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Stamps for pattern applications for DIC or markers tracking

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Abstract

Digital image correlation requires a surface pattern to monitor deformation, and while spray paint is widely used for this purpose, it suffers from drawbacks such as limited reproducibility and poor control over speckle characteristics. This study aims to develop stamps to apply patterns with greater consistency and control, and to demonstrate that such pattern speckle performs comparably to traditional spray paint speckle. For that purpose, speckles were applied to polymer surfaces using two techniques, ink stamping of circular dots and conventional spray painting. Their quality was first evaluated through numerical assessments, followed by digital image correlation analyses under both small and large strains. Small-strain behavior was studied using synthetically deformed images based on sinusoidal displacements, while large-strain performance was assessed via uniaxial stretching of a holed elastomer sample. Both speckle application methods yielded similar results in terms of image correlation accuracy and robustness across deformation scales proving that the produced stamps offer a viable alternative to spray paint, providing significant advantages in terms of control, reproducibility, and customizability of the speckle pattern, without compromising performance.

Keywords: Pattern, Stamp, Marker tracking, DIC

1 Introduction

Digital Image Correlation (DIC) is a powerful technique for measuring heterogeneous strain fields during deformation and is now widely used in both academic research

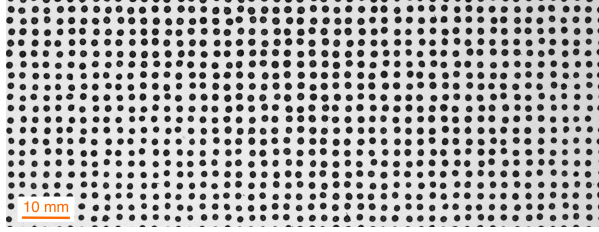


Fig. 1 Pattern produced using Correlated Solutions stamps, which offer the finest commercially available markers, though with low speckle density.

and industrial applications for material and structural testing. The method relies on tracking a natural or synthetic surface pattern by comparing a reference image to a deformed one to compute displacements, from which strain is derived. The accuracy of DIC measurements depends heavily on the quality of the recorded digital images, which is influenced by factors such as pattern quality, lighting conditions, camera and optics settings, and specimen alignment.

In the context of material characterization, most mechanical tests involving DIC are performed with synthetic patterns created using spray paint. This method is inexpensive and appears easy to apply, which explains its widespread use in mechanical testing laboratories. However, experienced users are well aware of the challenges: spray-painted speckles are highly user-dependent, difficult to control, and often require multiple attempts to avoid defects such as oversized spots in critical measurement areas. These limitations affect pattern consistency and introduce variability between tests. While airbrushing can produce finer and more uniform speckles, as noted by Dong and Pan in their review on speckle pattern fabrication [?], this technique is no simpler. Parameters such as nozzle diameter, spray distance, air pressure, and paint viscosity all significantly influence the outcome.

In recent years, other approaches to pattern generation have emerged with differing objectives. Academic efforts have often focused on optimizing speckle patterns for correlation performance, without particular concern for application difficulty or cost (see [?] and references within). In contrast, commercial solutions prioritize ease of use, offering tools such as stamps or rollers designed to quickly apply acceptable patterns and minimize errors associated with poor speckle quality. Examples include the 1.1 mm speckle stamp from Imetrum and the roller-based systems from Correlated Solutions and Dantec Dynamics, which produce speckles ranging from $180\mu\text{m}$ to 5.08mm in diameter. However, we identify two main reasons why stamping has seen limited adoption in practice. First, achieving high-quality patterns with commercial stamps remains difficult, either due to sub-optimal applicator design or poor pattern characteristics, for instance, the low dot density of Correlated Solutions' $180\mu\text{m}$ stamp (Figure 1). Second, stamped speckle patterns have not been systematically benchmarked against traditional spray-painted patterns, leaving their actual performance in DIC applications largely unvalidated.

To address these limitations, we developed silicone stamps specifically designed for laboratory use in mechanical testing. These stamps are capable of applying dense, circular ink spots quickly and reproducibly, even on non-flat surfaces, offering a practical and controlled alternative to traditional spray-painted speckles. To demonstrate the interest of the stamping approach, we compared stamp-generated and spray-painted speckles across three levels of evaluation: (1) a speckle pattern quality assessment, (2) response under digitally applied small strains using DIC Challenge 2.0 displacements, and (3) response under large strains in an experimental test on a rubber specimen. These comparisons aim to validate stamping as a convenient, repeatable, and accurate method for speckle generation in a wide range of DIC applications.

