Development of Digital Image Correlation for mechanical testing at cryogenic temperatures

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Abstract. Engineering use of superconducting magnets requires integrity of the magnet coils and their structural support under mechanical loading at cryogenic temperatures. Experiments were carried out to explore the potential of performing full-field strain measurements with DIC using a non-vacuum tight environmental chamber at low temperatures to -150°C. The chamber used in this work utilizes nitrogen gas at its boiling temperature to convection-cool the sample to cryogenic temperatures. Circulating convection loops inside the chamber during cooling was a major source of error. The convection loops were effectively disrupted by installing 12V DC computer fans inside the chamber, reducing the DIC strain noise floor from 0.53% to 0.19% and allowing quantitative measurement of plastic strains.

Introduction

Structural components in tokamaks operate under extreme hot and cold temperatures. The underlying structural steel supporting the plasma-facing armour needs to sustain temperatures beyond 600°C. On the other hand, the structural components for large-scale superconducting magnets, which are used for plasma confinement, are exposed to temperatures as low as the liquid Helium temperature i.e. -269°C. Digital image correlation (DIC) is arguably the only optical technique capable of performing full-field strain measurements on component's surface at such extreme temperatures with adjustable spatial and temporal resolutions. The development of DIC at high temperatures has largely been driven by the need for characterising thermo-mechanical response of materials and components in aerospace, nuclear and metal forming industries. In contrast, DIC at low and extreme cryogenic temperatures is not well-established. A limited number of studies have attempted to use DIC for mechanical testing at cryogenic temperatures. Pelegrin et al. [1] used a stereo-DIC setup to measure the contraction of a high temperature superconducting magnet coil, which was conduction-cooled to -120°C in a non-vacuum tight environmental chamber. Zhang et al. [2] developed a cryo-mechanical rig for materials testing at liquid helium temperatures. In this study, a single camera DIC setup was used to evaluate elastic modulus of Titanium samples from measured elastic strains at -253°C. A cryo-rig capable of testing materials at liquid Helium temperatures was also developed by Wang et al. [3] with an additional feature of super conducting magnet providing background magnetic field up to 3.5T. A stereo-DIC setup was used on this rig to study quench mechanism [4] and determine mechanical properties [5] of superconducting magnet tapes. Most of these studies [2-4] were focused on the development of cryo-mechanical rig and discussion on key technical aspects of DIC such as sample preparation, stereo calibration procedure and strain measurement noise floor were missing from these publications.

The Applied Materials Technology Group at the UK Atomic Energy Authority aims to develop DIC for determining meso-scale constitutive parameters of structural materials at cryogenic temperatures and testing superconducting magnet components joints under synergistic cryogenic-magnetic environments. In this work, experiments were carried out to explore the potential of performing quantitative strain measurements with DIC using a non-vacuum tight environmental chamber at -150°C.

Experimental setup and testing

The experiment setup consisted of a 5kN Instron universal test machine, which was fitted with an environmental chamber (Severn Thermal Solutions Ltd, UK) with the operating temperature range of -150 to +600°C. The chamber cooling mechanism utilized a solenoid valve, which was operated by a temperature controller to admit cryogenic gas into the chamber. The fan at the back of the chamber circulated the gas for uniform cooling. A stereo-camera setup from LaVision GmbH was used for DIC measurements, which consisted of a pair of 12-bit digital cameras with a CMOS sensor of 2056×2464 pixels, fitted with 200mm Nikon macro lenses. The cameras were mounted on a tripod, which was positioned in front of the chamber window providing an effective spatial resolution of 150 pixels/mm. Preliminary experiments revealed that the circulating fan at the back of the chamber was not very effective in dispersing the cryogenic gas and convection loops were formed inside the chamber causing distortions in the images captured by the DIC system. Two 12V DC computer fans were installed inside the chamber to disrupt these convection loops. In total, two tests for DIC noise floor assessment were performed on a 316 stainless steel dog-bone sample with a gauge section of 15×3 mm. DIC speckle pattern was created on the sample with a black base and white speckles using VHT flame-proof paint. For both the tests, sample was held in the grips with a pre-load of 50N. In the first test, 100 frames were captured at room temperature followed by 1000 images at -150°C with the computer fans switched off. In the second test, 100 and 1000 frames were captured at room temperature and -110 °C, respectively, with the computer fans switched on.

