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Thermo-mechanical toner transfer for high-quality digital image correlation speckle patterns

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ABSTRACT

The accuracy and spatial resolution of full-field deformation measurements performed through digital image correlation are greatly affected by the frequency content of the speckle pattern, which can be effectively controlled using particles with well-defined and consistent shape, size and spacing. This paper introduces a novel toner-transfer technique to impress a well-defined and repeatable speckle pattern on plane and curved surfaces of metallic and cement composite specimens. The speckle pattern is numerically designed, printed on paper using a standard laser printer, and transferred onto the measurement surface via a thermo-mechanical process. The tuning procedure to compensate for the difference between designed and toner-transferred actual speckle size is presented. Based on this evidence, the applicability of the technique is discussed with respect to surface material, dimensions and geometry. Proof of concept of the proposed toner-transfer technique is then demonstrated for the case of a quenched and partitioned welded steel plate subjected to uniaxial tensile loading, and for an aluminum plate exposed to temperatures up to 70% of the melting point of aluminum and past the melting point of typical printer toner powder.

1. Introduction

The surface of a specimen must provide sufficient variation in contrast to ensure that the full-field displacements measured using digital image correlation (DIC) [1,2] are accurate. Typically an artificial speckles are applied to a surface to obtain a high contrast random pattern. Recent studies have shown that the frequency content of the speckle pattern affects the accuracy [3–9] and spatial resolution [10,11] of DIC measurements for a given test setup and equipment. While there are no general mathematical formulations to define effective speckle patterns, extensive research has highlighted salient characteristics. For example, an average speckle diameter of a few pixels is required to minimize aliasing effects in the correlation analysis, while ensuring good spatial resolution (e.g., sampling of each feature by at least 3×3 pixels [1] or by 2×2 to 5×5 pixels [5]). Lecompte et al. [4] presented a quantitative evaluation of DIC measurement accuracy with respect to mean speckle size and subset dimension, highlighting the importance of selecting suitable combinations of speckle and subset size, while tailoring the subset size to the expected deformation field. Pan et al. [7] examined different speckle patterns with respect to measurement accuracy (bias error) and precision (standard deviation error). Lecompte et al. [6] investigated the effect of the speckle-to-surface area ratio (coverage factor) and, for a 15×15 pixel subset, demonstrated that the optimal speckle size is 5×5 pixels and the optimal coverage lies between 40% and 70%. Pan et al. [3] proposed an alternative approach where the average pattern gradient is related to both bias and standard deviation of the error, in agreement with Wang et al. [12].

Depending on the surface material and specimen size, different patterning methods may be required. In many cases, it is challenging to implement the practical recommendations reported in the literature to create effective speckle patterns. Spray painting using airbrushes is the most common technique for specimen sizes in the range ~1 mm to ~100 mm (e.g., [1,13,14]). In fact, speckle size can be controlled in a simple and practicable fashion through a combination of ink viscosity, nozzle size and spray distance, while the density of speckles can be adjusted based on spraying time. However, for specific applications (e.g., on relatively large regions of interest as in the examples in Fig. 1 [15,16]), the need to create speckle patterns with particles having well-defined and consistent shape, size and spacing (e.g., [9,17]) has prompted the

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development and implementation of other suitable techniques. For example, Helm [18] used a stamp made from a steel plate covered with a pattern of felt disks to create speckles with a diameter of approximately 10 mm on the $2.1 \times 2.1\ m^2$ surface of a reinforced concrete slab. Ghorbani et al. [15] used flexible polymer stencils to spray paint numerically-designed speckle patterns on the surface of full-scale concrete and masonry walls. Here, the use of relatively large speckles, for which spray painting is impractical, becomes necessary to ensure a suitable balance between measurement accuracy and spatial resolution, enabling the identification of faithful crack maps at any given loading stage [15]. For the case of smaller regions of interest, El-Hajjar and Petersen [19] demonstrated the use of laser-printed adhesive polyvinyl chloride coatings on fiber-reinforced polymer coupons, and applications based on stamping [20,21] and other techniques [22,23] have been reported.

This paper introduces a novel technique to create speckle patterns for DIC measurements by means of a thermo-mechanical process where melted toner is transferred from printed paper onto the measurement surface. The proposed technique, which is widely exploited in the manufacturing process for low-cost electronic printed circuit boards, enables the creation of patterns with consistent speckle size and density in a repeatable, simple, rapid and inexpensive fashion. First, the procedure is presented in detail. Then, the tuning and quantitative quality assessment of the resulting speckle patterns are discussed, together with the applicability to different materials and surfaces. Finally, proof of concept is demonstrated for (a) a welded steel plate subjected to uniaxial tensile loading, and (b) an aluminum plate exposed to different temperatures up to 451 °C, i.e., relatively high temperatures for which specialized patterning techniques need to be enlisted (e.g., [24]).

