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Determining the tensile response of materials at high temperature using DIC and the Virtual Fields Method

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ABSTRACT

An experimental approach based on Digital Image Correlation (DIC) is successfully applied to predict the uniaxial stress-strain response of 304 stainless steel specimens subjected to nominally uniform temperatures ranging from room temperature to 900 °C. A portable induction heating device equipped with custom made water-cooled copper coils is used to heat the specimen. The induction heater is used in conjunction with a conventional tensile frame to enable high temperature tension experiments. A stereovision camera system equipped with appropriate band pass filters is employed to facilitate the study of full-field deformation response of the material at elevated temperatures. Using the temperature and load histories along with the full-field strain data, a Virtual Fields Method (VFM) based approach is implemented to identify constitutive parameters governing the plastic deformation of the material at high temperature conditions. Results from these experiments confirm that the proposed method can be used to measure the full field deformation of materials subjected to thermo-mechanical loading.

1. Introduction

Determining the mechanical response of materials at elevated temperatures is a subject of great interest in metal forming as well as aerospace and aero-engine industries. Measurement of the deformation response under tensile loading at high temperatures is essential to establish the thermomechanical and thermophysical properties of materials as a basis for determining the reliability of a component or structure exposed to elevated temperatures. However, there are certain challenges associated with accurate measurement of high temperature tensile response of materials. Conventionally, high temperature tensile behavior of an engineering material is obtained by conducting experiments in well-controlled environments while measuring the global deformation response using extensometers [1,2]. In this context, the term extensometer refers to either contact or non-contacting methods that provide an average measurement over a specified gage length. Although this methodology provides acceptable results and is widely used in engineering applications, accuracy of the deformation measurements will be highly sensitive to the equipment used in the experiment. Moreover, in cases where the presence of local phenomena gives rise to considerable localization of deformation, extensometer-based strain measurements may not provide quantitative evidence of such deformation localization phenomena [3]. On the other hand, temperature-resistant strain gages provide a reliable approach for strain measurements performed at significantly high temperatures, with the capability to measure the strain localizations. However, the application of such temperature-resistant strain gages is limited to point measurements and relatively lower working temperatures [4–6].

Recent advances in the area of non-contacting full-field measurements have proven to provide reliable alternatives for the conventional material testing methods. In particular, digital image correlation (DIC) is one of the most appealing techniques, having the capability of providing accurate information on the deformation response of materials subjected to extreme conditions, with the benefit of use of straightforward specimen preparation [7]. Three dimensional DIC (3D-DIC) has the capability to adjust the spatial resolution, ability to take measurements on curved surfaces [8] and on specimens having different sizes and/or shapes [9–11]. The method has also been shown to be suitable both for static and dynamic measurements [8,12]. The first work in this area was performed by Lyons et al. [14] in 1996. In this study, the authors conducted a series of experiments to assess the capabilities of 2D DIC in the measurement of full-field deformations at elevated temperatures. It was found that the variations in the refractive index of heated air outside the furnace can result in substantial image distortions. It was also found in this work that the visible thermal radiation emitted by the material when heated to temperatures above 650–700 °C alters the contrast and the intensity of the speckle pattern, and consequently introduces significant amounts of errors to the image

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correlation process. More recent works have studied DIC for measuring strains at temperatures ranging from room temperature to 1200 °C. Grant et al. [15] presented a method that overcomes the black body radiation issue by implementation of optical filters and special illumination sources, providing accurate DIC measurements up to 1100 °C. In another research, Wu et al. [16] implemented a single-lens 3D-DIC approach to measure the thermal linear expansion of an alumina ceramic plate up to a temperature of 1200 °C. In this work, Wu et al. [16] proposed a calibration-free single lens 3D-DIC system based on bilateral telecentric lens and a bi-prism to facilitate measurement of out-of-plane displacements at high temperature conditions.

Another limitation associated with the application of DIC at high temperatures is due to the deteriorating effect of extreme temperatures on the speckle pattern. In recent years, the application of novel speckling methods capable of sustaining integrity and efficiency at extreme temperatures has been studied. Application of temperature-resistant coatings such as LSI boron nitride and aluminum oxide-based ceramic coatings [14], temperature resistant white Y_2O_3 paint and other ceramic paints [17] a mixture of black cobalt oxide with liquid commercial inorganic adhesive [18] and the use of plasma sprayed tungsten powder as the speckle pattern are examples on novel speckling methods, facilitating the application of DIC in temperatures up to 2600 °C [13].

