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# A high-fidelity strain-mapping framework using digital image correlation

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ABSTRACT

A practical framework is developed in this work for extracting high-fidelity quantitative strain information from three-dimensional digital image correlation (3D-DIC) experiments. The framework is applicable for continuum-scale deformation in elastic and plastic regimes in the presence of macroscopic strain gradients. The framework is developed, demonstrated, and validated by conducting 3D-DIC experiments and corresponding finite element analysis (FEA) on polycrystalline aluminum tensile specimens with and without macroscopic strain gradient subjected to uniaxial tensile deformation in both elastic and plastic regimes. The developed framework is expected to be applicable for continuum-scale deformation in other classes of materials.

## 1. Introduction

For decades, improvements in materials have played a significant role in advancing aerospace mechanical and structural designs. Super-alloys, ceramic matrix composites, polymer matrix composites, and nano-enhanced composites have been the focus of aerospace industry for low- and high-temperature structural applications such as: gas turbine engine components (blades, vanes, combustor liners, turbine disks, rotor and fan blades), wing leading edges of hypersonic flight vehicles, nozzle exit ramps for advanced rocket engines, helicopter rotor blades and gearbox housings, among many others [1–13]. While some of these advanced materials concepts are at the emerging stage of the applications delineated above, their success would proliferate throughout the aerospace industry as a common benefit to result in more economical, lighter, stronger and safer aircrafts. However, this success has been partly inhibited by a lack of understanding of the fundamental behavior of these materials at multiple length scales (e.g. nano-, submicron-, and macro-scales) under complex loading and severe environmental conditions. This lack of understanding is further exacerbated by the highly heterogeneous and locally anisotropic character of some of these materials, e.g. composites, on distribution of stresses and strains, as well as their failure mechanisms. Fundamental understandings of material behavior and failure can enable efficient design of lower cost, safer and more robust aerospace structures. On the other hand, inadequate understanding of failure mechanisms in these materials – usually obscured by the difficulty of visualizing damage evolution and presence of multiple interacting failure mechanisms – is yet another stumbling block for their use in critical aerospace applications. Many studies [14–21] have been performed to identify and understand the complex failure mechanisms in heterogeneous materials and to propose solutions to improve their resistance against failure. However, further understanding of the micromechanics of damage and failure processes in these materials under applied load will not only make these materials more useful but also will contribute to an improvement in safety and design of engineering components made from them. More importantly, as materials complexity evolves to meet the extreme challenges of their environments, it is critical to characterize and understand their fundamental behavior.

In recent years, optical full-field strain-mapping techniques such as Digital Image Correlation (DIC) have increasingly been used in research and industry for in-situ displacement and strain measurements of a specimen subjected to external stimulus (mechanical, thermal, thermo-mechanical, etc.), enabling improved characterization of materials and components at various length scales [16,22–31]. DIC is a non-contacting technique for measurement of surface displacements of an object by tracking deformation of a speckle pattern through a series of digital images acquired during a test [32–34]. Displacements are

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obtained by imaging a speckle pattern on the material surface during a test and subsequently correlating each image of the deformed pattern to that in the un-deformed state. Strains are obtained by differentiating the displacement fields. The technique combines pixel level displacement accuracy with high spatial resolution, where strain gauges and extensometers lack the requisite resolution and fidelity. Due to the miniscule motions that are often of interest in engineering applications, the resolution requirements are much higher than those for most other applications. DIC has been performed with many types of object-based patterns, including lines, grids, dots and random speckle patterns [35], however, it is most common to employ stochastic patterns. In the past several years, two-dimensional DIC (2D-DIC) has undergone rapid growth worldwide [35]. However, as 2D-DIC uses predominantly in-plane displacements and strains, relatively small out-of-plane motions will change the magnification and may introduce errors in measured in-plane displacements [35]. As a result, three-dimensional DIC (3D-DIC) has been used for a wide range of applications and, hence, the present work is focused on 3D-DIC. Novak and Zok [23] demonstrated that DIC could be used when high thermal loads are present in a specimen. DIC is also suitable for studies spanning a large range of strain rates that typically span several orders of magnitude from creep [36–38] to shock and impact [39–41]. In principle, these attributes make DIC eminently suitable for probing strain distributions in various materials for a variety of testing conditions. However, to date, for the most part, DIC measurements have been focused on qualitative understanding of deformation and fracture rather than quantitative correlation with analyses. Despite numerous advantages DIC measurements offer, obtaining high-fidelity quantitative information from such measurements is still challenging, specifically when strain gradients and materials heterogeneities are present.

