



Chapter 5

A Sublimation-based Pattern Generation Technique for Deformation Analysis of Additively Manufactured Specimens

Nicolas A. Yusim, Angel Matos-De Los Santos, Austin M. Giordano, and Fu-Pen Chiang

Abstract A deformation analysis method is proposed for additively manufactured (AM) specimens, utilizing sublimated speckles for analysis Computer-Aided Speckle Interferometry (CASI). This approach allows precise control over the size and density of the sublimated patterns, which are integrated into the surface of the AM specimen through the heat and pressure applied during the fused deposition modeling (FDM) 3D printing process. This technique creates the speckle pattern without altering the specimen's integrity. The sublimation-deposited speckle patterns facilitate the exploration of various pattern-generation methods (e.g., pseudo-random, Goodman) to identify the optimal speckle pattern. The material behaviors of the speckled and un-speckled specimens are characterized and compared to determine the impact of the speckle pattern on the specimen's material properties.

Keywords Speckle · Additive manufacturing · Sublimation · DIC (Digital Images Correlation)

Introduction

Additive manufacturing (AM) is an extremely lucrative industry valued at 20.37 billion USD in 2023 and expected to grow to a 88.28 billion-dollar industry by 2030 [1]. This rapid industry growth is due in part to AM's continuously improving ability to manufacture consumer grade, end use products [2]. These improvements come in many forms such as new materials, modifications to the current manufacturing method, and modifications to tool path generation algorithms [3]. With the swift inclusion of AM parts into many consumer products comes an inherent need to validate their structural performance to ensure safe and effective use by the consumer.

In this paper, an alternative method of applying a fully customizable deformation pattern of choice onto a specimen manufacturing with Fused Deposition Modeling (FDM) is presented. This method uses sublimation paper which is able to transfer ink onto a surface through use of heat and pressure [4]. By applying the sublimation paper onto the heated surface where the specimen is manufactured, the pattern is transferred without altering any material properties on the surface while maintaining the resolution of the pattern. The deformation analysis method technique chosen to evaluate this method is Computer Aided Speckle Interferometry (CASI) [5] due to its ubiquity within the experimental mechanics field. This was combined with FDM printing since the heated manufacturing surface provides substantial heat to successfully sublimate the pattern into the specimen.

Speckle theory

Speckles are generated when an opaque surface is illuminated by a coherent light source, such as a laser. Wavelets from the laser are reflected off of the surface and interfere with each other at a chosen plane of focus to create a speckle pattern as shown in Fig. 1 a [5, 6, 7]. This interference results in a laser speckle pattern similar to the one shown in Fig. 1 b.

Nicolas A. Yusim · Angel Matos-De Los Santos · Austin M. Giordano · Fu-Pen Chiang
Laboratory for Experimental Mechanics Research, Department of Mechanical Engineering at Stony Brook University,
Stony Brook, NY 11794-2300, USA.
e-mail: nicolas.yusim@stonybrook.edu; angel.matos-delossantos@stonybrook.edu; austin.giordano@stonybrook.edu;
fu-pen.chiang@stonybrook.edu

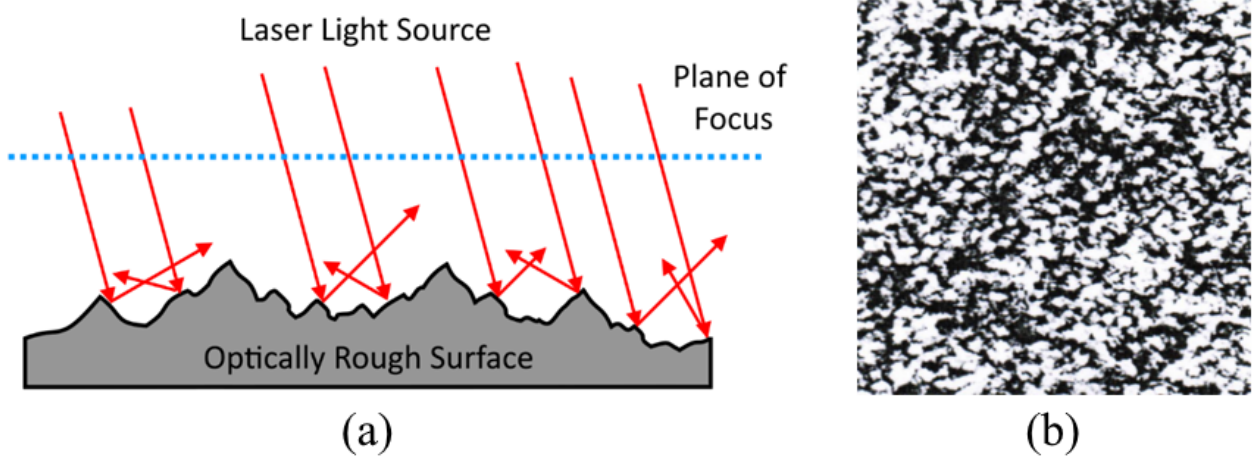


Fig. 1 (a) Graphical representation of laser wavelet interference next to (b) enlarged view of laser speckles

