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Effective approaches towards microstructural strain mapping of AZ31B Mg sheet material using digital image correlation

Srinivasan Nagarajan[a,*], Mukesh K. Jain[a], David S. Wilkinson[b], Raja K. Mishra[c]

[a] Department of Mechanical Engineering, McMaster University, Hamilton - L8S 4L8, Ontario, Canada
[b] Department of Materials Science and Engineering, McMaster University, Hamilton - L8S 4L8, Ontario, Canada
[c] General Motors Research and Development Center, Warren - 48090-9055, Michigan, U.S.A

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ABSTRACT

A simple, fast, cost-effective and robust specimen surface patterning procedure based on chemical etching has been developed to obtain microstructural strain fields using digital image correlation (DIC) in AZ31B Mg alloy. Due to extensive changes in the microstructural features and surface roughening during deformation of Mg alloys, conventional DIC strain calculation can lead to erroneous results as well as loss of correlation (decorrelation) in local zones in the microstructural field. Therefore, an incremental DIC scheme has been explored in this study to map the full field microstructural strain distribution in AZ31B Mg sheet subjected to large tensile strains. It is shown that compared to conventional correlation, the incremental scheme maps microstructural strain fields with minimal decorrelation in localized zones up to large macroscopic plastic strains. The error and standard deviation in the microstructural strain calculated using conventional correlation follows a decreasing trend with increase in subset size, whereas those calculated by the incremental scheme are almost constant with subset size variation. The results suggest that for microstructural strain calculation requiring high spatial resolution (i.e. smaller subset size), incremental correlation yields better accuracy and precision than the conventional scheme irrespective of the magnitude of strain.

1. Introduction

Understanding the effect of material microstructure on the mechanical response can enable the development of improved plasticity models that incorporate the effect of local phenomena. Over the past two decades, DIC has emerged as a useful tool to study the microstructural strain evolution in materials [1–4]. DIC correlates the deformed image with the undeformed (or reference) image, based on the gray value matching of smaller regions of interest, so-called subsets, to obtain surface displacements and strains over the imaged region. As a precursor to DIC analysis, an artificial speckle (or random dot) pattern is applied to the specimen surface to achieve distributed gray values and enable subset matching. DIC, when applied to recorded high magnification microstructural images of a deforming specimen, provides micro-scale surface displacements and strains which are quite useful in understanding the ductile damage development [3] and the micromechanics of multi-phase materials [4]. Errors in the computation of displacement and strain using DIC are composed of two components, namely, systematic or mean bias error (i.e. accuracy) and random error or standard deviation error (i.e. precision) [5]. Systematic errors arise from the correlation algorithm (correlation criteria, interpolation scheme, and displacement shape function) and random errors stem from image noise varying primarily with the image quality (sharpness and contrast) [6]. Both these errors vary significantly with subset size, speckle size and lens distortions [7–8]. Of these, experimentally controlled factors are the image quality, speckle size and subset size. Smaller speckle size leads to selection of smaller subset sizes that improves the spatial resolution for displacement measurement. However, the speckle size must be large enough to generate a local contrast for the chosen magnification. If the density of the random dot pattern is lower, it restricts choosing smaller subsets to achieve high spatial resolution. The measurement resolution of DIC also depends on the density of the random dot pattern. The random dot pattern that covers 50% by area fraction of the image has been suggested for optimum measurement resolution [9]. The random dot feature must in general be oversampled covering about 15–20 pixels [10]. To assess the quality of the random dot patterned image, a parameter called mean intensity gradient which is closely related to systematic and random errors has been proposed [11], and given by

$$\delta_f = \sum_{i=1}^{W} \sum_{j=1}^{H} \left| \nabla f(x_{ij}) \right| / (W \times H) \tag{1}$$

Where W and H are the width and height of the image in pixels, $|\nabla f(x_{ij})| = \sqrt{f_x(x_{ij})^2 + f_y(x_{ij})^2}$ is the modulus of the local intensity gra-

* Corresponding author.
E-mail address: srini0497@gmail.com (S. Nagarajan).

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dient vector and $f_x(x_{ij})$, $f_y(x_{ij})$ are the intensity derivatives at pixel (x_{ij}) along x and y directions. A random dot pattern with large mean intensity gradient will lead to small displacement measurement errors. The bit depth of the image also influences the standard deviation of errors in displacement measurement. It has been reported that with decreasing bit depth, standard deviation of errors in the displacement measurement increases [12]. In other words, precision decreases with decreasing bit depth. The subset size should be such that it at least encompasses 3 to 6 random dots. Increasing the subset size yields higher strain measurement accuracy, but reduces spatial resolution. Accuracy and spatial resolution are competing factors in DIC for homogeneous strain measurements [7]. In the case of heterogeneous strains, there is an upper limit for subset size, since too large a value may lead to an incorrect approximation of the underlying deformation by the displacement function defined in the algorithm, resulting in high systematic error [13]. The uncertainty in strain measurement using DIC is also reported to depend on the magnitude of deformation [13]. At the microstructural scale, the measurement accuracy of DIC applied to scanning electron micrographs are degraded by inherent image distortions such as spatial and drift distortions [14,15]. Spatial distortions are due to interference of electron optics by the stray electric fields while drift distortions are associated with the raster scanning of the electron beam while recording the image. On the other hand, errors due to image distortions based on measurements from optical microscopes are considerably less and negligible [1].