2 Stamp Pattern

2.1 Stamp and application

Patent-pending molds have been developed to produce silicone stamps with precisely controlled surface patterns (Figure 2). The process is similar to recent efforts to make inexpensive multifluidic silicone stamps [?], and relies on vat photo-polymerization to produce the cast mold. This method is particularly attractive due to its low cost, high-quality printers are available for under \$1000, and its unmatched resolution among 3D printing technologies. The stamps, called Microstamp, are designed for effortless ink transfer onto both flat and curved surfaces, making them ideal for marking samples for Digital Image Correlation (DIC) or particle tracking. Section A describes the fabrication and application process step by step. The surface patterns primarily consist of randomly distributed circular pillars. Their size, shape, and density can be customized to meet specific application requirements. Currently, the smallest achievable pillar radius is 90 microns, and the maximum pattern density reaches 45%. In addition to random patterns, other designs such as checkerboard, grid, and Turing structures, have also been successfully fabricated. Figure 2 shows some example of patterns inked on a polymer surface. Additionally, the inclusion of recognizable reference elements is possible, offering an advantage for quantitative comparisons between experimental measurements and simulations.

The primary goal of these stamps is to serve as an alternative to spray paint, for the application of speckles on samples that are to be mechanically tested. By providing precise control over speckle characteristics, they ensure consistency and repeatability in experimental measurements. In the following sections, we have studied Microstamp performance for DIC analyses in comparison with a spray paint speckle.

2.2 Speckle quality assessment

In the characterization of speckle patterns, factors such as size, contrast, contrast gradient, and density play a crucial role. The optimal speckle size ranges between 3 and 5 pixels to prevent aliasing [?], while the gap between individual speckles should cover at least 3 pixels [?]. Regarding density, the ideal target window ranges between 35% and 55% [?].

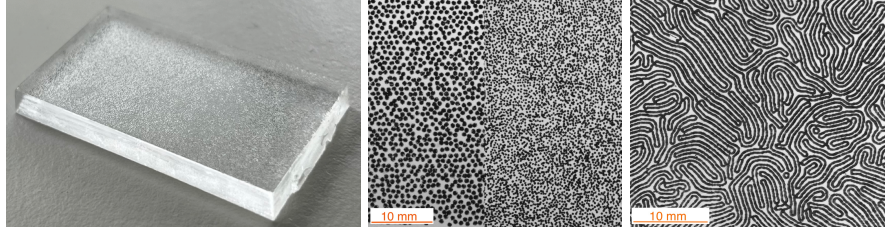


Fig. 2 Left: Silicone stamp for pattern application, Middle: ink stamped dots, Right: ink stamped Turing pattern.

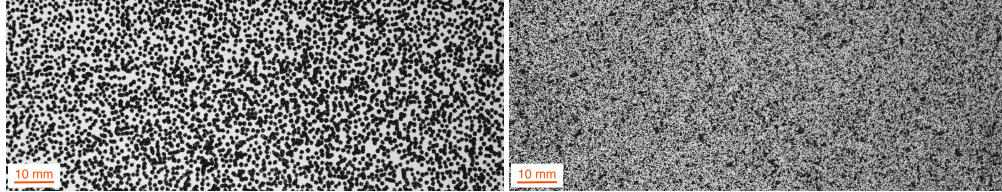


Fig. 3 Microstamp and spray paint speckles applied on a polymer plate used for speckle analysis and digital deformation.

Speckle quality is typically assessed through the autocorrelation function, as well as the mean bias error and standard deviation for subpixel displacements. To evaluate these properties, we prepared two types of speckles: one by applying an inked stamp and another one by spraying black paint. Images of the speckles were taken with a 5120×3840 pixels JAI SP 20000 camera equipped with a telecentric lens magnification 0.245 of working distance 405 mm, giving a resolution of 26.12 microns/pixel. This will be applied for the rest of the study.

Figure 3 shows images of both speckles applied on white painted polymer plates. The plates were securely positioned in grips, ensuring that the camera, optics, and lighting conditions remained consistent.

First, the gray-level distributions of both images are displayed in Figure 4 showing significant differences and highlighting the strong contrast between the white background and black marks for Microstamp speckle. Then, the images were analyzed using the autocorrelation function, which exhibits in both cases a sharp peak (Figure 5). To estimate the mean speckle size, we calculated the autocorrelation radius, defined as the half-width at half-height of the autocorrelation function peak [?]. The measured values were 4 pixels in both the X and Y directions for the Microstamp pattern, and 2 and 3 pixels in the X and Y directions for the spray paint speckle. Microstamp has the advantage of providing the same result in every direction.