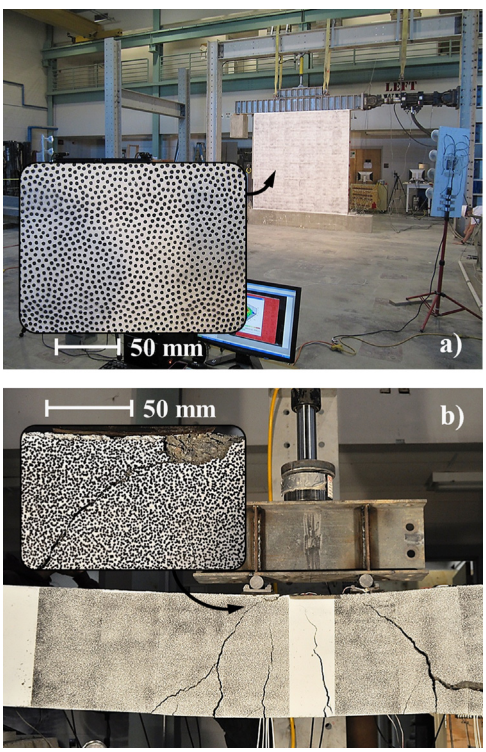

Fig. 1. Numerically-designed speckle pattern on large-scale concrete specimens: (a) $2.4 \times 2.5\ m^2$ concrete masonry wall surface [15]; and (b) 330 mm deep reinforced concrete beam [16].

2. Methodology

The desired speckle pattern is numerically designed, printed on paper using a conventional laser printer, and then thermo-mechanically transferred onto the measurement surface. These three steps are detailed as follows.

2.1. Speckle pattern design

Circular speckles are used to minimize local features associated with preferential directions. An ordinate grid of speckles with a given diameter and on-center spacing is numerically generated (Fig. 2a). The ordinate grid is then perturbed by adding to the horizontal and vertical coordinates of each speckle a random amount of noise, which is extracted from a normal distribution. The resulting patterns (Fig. 2b) are approximately spatially isotropic for the subset sizes used in the proof-of-concept experiments presented herein (i.e., 21×21 pixels and 41×41 pixels). The strategy of perturbing an ordinate grid instead of randomly positioning the speckles on a given surface area aims at providing a more homogeneous speckle distribution. In the examples presented in this paper, a 4.5 pixel speckle diameter is used as it lies in the desirable range of 2–5 pixels [5]. The original on-center spacing of the speckles in the ordinate grid is 6 pixels (Fig. 2a). The horizontal and vertical coordinates of each speckle are then perturbed by adding random values in the range ± 2.5 pixels (Fig. 2b). The resulting coverage factor is 42%, which lies in the recommended range of 40–70% [6].

Dark speckles on a light background without intermediate gray levels are used to maximize contrast and thus measurement signal-to-noise ratio. It is noted that this does not imply a binary color distribution in the image acquired by the camera as the filtering of the camera optics softens the dark-to-light transition, resulting in a blurring of the speckle edges (Fig. 2c).

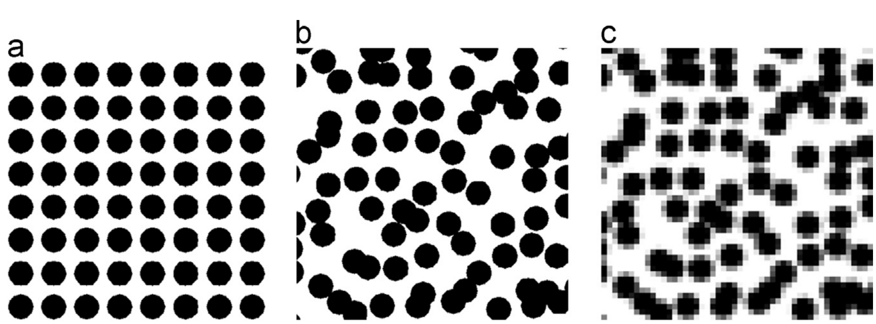

Fig. 2. Design of speckle pattern: (a) original ordinate grid; (b) random pattern; and (c) downsampled random pattern representative of pattern framed by camera.