Various speckle patterning methods such as thin film patterning by chemical vapor deposition [16], photolithography [16], electron beam lithography [17], template patterning [18], focused ion beam milling [19] and nano particles drop casting/self assembly [20,21] have been employed in the past to map the micro-scale strain gradients via DIC. A surface patterning method by microparticle adsorption for high temperature microscopic displacement and strain measurements has also been proposed [22] and reported suitable for macroscopic measurements as well [23]. However, many of these techniques are expensive, time consuming and involve elaborate patterning procedures that often require specialized equipment. Also, the pattern (particularly with micro-grids and thin films) deposited on the microstructure may conceal any evolving microstructural features such as slip lines or twins. In addition, such patterns can get degraded and sometimes loose adherence to the materials' surface during deformation, making them inappropriate for measuring large plastic strains. The quest for a simple, fast, and cost-effective microscale patterning method has led to the development of patterning by chemical etching for microscale DIC studies [24,25]. Etchants such as a solution of Fe (III) chloride + HCl [24] and Keller's reagent [25] have been used in the past to generate a random dot pattern on copper and aluminum samples respectively. However, this approach has not been explored effectively for quantitative analysis of the inter- and intra-granular strain gradients in a microstructural field.

Apart from achieving high contrast patterns, DIC strain mapping with minimum error and decorrelation at large strain has been yet another key challenge. It is reported that the accuracy and precision of strain measurement by DIC in heterogeneous strain states are relatively low [13]. Decorrelation during microscale strain mapping using DIC occurs due to the evolution of new microstructural features such as slip lines, twins, and surface steps etc. This is because, these new features alter the gray values of the subsets in the deformed image, thereby diminishing the possibility of tracking them by subset matching. In a recent study on pure magnesium, decorrelation is reported to degrade the microstructural strain field obtained using DIC at a macroscopic plastic strain of just 0.025 during tensile deformation [26]. These problems can be minimized with the so-called incremental DIC method. In conventional DIC analysis, each image is correlated to the reference (undeformed) image. However, in the incremental DIC scheme, each image is correlated with its previous image to track the subset displacements [27]. In other words, every image is used as an updated reference image to the successive image with continuous tracking of displacement of subsets in the first reference image to obtain the total strain. For materials such as rubbers, polymer foams and soft tissues, which exhibit large deformations (viscoelastic strains typically greater than unity) leading to enormous changes in the macroscopic surface features, incremental correlation has been found useful in calculating strain fields [28]. However, the systematic error in the incremental DIC method is larger than with the conventional method. This is because the location of the subset centers in every new reference image (which actually are deformed subsets) may be in the non-integer pixel position and that calls for interpolation of gray values, thereby introducing additional systematic errors in the measured displacements [29]. An attempt was made in the past to obtain strain increments between two micrographs of successive loading steps by the conventional approach (so called step-by-step correlation) [30]. Such approaches involve assigning new subsets (in integer pixel position) for every new reference image which in reality has deformed subsets of the undeformed image. However, the incremental DIC method is different as it involves tracking the displacement of subsets of the undeformed image in all of the deformed images to map the total strain evolution. It should be noted that while incremental DIC has been occasionally applied in the past [31] to investigate the microstructural strain distribution, it has not been critically assessed for its accuracy and resolution towards microstructural strain measurement.

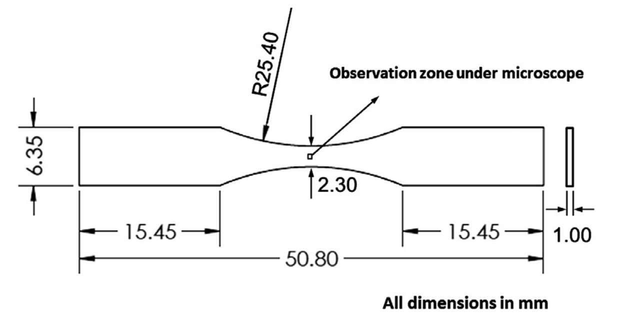

Fig. 1. Schematic illustration of specimen dimension.

In this paper, we propose a chemical etching based random dot patterning procedure for microstructural strain mapping using DIC in AZ31B Mg sheet material with a wide range of grain sizes. The incremental DIC scheme is then explored to calculate the microstructural strain in specimens that was subjected to in-situ uniaxial tensile loading under optical microscope up to large plastic strains. The effect of subset size and the magnitude of strain on the accuracy and precision (standard deviation of errors in measurement) of microstructural strain measurement by conventional and incremental correlation methods are critically investigated.

2. Material and methods

Hourglass-shaped tensile specimens with a cross-sectional area of 2.3 mm^2 in the minimum width region were machined from AZ31B Mg sheet (see Fig. 1). The hourglass shape helped to localize strain in the minimum width region (region of observation) and study the effectiveness of both the DIC methods in computing strain fields at large strains (in terms of decorrelation, accuracy, and precision). Specimens were then heat treated at 450 °C for 7 h and 550 °C for 48 h under an argon atmosphere to achieve an average grain size of 16 µm and 73 µm respectively. They were then ground, polished and etched with picral solution to reveal grain boundaries. Subsequently, specimens were etched with aqueous zinc sulfate solution to initiate the redox reaction

$$Mg(s)+ZnSO_4(aq) \rightarrow MgSO_4(aq)+Zn(s);$$

$$Mg - 2e^- \rightarrow Mg^{2+} \text{ (oxidation) // } Zn^{2+}+2e^- \rightarrow Zn \text{ (reduction)}.$$