Next, the images were subjected to a series of uniform horizontal displacements, $u_{applied}$, ranging from 0.05 pixels up to 1 pixel. The displacements were analyzed using Digital Image Correlation (DIC) to evaluate the mean bias error, defined as $\bar{u} - u_{applied}$, where \bar{u} is the mean displacement measured by DIC. The standard deviation was

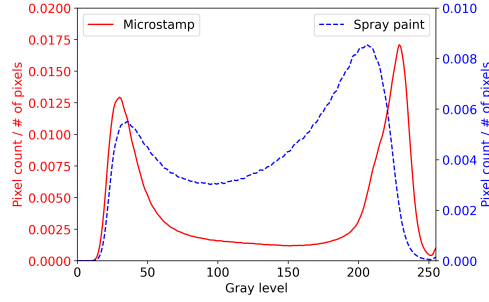


Fig. 4 Gray-level distribution of images Figure 3.

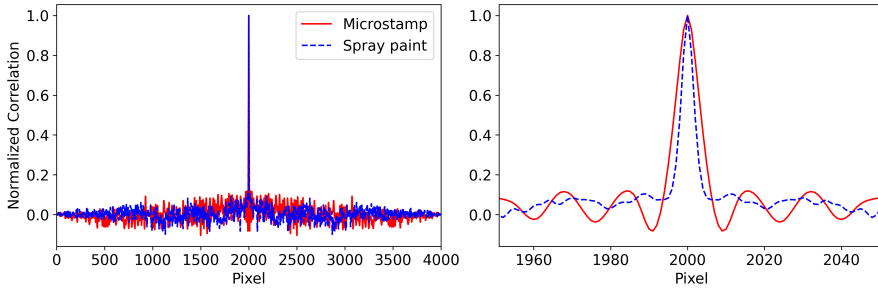


Fig. 5 Comparison of the autocorrelation functions for Microstamp and spray paint speckles, calculated from the images in Figure 3. Right image is a close up at the peak.

computed as $\sqrt{\frac{1}{N-1} \sum_{i=1}^N (u_i - \bar{u})^2}$. Figure 6 presents these quantities as a function of the applied subpixel displacement. Microstamp pattern exhibits a lower mean bias error but larger dispersion in the obtained values. We will discuss later the impact of these differences. Finally, the influence of image noise was assessed by adding Gaussian noise with standard deviations of 2, 5, 10, 20, and 30 gray levels to the image that exhibited the largest mean bias error in Figure 6. For each noise level, ten noisy images were generated. The corresponding average mean bias error and its standard deviation, normalized by the value obtained without noise, are plotted in Figure 7 as a function of the noise amplitude for both speckle types. It can be observed that the speckle obtained with spray paint is less sensitive to noise.

Several authors [?] have proposed global image-based quality metrics that avoid the need to deform images or run full DIC analyses. Among them, the Mean Intensity Gradient (MIG), introduced by [?], is one of the most widely used. It quantifies the average intensity gradient across the entire reference image as an indicator of speckle pattern quality. The calculated MIG values for the Microstamp and spray-painted speckle patterns were 27.65 and 30.96, respectively, favoring the spray paint. However, according to [?], a higher MIG should correspond to a lower mean bias error in DIC results, something not observed in our case. This discrepancy

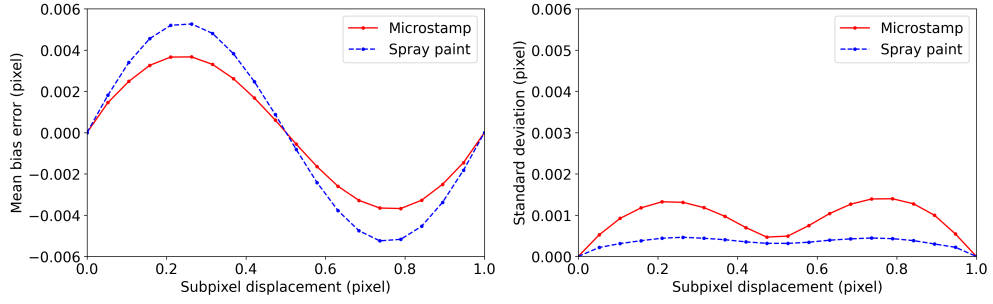


Fig. 6 Mean bias error and its standard deviation with respect to the applied subpixel uniform horizontal displacement.

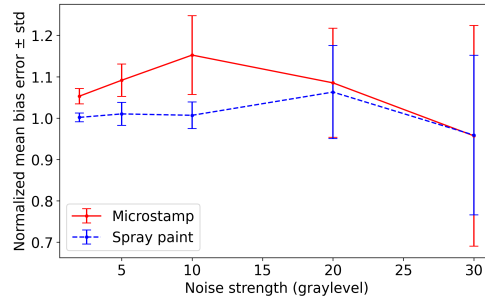


Fig. 7 Normalized mean bias error as a function of Gaussian noise level for both speckle patterns, evaluated on the image with uniform horizontal displacement that produced the largest mean bias error in Figure 6.

suggests that the MIG value alone may not be a reliable predictor of measurement quality in all situations.

