outside an environmental chamber while focusing through a window on a test specimen inside. This is critical for use with the intended high-temperature testing. When focused at such a distance, the camera and lens have a field of view of about 2.2 x 1.7 mm. The camera and lens were then aimed at a series of Ronchi rulings and a USAF 1951 test target. The resolution was found suitable to resolve at least 101.6 line pairs per mm.

The senior design team customized the lens for use in both high-magnification and high-temperature settings. The team designed the assembly and tested it based on three criteria:

1) It must be able to produce images of small regions of interest (in this case, on the scale of 2 mm across).

2) It must demonstrate a long working distance (in our case, approximately 10 inches), allowing the camera to view high-temperature materials through a window without exposing the sensor to a damaging environment.

3) It must transmit light in the UV range while blocking visible light to eliminate oversaturation of the image by longer wavelengths.

The senior design team concluded in their initial testing of the lens assembly that all three of these requirements were met.
OBJECTIVES

The project detailed in the remainder of this report further demonstrates the fulfillment of each requirement that was set by the design team as outlined in the previous section in a variety of experimental settings while taking meaningful measurements using DIC. The objectives of this project are as follows:

- Conduct high-temperature tests in an environmental chamber, simultaneously using a camera with the custom lens and a camera with a commercial, low-magnification lens to capture images
- Capture rigid body motion of a speckled specimen with both camera and lens assemblies, comparing the applied translation to DIC measured displacements for each camera
- Produce DIC images during a mechanical deformation test in an environmental chamber to compare viability of the custom lens setup to the commercially-available lens and camera

The size of the field of view, the standoff distance from the specimen, capturing images through a viewing window of a temperature chamber, and transmitting only in the non-saturated UV range are all found to meet the design requirements through the fulfillment of these objectives.
METHODS

To meet the objectives, three different types of testing were designed and carried out: a thermal test to capture high-temperature images, a rigid body motion test to rigorously compare DIC measurements made with the custom lens with known displacements, and a mechanical deformation test to demonstrate the use of the custom lens in a fully experimental environment.

In this demonstration of the UV magnification lens, the specimen geometry matches the geometry of a specimen planned for studying the effect of embrittlement on the strength of zirconium-alloy nuclear fuel rod cladding at accident conditions [26], a ring approximately 12.7 mm in diameter, 5 mm in width, with a wall thickness of 1.2 mm. The testing described in the following chapters will be at elevated temperatures, and high magnification will be needed to view the features of interest. The high-magnification lens, focused on a single section of the thickness of the ring, will be used with a camera to capture images at the same time as another camera and traditional lens are capturing images of the entire ring.

Thermal Test

The initial tests conducted were to demonstrate the high-temperature capabilities of the custom lens in comparison to the shortcomings of a traditional lens and camera setup. The primary focus was obtaining images that demonstrated loss of the speckled area in the image due to visible radiation when the commercial lens was used and images that demonstrated no problems stemming from visible radiation when the custom lens
was used. DIC was not performed for these tests; however, the working distance and field of view were tested in the production of these images.

For the tests, T-316 stainless-steel tube specimens were used with dimensions similar to those of the zirconium-alloy cladding used in many light-water nuclear reactors. Steel is used in this test because it can effectively demonstrate the capability of the lens for the specific cladding geometry without the associated high cost. The rings were cut from the end of the tubing, which has a 12.7-mm outer diameter and 1.20-mm wall thickness. They were cut to a width of 5 mm.