With the rapidly growing applications of digital image correlation in the area of material characterization, further research is required to establish simpler high temperature DIC techniques that overcome the previously described limitations. It is also beneficial to devise experimental techniques that employ portable heating systems compatible with multiple testing machine configurations and for different sample sizes and geometries, in order to take advantage of the convenience of the DIC's simple and versatile setup equipment. In light of this, the present work focuses on the application of a portable high temperature 3D DIC measurement system that can be employed with a wide range of specimen geometries and sizes. The effectiveness of the system is verified by successfully conducting tensile experiments at temperatures up to 900 °C to study the thermomechanical properties of a 304 stainless steel specimens. The advantage of conducting full-field measurements over the conventional test methodologies are highlighted in an analytical study based on the method of virtual fields, which facilitates the identification of the constitutive response of the material with acceptable accuracy.

2. Experimental

2.1. Material and specimen geometry

Flat dog-bone specimens are extracted from an as-received plate of commercially available low-carbon 304 stainless steel. This material is selected due to its non-magnetic and excellent scaling resistance characteristics. Tensile specimens are coated with a thin layer of ultra-high temperature resistant white yttrium oxide spray paint. The maximum working temperature for yttrium oxide coating used in this work is reported by the manufacturer as 1500 °C. A high temperature black silica-based ceramic paint is then applied on top of the white coating to obtain a fine speckle pattern, used for the image correlation purposes. Black speckle particles with an average size of 50 μm are produced in this way. Specimens are kept at room temperature for 24 h to let the paint fully dry. Fig. 1 illustrates a tensile specimen with a magnified view of the speckle pattern in the area of interest.

2.2. Tensile experiments

Tensile experiments are initially carried out at room temperature to obtain the reference stress-strain response of the material. To do so, the specimen is inserted into hydraulic clamp grips of a conventional tensile frame. The specimen is then loaded in displacement control

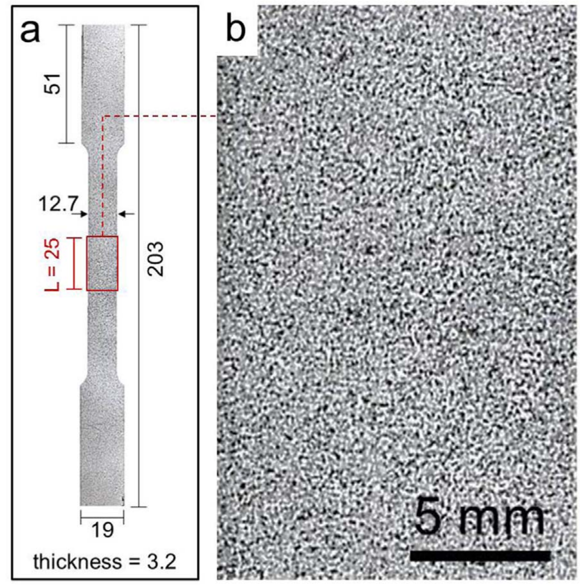

Fig. 1. (a) Tensile specimen geometry with a magnified view of the area of interest shown in (b). All dimensions in mm.

mode at a constant cross-head speed of 10 mm/min. The synchronized load data is used with the measured strain data to determine the true stress. True strain and true strain rates are determined using the full-field strain data obtained from DIC, as discussed in more detail in forthcoming sections.

To conduct experiments at high temperatures, an induction heating system is used in conjunction with the tensile frame used in room temperature experiment. The induction heating system employed is a portable table-top unit [17,19]. Using the appropriately dimensioned coil system, the induction heating system is suitable for a wide variety of specimen geometries and loading systems [19]. The induction heater is equipped with a water-cooled copper coil system that heats up the specimen at a rate of 1.6 °C/s and provides relatively uniform temperature distribution in the heated area. Prior to the onset of the tensile experiments, a steel specimen is clamped at the bottom grip of the tensile machine inside the coil and heated to the target temperature. After a dwell time of several minutes to achieve nominally uniform conditions at the target temperature, the specimen is clamped at the top grip and the tensile loading experiment is immediately initiated. Target temperatures used in this work are 300 °C, 500 °C, 700 °C and 900 °C. The temperature of the specimen is measured during the tensile experiments using a non-contacting infra-red thermometer, with a nominal measurement accuracy of ±1 °C. Temperature history of the specimen at the location of the area of interest is recorded at the same sampling rate used for load and image acquisitions. Reproducibility of the results is ensured by conducting several experiments per target temperature. Fig. 2 illustrates the experimental setup in this work. Note that the heating coil system is positioned such that the maximum temperature is always achieved inside the area of interest. Due to the fact that the deformation is mostly localized in areas over which the highest temperature is applied, the camera system was positioned by making sure the location of the localized necking would be encompassed inside the area of interest.

2.3. Imaging and digital image correlation

Three-dimensional digital image correlation is utilized to measure the full-field deformation response of the specimens subjected to tensile loading at high temperature. To this purpose, a pair of 5 MP CCD cameras, each equipped with a 100 mm macro lens is used to acquire stereo images during deformation. Synchronized stereo image