In the next section, we compare the performances of both speckles for DIC analyses involving infinitesimal and large strains.

3 Benchmarking Microstamp

We conducted two types of tests to evaluate the performance of the speckle patterns. First, we applied numerically small vertical sinusoidal displacements, as introduced in the DIC Challenge 2.0 [?], to both reference images. Second, we marked holed specimens of styrene-butadiene rubber with each speckle pattern, subjected them to large uniaxial tensile strains, and compared the resulting local strain measurements. All DIC analyses were performed using open source 2D digital image analysis software NCORR [?]. Note that the software has been satisfactorily evaluated according to the procedure [?].

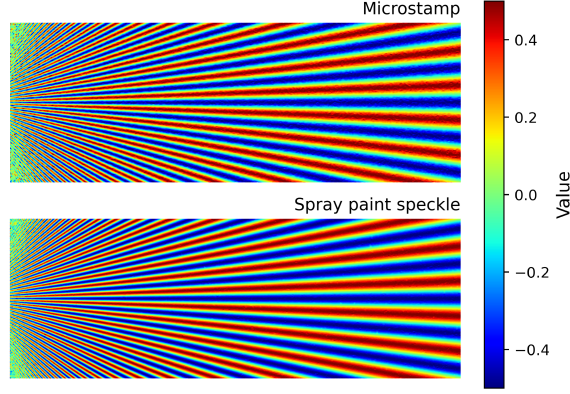


Fig. 8 Qualitative comparisons of the estimated displacements by DIC analyses with subset radius of 10 pixels.

3.1 DIC challenge

Both images in Figure 3, each with a resolution of 5000×1901 pixels, were subjected to a synthetic vertical displacement field defined as,

$$u_y(x, y) = 0.5 \times \sin\left(\frac{\pi}{2} + 2\pi \frac{y - (1901/2)}{\lambda(x)}\right), \quad \lambda(x) = 25 + x \frac{355}{5000}. \quad (1)$$

First DIC analyses were performed between the reference and deformed images using different subset radii from 10 to 30 pixels for both speckles and found an optimal value for 10 pixels which is the minimum subset size allowed by NCORR. Actually, the estimated mean speckle sizes in the previous section, are in favor for an optimal subset radius of about 10 pixels for the spray-paint speckle but not for Microstamp which should require a value of at least 15 pixels in order to contain a minimum of three spots. However, the difference of results register between subset radii of 10 and 15 pixels was not significant in the case of small strain and therefore results were compared using the same subset size for both speckles.

Both patterns produced consistent results as displayed in Figure 8: accuracy is poor when the sinusoidal period is short, but improves significantly as the period increases. This outcome was expected, as it is well known that DIC accuracy deteriorates when the displacement wavelength is smaller than the subset size. A quantitative impact of the subset radius may be found in Appendix ??.

Figure 9 presents the DIC estimates of the vertical displacement u_y at several locations in the deformed images in comparison with the applied displacement. Results provided by the spray-painted speckle are smoother probably reflecting the larger standard deviation recorded in Figure 6. However, Microstamp is also in good agreement with the applied displacement.

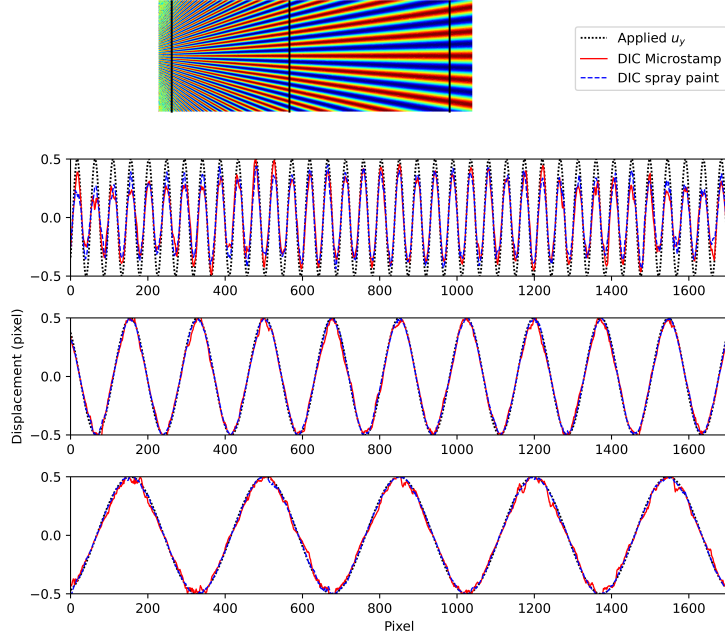


Fig. 9 Quantitative comparisons of the estimated displacements by DIC analyses along black lines from left to right corresponding to results from top to bottom. Subset size is 10 pixels.