The specimens were tested in a temperature-controlled load frame chamber, the Gleeble 1500D, shown in Figure 3. The Gleeble has a load capability of up to 10 kN in both tension and compression. It heats the specimens by passing a current through the grips to an electrically conductive specimen, reaching the desired temperature through resistive heating while cooling the grips with recirculating cooling water. Temperatures of at least 1600 °C have been achieved with the Gleeble to demonstrate DIC [27], and the machine is rated for use to 3000 °C.
Custom hooked grips were made from T-303 stainless-steel rods with a diameter of 10 mm, shown in Figure 4. These grips are threaded so that they can be loaded into the Gleeble as a normal rod specimen would be. On one end of the rod-shaped grip is threading (Part A), which is designed for use with the current Gleeble specimen grips. The back face of the specimen rests on a flat surface down the shaft of the grip (Part B). At the right end of the grip is a semicircle-shaped hook (Part C), which goes on the inside of the ring. Each grip is fastened into the Gleeble and the ring is placed over the two semicircles. Once loading begins, the inside face of the ring comes into contact with the curved face of the semicircle hook (A) and the bottom face of the ring remains in contact with the flat face of the grip (C). The radius of curvature of the semicircle hook is slightly smaller than the inner radius of the ring, meaning that initially the two will contact only
at one point on the circumference of the ring (the point of contact here is a line extending along the width of the ring/the height of the semicircle hook). These slightly different radii allow the ring to be placed over the hooks. However, once loading begins, the ring will slightly deform to fit the shape of the hook, increasing the contact area between the ring and hooked grip.

![Diagram of Hooked Grip with A) Threaded End, B) Flat Ring Resting Surface, C) Semicircle Grip](image)

The setup of the grips and ring specimen was designed so the current will be constant through the grips and the ring. Because power dissipated is proportional to the heat, the greatest heat will be experienced through the region with the greatest resistance, and therefore the region with the smallest cross-sectional area, as shown in Equation 2.

\[ P = I^2R = I^2\rho/A \] (2)

The contact area between the grip and ring is critical to the high temperature testing. Without good contact, the ring specimen will not heat properly. There must be a path for current to flow through. If contact is poor then electrical resistance will be due to
contact resistance rather than resistance of the material itself. When good contact is maintained, the area to heat up the most will be the ring, rather than the grip or the grip-ring interface, since resistance is greatest where the cross-sectional area is smallest.

The highest temperature also occurs in the part of the specimen furthest away from both grips, meaning that the ‘hot spot’ is focused on a very small area of the specimen. This provides a small region where the most interesting phenomenon occurs and thus a meaningful area where the camera with the custom lens is focused.

The speckle pattern needed for sufficient correlation by the software was applied to the top surface of the ring. The high contrast background was applied with a white, VHT, high-temperature, spray-paint primer. The speckle pattern was produced with a black color of the same VHT paint, which was applied by making a fine mist of slightly thinned paint with an airbrush above the surface, letting the mist droplets settle onto the white surface. This resulted in a very small, high-contrast, black-speckle pattern on a white background appropriate for both the larger and the smaller field of view. The speckle size varied, but the smallest speckles were roughly 10-20 nm across as shown in Figure 5. Some larger speckles were also deposited in the speckle featured, but were not present on the ring.
K-type thermocouples were welded to the outside of the ring specimen, centered 2.5 mm from both the top and bottom surfaces, to give temperature feedback to the thermal control system of the Gleeble. The specimen was loaded between the hooked rings, so that contact was barely maintained, as shown in Figure 6. It was oriented so the top flat surface of the ring was parallel to the viewing window. A small load was applied (0.5 kN), so the ring began to slightly deform, creating a better contact area for heating. Then, a thermal load was gradually applied, raising the temperature to 900 °C by increments of 50 °C. At each increment, an image was taken by each of the cameras. The grips were moved as the specimen was heated to allow for thermal expansion without allowing the electrical contact to be lost, while keeping the load at or below 1.5 kN to avoid significant permanent deformation. The temperature was decreased to room temperature, the load was released, and the test was completed.
Figure 6: Ring specimen (A) with K-type thermocouples (B), loaded into custom grips (C) in the Gleeble 1500D standard specimen grips (D)