Design of high-fidelity DIC experiments is complex, because numerous pre- and post-testing parameters at various length scales must be selected simultaneously to achieve requisite fidelity. Some of these parameters must be chosen before an experiment commences and some can be selected after the experiment concludes [22]. Furthermore, some of these parameters are intimately related to the length-scales associated with the material and the structure under consideration. In addition, if the results from DIC are to be used for model calibration and/or validation, the parameters should be consistent with the length-scale resolved in the models. Material behavior at various length- and time-scales could potentially span multiple orders of magnitude thereby adding further challenges and complexity for a common framework for DIC measurements. Therefore, validated DIC methodologies are essential to apply this useful experimental method to various deformation, time and materials length scales, and for quantitative extraction of strains specifically in the presence of strain gradients and inhomogeneities. A robust DIC methodology can enable efficient design and validation of mechanics and manufacturing models.

In essence, various DIC parameters could be categorized as follows:

a) Optics and correlation: stochastic speckle pattern, hardware setup, camera noise and illumination conditions such as lighting, magnification, brightness, contrast, blurring, imaging system calibration, and correlation criteria
b) Post-processing: facet (or subset) size, facet step and filter size
c) Length scale: microstructure and continuum length-scales
d) Deformation gradients: gradients due to inherent heterogeneities e.g. in woven composites or those due to specific geometric and loading configurations in the structure

The reliability of DIC measurements depend on the knowledge of uncertainty and the sources of errors. There have been numerous studies in the literature where effect of one or more of these parameters on the fidelity of DIC results was examined: Siebert et al. [42] demonstrated the influence of different camera parameters on the DIC accuracy, uncertainty and errors. Triconnet et al. [26] proposed guidelines to choose correlation parameters as a function of various stochastic speckle patterns and studied their effect on the uncertainty of measured displacement and strain quantities. Tong [43] examined performance of various DIC criteria using several digital images with various characteristics and assessed relative robustness, computational cost, and reliability of each criterion for strain mapping applications. Bornert et al. [24] determined the performances of several image processing algorithms for displacement error assessment using various speckle patterns, where they used several DIC packages based on different formulations. Berfield et al. [25] demonstrated the feasibility of using DIC at micrometer and nanometer length-scales and showed that successful application of DIC required the ability to generate a speckle pattern at those scales. Yaofeng and Pang [27] investigated the effect of facet size and image quality on the accuracy of deformation measurements by DIC. They provided guidelines for sample preparation, estimation of displacement errors, and facet size normalization for DIC. Recently, in a comprehensive study, Rajan et al. [22] provided guidelines for selecting DIC test parameters to maximize the extent of correlation and to minimize errors in displacements and elastic strains using specimens with various geometric configurations. However, their work is restricted to purely elastic deformation and their guidelines do not take into account the inherent microstructural length-scales such as grain size and its relation with the DIC parameters. Furthermore, their guidelines do not explicitly account for the length-scale associated with the strain gradient. The present paper overcomes these limitations by accounting for both the microstructural and strain gradient length-scales. In addition, the methodology is applied and demonstrated for both the elastic and plastic deformation regimes.

The objectives of this work are to develop a methodology for high-fidelity full-field strain-mapping of elastic and plastic deformations of polycrystalline materials at macroscopic continuum length-scales subjected to quasi-static loading conditions and to validate the methodology by conducting DIC experiments and comparing the results against Finite Element Analysis (FEA). In Section 2 we outline the experimental procedure, while Section 3 is concerned with brief description of the FEA procedure used. In Section 4, we develop and outline a step-by-step methodology for obtaining high-fidelity quantitative strains from DIC measurements, which is demonstrated and validated in Section 5.

## 2. Experiments

Uniaxial tension tests were performed on 3 mm thick aluminum 6061-T6 specimens with and without an open-hole. The specimens were of 'dog-bone' geometry with a gauge length of 60 mm and width of 12.5 mm. The open-hole specimens had a central hole of 3 mm diameter. Two speckling techniques were used for the DIC experiments. In the first technique, the samples were initially sprayed with a flat white spray paint and subsequently sprayed using a spray canister with flat black spray paint (referred to as "spray" method hereafter). In the second technique an airbrush with black water-soluble paint was used (referred to as "airbrush" method hereafter). As will be discussed later, the two techniques result in very different speckle sizes. The speckle size distribution was determined using ImageJ software (US National Institutes of Health, Bethesda, MD, USA). The mechanical tensile tests were performed using an MTS servo-hydraulic test frame (MTS 810, Minneapolis, MN) at a displacement rate of 0.05 mm/s. Three-dimensional (3D) DIC was employed to monitor speckled face of