3.2 Large strain test on a rubber sample

Two circular holes, each with a diameter of 5 mm, were punched into a rectangular sample of styrene-butadiene rubber to induce strain heterogeneity during uniaxial stretching (Figure 10). The specimen was pre-stretched to 100% strain and reused twice to compare strain measurements obtained with both speckle patterns. The latter were applied over a white paint layer, and tests were conducted shortly after application to prevent paint cracking. For reference, the sample's stress–stretch response is shown in Figure 10.

Best DIC analyses were obtained using a subset radius of $R = 12$ pixels for the spray-painted pattern and $R = 16$ pixels for the Microstamp pattern. These values are in line with the speckle size defined by the auto-correlation function. Figure 11 presents qualitative comparisons of longitudinal, transverse and shear strains at 100% stretch, shown in the deformed configuration. It is worth noting that NCORR outputs Euler–Almansi strain \mathbf{e} in the deformed configuration and Green–Lagrange strain \mathbf{E} in the reference configuration. Using identical color scales, the two strain maps appear very similar, indicating that Microstamp performs comparably to the spray-painted speckle.

For quantitative comparisons, strain values were extracted along a vertical and a longitudinal line intersecting at the center of the specimen in the reference configuration. As shown in Figure 12, both speckles yield similar strain values, further

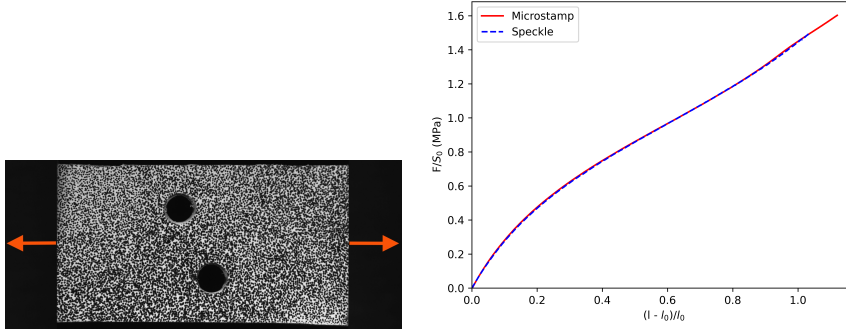


Fig. 10 Styrene butadiene holed specimen submitted to uniaxial tension and its stress-stretch responses recorded during tests.

confirming that the Microstamp speckle is on par with a well done spray paint speckle. Note that the choice of a smaller subset radius does not modify the averaged result but increase the noise around it. Additional comparisons along another set of lines are displayed in Appendix ??.

We have demonstrated that silicone stamps can be used to apply ink-based patterns that are sufficiently fine and dense to yield DIC results comparable to those obtained with high-quality spray-painted speckles. Since stamps work exclusively with ink, they are not suitable for high-temperature tests, where specific high-temperature paints, though often difficult to apply, may still be viable. On the other hand, stamps require no special skill for proper use, provided that a well-designed applicator is available, making them a convenient alternative to spray paint. They can be applied to both flat and curved surfaces, as long as the surface roughness remains low. However, significant surface rugosity also presents challenges for spray-paint speckles, as it creates shadows on the recorded images which locations may change under mechanical loading. Finally, as illustrated in Figure 2, stamp-applied patterns are not limited to random spots and could, in the future, be optimized for specific DIC applications.

4 Conclusion

Spray-painted speckles are widely used in DIC but are notoriously cumbersome and highly user-dependent. It is common for the speckle to require multiple attempts due to defects such as oversized spots in the measurement area. To address these limitations, we propose the use of ink stamps that can produce dense fine circular speckle patterns over a surface. Compared with existing commercial stamps, the new stamps presented in this work are easy and inexpensive to fabricate within a laboratory environment. They offer users a high degree of versatility in pattern design, enabling marker densities and spatial resolutions that, to our knowledge, have not yet been achieved with other available solutions.