The JAI CM-140GE-UV cameras, with which the custom lens was designed to be compatible, were paired with the custom lens and with a commercially available UKA Optics UV5035B 50 mm focal-length lens from Universe Kogaku America. The custom lens had the designed aperture opened as wide as possible, so the adjustable iris diameter was 20 mm. The UKA 50 mm lens had the aperture opened to give an effective f-number of 16. A single UV external light source with a peak wavelength of 365 nm was placed immediately outside the environmental chamber window. The window of the chamber was made of borosilicate glass designed to transmit through the UV range. The front of the custom lens was placed 10.5 inches above the specimen and the front of the 50 mm lens was placed 13 inches above the specimen. Each of the cameras and the light source were mounted using aluminum T-slot frames from McMaster Carr and were arranged so
that each camera was nearly perpendicular to the specimen surface. The camera and light source arrangement are shown in Figure 7. The entire optics setup with the Gleeble 1500 D control tower, load frame, and testing chamber is shown in Figure 3.

**Figure 7: Optics arrangement, with UKA Optics 50 mm lens and camera (top middle), custom lens (middle right), and UV light source (bottom left) over the environmental chamber viewing window**

**Rigid Body Motion Test**

The purpose of the final set of validation tests was to capture images of the same specimen, then perform DIC measurements in a way that would allow more rigorous testing of the accuracy of those measurements. To accomplish this, rigid body motion of the ring was captured with both cameras at 300 K in order to compare with the known applied displacements. This enabled better comparison of the camera and lens pairings.
The specimen was placed on a translating stage with micrometer measurements for applied vertical and horizontal displacements made by Thor Labs Inc. The stage was fixed to a stabilized table, and the cameras were fixed to the same table to minimize any displacement of the specimen relative to the cameras, aside from those displacements purposely applied. The cameras were perpendicular to the stage so the translations applied would result in nearly in-plane motion. Only one UV external light source was used in this test. The custom lens was placed 10.5 inches away from the specimen and the 50 mm lens was placed 13 inches away in order to replicate the distances that would be required if the test were performed through the viewing window of the Gleeble environmental chamber. The rigid body motion experimental setup is shown in Figure 8.

Displacements were applied to the specimen with the stage and images were taken with both cameras after each movement. Motion was minimal enough that the majority of the specimen within the field of view of the reference image captured by the custom lens and camera pairing remained in the field of view of subsequent images. This prevents subsets from being dropped as the region moves out of the image. Purely vertical, purely horizontal, and then a mix of horizontal and vertical translations were applied.
Figure 8: Rigid Body Motion Experimental Setup with lenses (left), UV external light source (top center), and translating stage with specimen (right)

**Mechanical Deformation Test**

The following tests were focused on capturing images during mechanical deformation to be used with the DIC software, with the purpose of producing strain-contour plots. This was designed to demonstrate the ability of the custom lens to be used in an experimental setting, requiring the proper working distance and field of view. These tests were not performed at high temperature.

The specimen was loaded in the same grips and with the same method as outlined in the previous high-temperature test section. The aperture settings, camera arrangements and orientations were identical to those of the previous tests. The primary difference between the two tests was the addition of another UV external light, identical to the one
previously used, to improve speckle contrast for DIC calculations. This arrangement can be seen in Figure 9.

Figure 9: Mechanical deformation test setup, with additional UV external light source

The specimen was loaded by increasing the distance between the grips through manual displacement control and monitoring the load reported by the load frame. The load was increased from the 0.5 kN preload necessary to ensure contact between the grips and specimen to 2.1 kN. Images were captured at increments of roughly 0.2-0.5 kN as the specimen was loaded. After reaching 2.1 kN, the specimen was unloaded and the test was completed.
RESULTS

Thermal Test Results

Images were successfully captured at the increments intended using both the custom lens and the 50 mm lens. Figure 10 through Figure 13 show the results for 50 °C, 500 °C, 800 °C and 900 °C, respectively. For readability, the high-magnification images on the left of each figure have been artificially brightened by a factor of 2.5 using MATLAB software for clarity in this report. The actual images used for processing in the DIC software were not brightened. Significant visible radiation can be seen in the unfiltered, low-magnification setup as temperatures increase, while only slight, uniform changes appear in the custom lens. Note that the custom lens image comes from the region at the bottom center of the ring in the traditional lens image, shown in Figure 10.