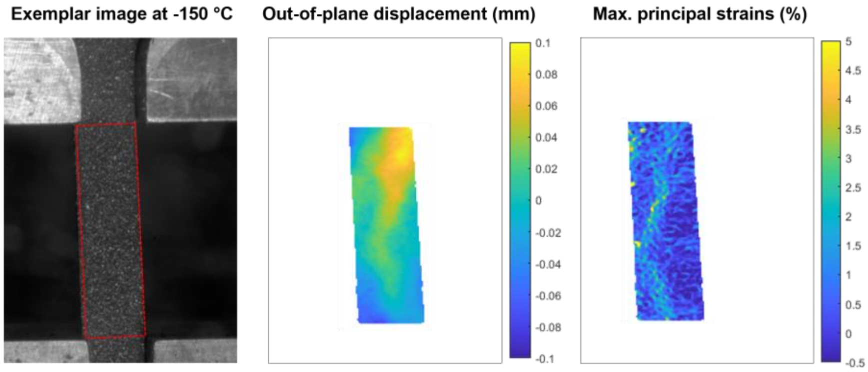

Figure 1. Exemplar image at -150°C (left) and the corresponding out-of-plane displacement (middle) & maximum principal strain (right) map.

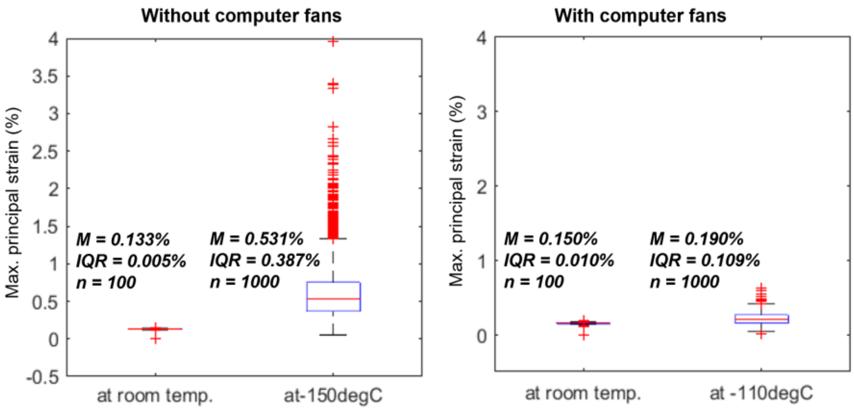

Figure 2. Box and whisker plot showing the comparison of the strain noise floor at room and low temperatures for test 1 (left) and test 2 (right). *M* and *IQR* are the median and interquartile range of the strain distributions, whereas *n* represents the number of strain maps involved in the statistical analysis.

Results and discussion

Fig. 1 shows an exemplar image acquired at -150°C with the computer fans switched off. Localized features can be observed in the displacement and strain maps in Fig. 1, which were caused by variations in the refractive index of air inside the chamber. DIC noise floor analysis was performed by determining the median value of the maximum principal strain map for each of the captured images. Box and whisker plots in Fig. 2 represent the distributions of the median strain values for the strain maps at room and low temperatures. For the first test, the median (M) of the strain distribution at -150°C was almost 4 times the distribution median at room temperature, rendering it impossible to perform quantitative measurements with DIC at such low temperatures. In the second test, the strain distribution median at -110°C was reduced to 1.3 times the strain distribution median at room temperature by effectively disrupting the convection loops with the help of computer fans; this noise floor allows for quantitative measurement of plastic strains. To the best of author's knowledge, no published study has performed quantitative DIC strain measurements at such low temperatures using convection cooling in an environmental chamber. Another important statistical parameter to consider is the interquartile range (IQR), which represents the spread of the distribution. Future work will focus on the deployment of computer fans capable of providing higher air flow rates for effective disruption of convection loops to further reduce the DIC noise floor, which would allow quantitative measurements of elastic strains as well.

Conclusion

A feasibility study was carried out to explore the potential of performing DIC measurements using a non-vacuum tight environmental chamber, which utilizes nitrogen gas at its boiling temperature to convection-cool the sample to -150°C. One of the major problems with this setup was the circulation of convection loops in the chamber during cooling, which caused significant distortions in the DIC images. Computer fans were installed inside the chamber to disrupt these convection loops, which helped reduce the strain noise floor from 0.53% to 0.19%, allowing quantitative measurement of plastic strains.

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