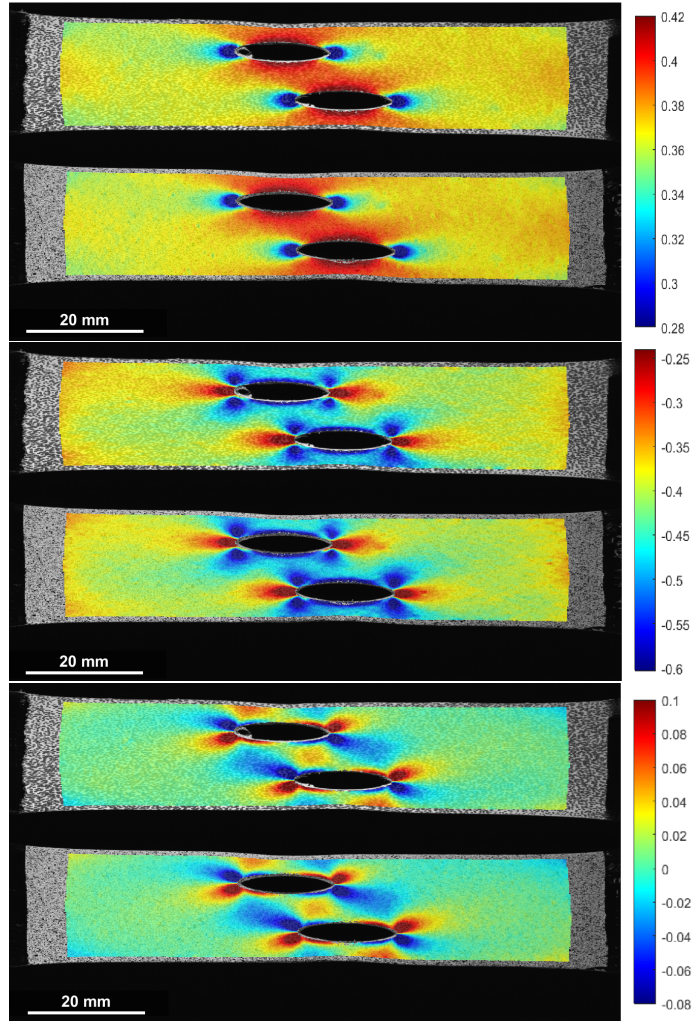


Fig. 11 Qualitative comparisons of the strain fields, e_{xx} , e_{yy} and e_{xy} from top to bottom, obtained with Microstamp and spray paint speckles when the samples are submitted to 100% macroscopic stretch in the longitudinal (x) direction.

To evaluate their performance, the stamp-generated speckles were benchmarked against traditional spray paint patterns under both small and large strain conditions. The first benchmark involved numerically deformed images based on the DIC Challenge 2.0, while the second involved an experimental large-strain test on a holed elastomer sample. In both scenarios, the strain fields obtained using the stamp were in excellent agreement with those from the spray-painted speckle.

While a well-made spray paint speckle pattern appeared to lead to slightly smoother displacement fields, the stamping method offers key advantages: it is fast,