Figure 10: High-Magnification (left) and Low-Magnification (right) at 50 °C. Red box shows placement of high-magnification image
Figure 11: High-Magnification (left) and Low-Magnification (right) at 500 °C

Figure 12: High-Magnification (left) and Low-Magnification (right) at 800 °C

Figure 13: High-Magnification (left) and Low-Magnification (right) at 900 °C
Rigid Body Motion Test Results

The same VIC-2D software was used for analysis of the displaced images, compared with the reference images, as was used in the mechanical deformation test analysis. Similar subsets were explored, but strains were not computed because none were expected. Rather, only vertical and horizontal displacements were compared. Figure 14 shows the horizontal applied displacements and averages of the measured displacements of the subsets in each high-magnification picture and each low-magnification picture. A similar plot for vertical displacements is shown in Figure 15.

Figure 14: Horizontal Applied Displacement for High- and Low-Magnification Images
Both plots include a line at a 45-degree angle, representing perfect agreement between applied and measured displacements. Uncertainty bands represent twice the standard deviation of the measured displacements across all subsets of the image. Several different subsets and step sizes were explored, ranging from subsets of 25 pixels to 57 pixels. The best correlation was found with the 25 pixel and 33 pixel subset sizes for the high magnification. A contour for the vertical displacement of the high-magnification image, which had both horizontal and vertical displacements applied, is shown in Figure 16.
The low-magnification images gave significantly less useful data, as can be seen in Figure 14 and Figure 15. Again, several subset sizes were investigated. The best correlation results without dropping a significantly large number of subsets came with a subset size of 11 pixels. A sample contour plot is given in Figure 17.
Mechanical Deformation Test Results

The specimen was deformed as described in the methods chapter, up to 2.1 kN force. The applied loads and the measured displacements reported by the load frame at times corresponding to the images taken are found in Figure 18. It is important to note that the specimen began to plastically deform at the bottom of the ring, resulting in a wider diameter at the front surface of the ring than at the back surface, relative to the camera. Thus, the displacement of the grips reported by the load frame is not the same change in length that would be used to calculate strains for the top surface measured by DIC.
Figure 18: Force vs Displacement, as reported by Gleeble 1500D

The reference image and the images taken at each increment described in Figure 18 were imported into VIC-2D, a commercial DIC software package by Correlated Solutions, LLC. The software was run with a subset size of 83 pixels for both the low- and high-magnification images. The region of interest was set to be the area encompassed by the speckled part of the specimen. In most of the displacement increments, the average strain over the region of interest in the high-magnification images did not match the expected strains based on the reported displacements of the load-frame grips. A sample contour plot of Lagrange strains in the vertical direction (from the reference of the image)
for the high-magnification image of the second applied displacement is given in Figure 19. A subset size of 83 pixels with a step size of 8 pixels was used.

![DIC Contour Plot of Strain in Direction of Loading (Vertical), High-Magnification Lens image; subset 83 pixels, step size 8 pixels. Vertical strain is $\epsilon_{yy} = \Delta l/l_0$.](image)

Similar contour plots were created for the low-magnification images. However, as expected, the subset size necessary for an acceptable correlation approached the size of the ring surface in the images, resulting in the contour plots seen in Figure 20. These images dropped many of the subsets on the ring because there was not enough data in the image to correlate and fit within the bounds of the region of interest, even when a subset size of 29 pixels and a step size of 12 pixels were used.
Figure 20: DIC Contour Plot of Strain in Direction of Loading (Horizontal), Low-Magnification Lens image; subset 29 pixels, step size 12 pixels. Horizontal strain is $e_{xx} = \Delta l/l_0$. 
DISCUSSION OF RESULTS

The high-temperature test demonstrated the ability of the custom lens to transmit UV light and thereby prevent oversaturation of the image by longer wavelengths of light. Comparing the images in the previous chapter shows the difference that the custom lens assembly makes compared to a commercially-available lens without a UV filter. Figure 10 shows the reference image of just above room temperature, where both camera setups produced usable images. Figure 11 shows the specimens at an elevated temperature, but still before visible radiation occurs. The high-magnification image is slightly lighter and the low-magnification image shows some lightening as well. In Figure 12, a trace amount of visible radiation is apparent at the bottom surface of the ring in the low-magnification image. This is where the specimen is beginning to heat up as it approaches a temperature where the visible light will emit with greater intensity. Figure 13 shows very significant saturation in the low-magnification image. Any speckle that would have been visible in the image is lost in this region of saturation.

At high temperatures, the high-magnification lens produced images that were not affected by the visible emission of a hot specimen, unlike the images produced by a low-magnification lens without a UV filter. In a conventional setup that doesn’t take the visible emission effect into account, the region of the specimen where glowing occurs would be lost. For many materials, this lost area is also where the material will yield first, thus the critical area would not have usable data. In contrast, the custom lens fulfilled the criteria to transmit in the UV range without producing overexposed regions in the images and it was shown by comparison that it outperforms other alternatives.
The mechanical deformation test showed that the custom lens can be implemented successfully into an experimental setup to produce images that are compatible with DIC. The working distance was effectively utilized, placing the end of the lens at least 10 inches away from the specimen, thereby allowing tests to be carried out on specimens being tested in environments unsuitable for cameras and sensitive optics.

Images were taken through an observation window, which is another crucial capability of the lens for it to be beneficial in similar testing conditions. It should be noted that an additional light source was used, as the speckle pattern was darker than is preferable (see Figure 19 for the dark speckle under the contour). With 13 singlet lenses in the assembly, the transmissivity is low and images appear less bright. This can be countered in an experiment by opening the aperture, but, that can have potentially negative consequences in a less focused image due to decreased depth of field. It can also be improved by increasing exposure time, but this can also have deleterious effects, leading to blurring of the image if the object is moving. With specimens in a chamber that is prone to vibration, this can be an especially difficult problem to overcome. Thus, it is important to ensure that sufficient light reaches the specimen when the lens is used, especially in a naturally dark environment such as a testing chamber.

It can be seen in the images taken with the custom lens that a slight ‘ghost ring’ image appears, centered on the middle of the image, as seen in Figure 21. This was noted by the senior design team’s final report. However, the results of the rigid body motion tests demonstrate that this does not necessarily interfere with the ability of DIC to measure the deformation. The results of that test clearly demonstrate that images
produced by a camera fitted with the custom lens can accurately measure the
displacement of a specimen. When comparing the contour plots with the ghost ring
placement in Figure 16, there is no correlation between the areas where the ring appears
and the dropping of subsets in the image due to a poor correlation from the DIC software.

One of the most impressive capabilities offered by the custom lens is the
improvement in the field of view and its potential application to this and many other
experiments, where small features are to be studied and a high-temperature range is
desirable. The field of view for the camera with the custom lens was 2.32 mm across. The
analysis of the ring specimen presented here is an ideal case for highlighting the
advantages to using this custom high-magnification lens. In high-temperature testing, the
camera must remain outside the chamber to protect the sensor from the damaging
environment. When a low-magnification lens is used outside the chamber, the entire ring
will be captured in an image, yet the majority of the image will not be filled. The
difficulty that arises with this comes from the thickness of the ring being viewed. The actual ring surface only takes up a small part of the image. This makes accurate DIC results of the area of interest difficult to achieve. If only a fraction of the image is filled with useful data and subsets, then most of the image is being wasted on something other than the small area where the study is focused. This is particularly true if the reason for study of the specimen or the material comes from the desire to study phenomena occurring on a microscale. For example, in the testing of this ring, which mimicked the test setup for nuclear fuel cladding, the area that undergoes the greatest deformation due to the simulated hoop stress is at a specific point. If a traditional, low-magnification system is used to produce the image, most of the surface that already makes up a small part of the large field of view is also spent on non-essential strain measurements. Instead of using the majority of the pixels in an image to make the measurement, the area of interest is covered with only a few subsets. As a result, the majority of the captured data is wasted on unimportant regions. This essentially renders the results not a true full-field measurement.