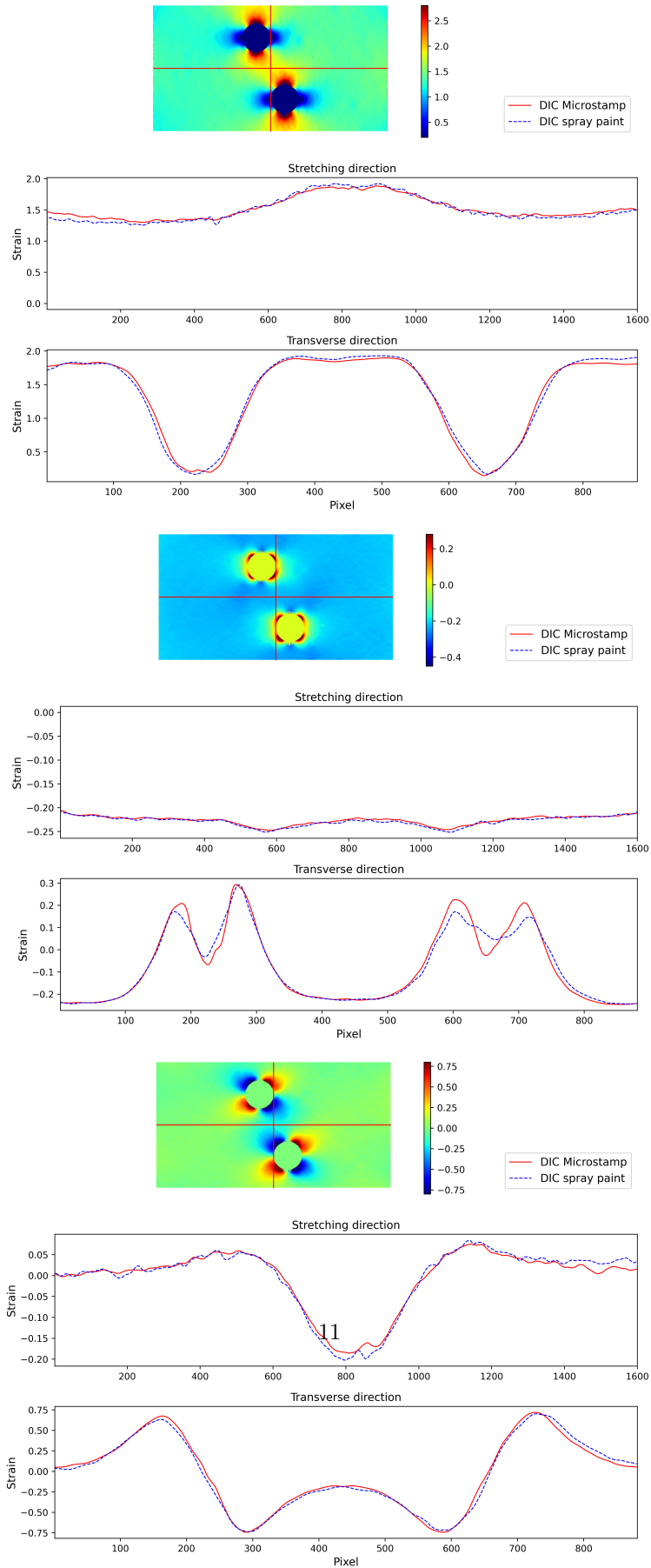


Fig. 12 Quantitative comparisons of the strain fields, E_{xx} , E_{yy} and E_{xy} from top to bottom, along the drawn lines, obtained for the analyses shown in Figure 11.

reproducible, and largely independent of user skill. Additionally, stamps with customized pattern size, shape, and spatial density gradients can be easily fabricated, opening new possibilities for tailored testing applications.

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Conflict of interests. On behalf of all authors, the corresponding author states that there is no conflict of interest.

Appendix A Stamp fabrication and application

The fabrication and application of the stamps are described step by step below.

1. A text file specifying the positions of the dot centers is generated. The initial grid of points is incrementally perturbed to introduce a controlled degree of randomness.
2. The mold is created using Gmsh [?]. Cylindrical holes are extruded from a rectangular box to form the desired pattern. The corresponding `.geo` file is then meshed and exported as an `.stl` file. When the number of holes exceeds approximately 20,000, it is recommended to generate the geometry incrementally by adding holes in batches to reduce computation time and file size.

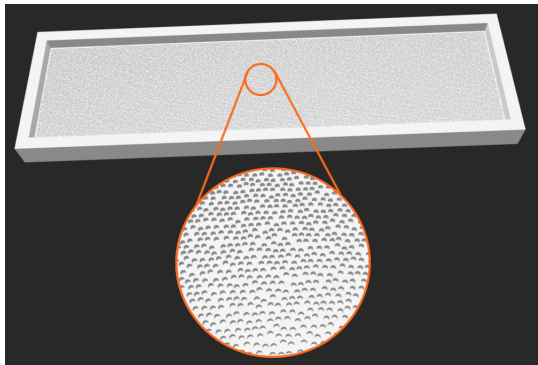


Fig. A1 Example of an STL file generated from the Gmsh geometry.

3. The `.stl` file is sliced in Chitubox to produce a `.ctb` file compatible with the 3D printer. The molds were printed using a Phrozen Mini 8K printer with standard AquaGray 8K resin.
4. A generic silicone used for dental molding is prepared by mixing, degassing, and then pouring it into the printed mold.
5. After curing, the stamp is positioned on a roll applicator specifically designed to ensure uniform application of the pattern on flat surfaces.

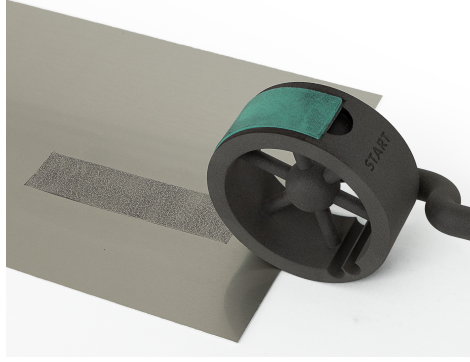


Fig. A2 Roll applicator used to apply the pattern evenly onto a flat surface.

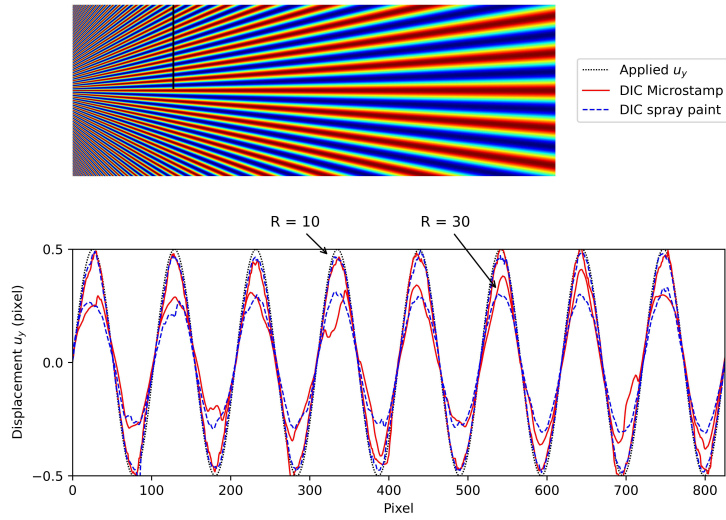


Fig. B3 Quantitative comparisons of the displacement u_y along the black line estimated by DIC analyses for subset radii 10 and 30 pixels.