An additional difficulty with getting meaningful data from the low-magnification image comes from choosing the region of interest or interrogation region for the software to correlate. The size and shape of this region has an effect on the subsets used in the correlation, especially in the case where the thickness of the ring approaches the subset size. Three different approaches to the shape of this region were used, with varying advantages and potential problems: a region encompassing the entire ring and the grips
(Figure 22), the same region with a slot for the gap between the grips excluded (Figure 23), and an annulus encompassing just the ring itself (Figure 24).

*Figure 22*: Circular region of interest (left) and accompanying horizontal strain contour (right) from mechanical deformation test, ranging from -0.05 (purple) to 0.015 (red).

*Figure 23*: Circular region of interest with slot (left) and accompanying horizontal strain contour (right) from mechanical deformation test, ranging from -0.05 (purple) to 0.015 (red).
The largest region of interest (ROI) is the least likely to drop subsets that are on the ring specimen (Figure 22). However, this also picks up the motion of the semicircular part of the grips because of the natural surface texture and gives an artificially high reading for the strain at the gap between the grips. To eliminate this artificial strain, the slot was excluded in the next ROI arrangement (Figure 23). This removed some false data while still allowing the same amount of data from the ring specimen, but it also has a lot of unnecessary subsets and can slow down computation time. The most efficient use of computing time comes with the last arrangement (Figure 24). However, as DIC tends to drop data near the edges of the ROI and the region is very thin, the DIC data spans a very limited area. The optimum ROI depends on the individual experimental application, and the tradeoffs between each method must be weighed to find the best fit.

These problems with the low-magnification images can be contrasted with the use of the custom high-magnification lens. In this approach, the camera is focused on just the small region of interest where the greatest strains are expected. The field of view matches the thickness of the ring, maximizing the use of each subset and effectively capturing the
strains in a full-field measurement. In this way, a much more thorough and rigorous measurement is made, providing a much more comprehensive understanding of the phenomenon being investigated.

One of the greatest challenges inherent in this setup is the generation of a suitable speckle pattern. The methods used to produce the high contrast pattern in this project worked to some degree; however, it was found that for the mechanical deformation tests, the speckle was less visible. For the software to be able to correlate the images, large subset sizes had to be used. This could be remedied by implementing a smaller speckle pattern. A smaller speckle would become unusable for a camera with a traditional lens at some point and would not have worked in this project, but, in an experiment where only the custom lens was used, a smaller speckle size would be beneficial.
CONCLUSION

The custom high-magnification UV lens was found to meet all three criteria: (1) It transmitted light in the UV range while blocking the high-intensity longer wavelengths through the use of a filter, while a traditional lens and camera did not, (2) it was able to produce a field of view that was 2.32 mm across, a significant improvement over commercial UV lenses, finally, (3) it was demonstrated in an experimental setup with a working distance of 10.5 inches, allowing it to be placed outside an environmental chamber window and to be protected from hazardous conditions.

Images produced by a camera fitted with the custom lens during a live loading were able to produce strain contour plots. DIC results of rigid body motion were compared with the applied displacements with positive outcomes. Speckle size is an important consideration when using the custom lens, as well as ensuring sufficient lighting is present.

The custom lens is capable of being used in future work where measurements of strain on a small region of interest, on the order of 2 mm, are desired at high temperature. This has potential application for material characterization of nuclear materials at accident conditions, studying microcrack fatigue or stress corrosion cracking, or other phenomena on a microscale at high temperatures. It can be beneficially implemented in these conditions to produce accurate, full-field strain and displacement measurements.
REFERENCES


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