Appendix B Impact of DIC subset size on small strain analyses

Figure ?? shows a quantitative evaluation of the impact of the subset radius for both speckles for DIC analyses with NCORR on images Figure 3 deformed by Equation (1) by plotting the displacement u_y recorded along the black line.

Appendix C Supplemental results at large strain

To complement the large strain analysis, further comparisons were performed at multiple locations across the specimen's surface. As illustrated in Figure ??, both speckles again led to comparable strain fields, reinforcing their equivalence for DIC applications.

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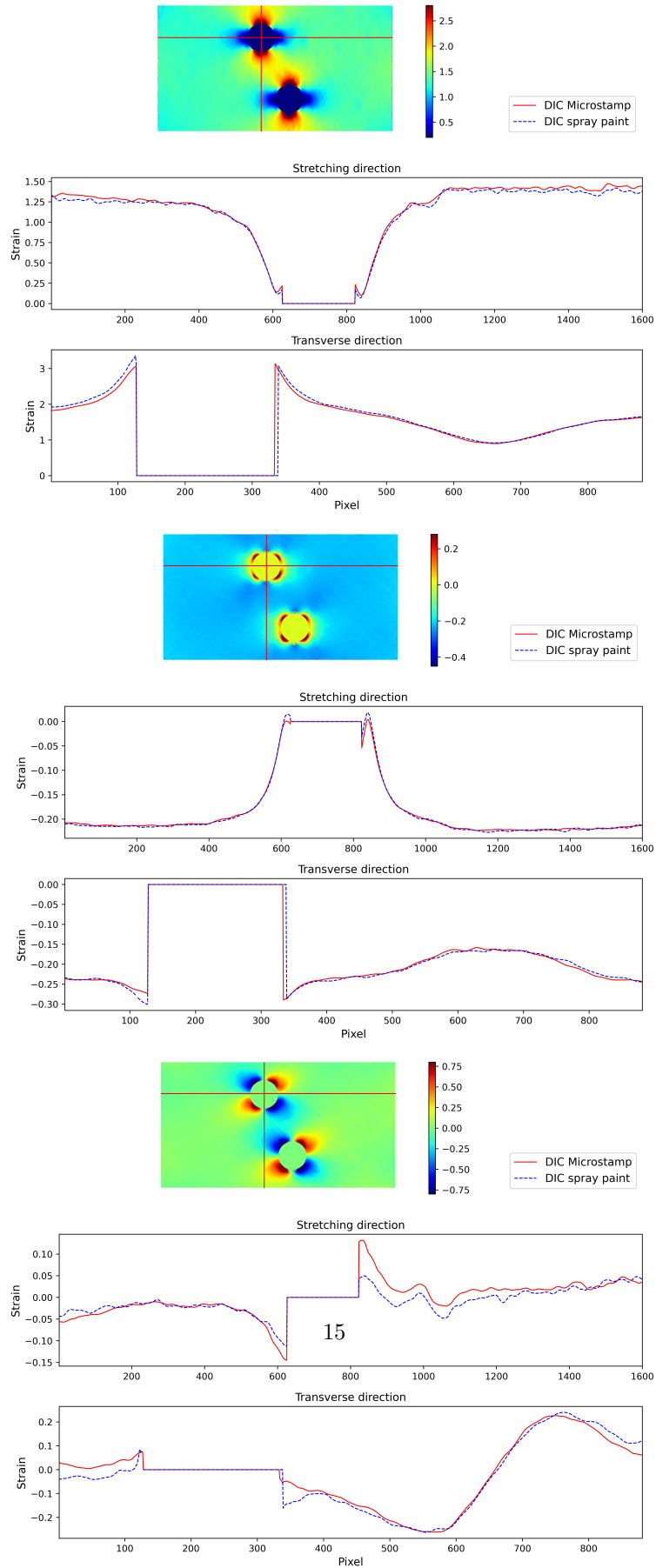


Fig. C4 Quantitative comparisons of the strain fields, E_{xx} (top), E_{yy} (middle) and E_{xy} (bottom) along other lines, obtained for the analyses shown in Figure 11.

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