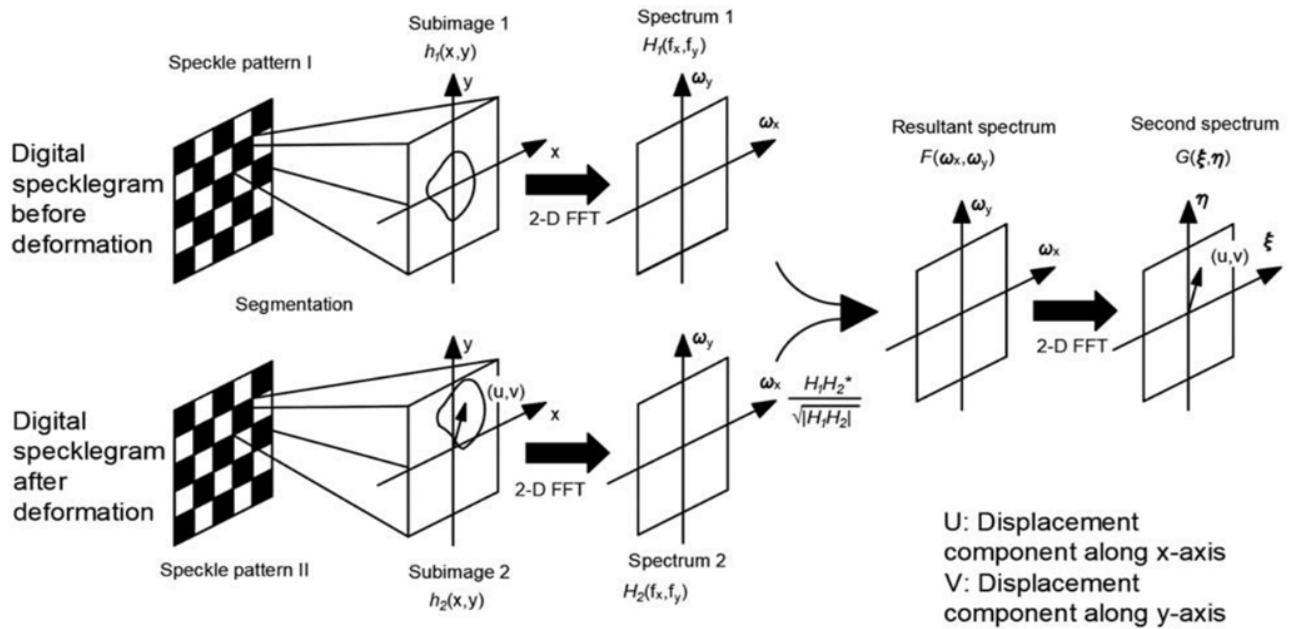


Fig. 2 Computer Aided Speckle Interferometry Algorithm

Speckle interferometry was simultaneously developed into two digital methods, Digital Image Correlation (DIC) and CASI; The fundamental difference between the two being that DIC matches a kernel of speckles to its deformed location to get displacements while CASI uses optical processing techniques to obtain displacements [6, 7]. The CASI Algorithm is shown below in Fig. 2.

The digitization of speckle interferometry has led to the development of multiple pattern generation techniques to simulate the naturally occurring laser speckle pattern. Some examples of these pattern generations techniques include the Pseudo-Random pattern and the Goodman pattern among others. Examples of the Pseudo-Random pattern, the Goodman pattern, and laser generated speckles are shown below in Fig. 3.

The Pseudo-Random pattern generates a grid of random black and white pixels using a built-in MATLAB function [8], while the Goodman pattern is a mathematical representation of laser speckle interference made by generating random phasors in a table in accordance with the equation below [9]:

$$e^{(2i\pi \cdot rand)} \quad (1)$$

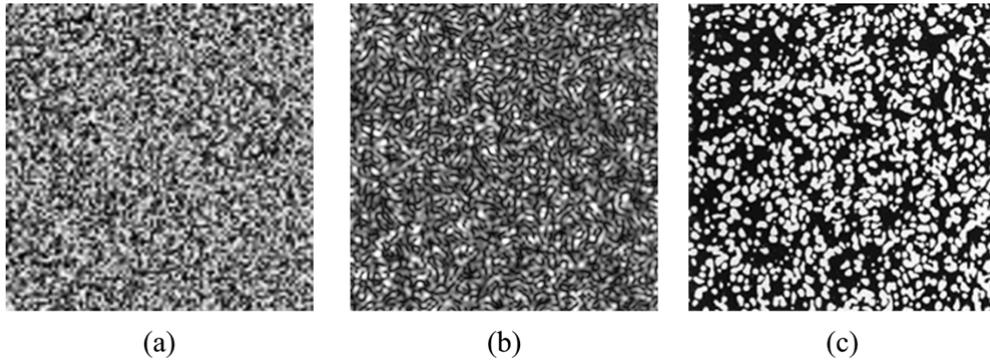


Fig. 3 (a) Pseudo-Randomly generated speckle pattern, (b) Goodman generated speckle pattern, (c) laser generated speckle pattern

Sample Preparation

Specimens presented in this paper were manufactured in accordance with ASTM D638-14 standard for tensile properties of plastics using white poly lactic acid (PLA). A MATLAB program was developed to produce a Goodman pattern with a speckle size of 8 pixels for the maximum capacity of the inkjet printer used. In this paper the print resolution of the inkjet printer is limited by its minimum axis resolution of 1440 dpi. An initial Goodman pattern was generated with 16384×16384 pixels, which is then cropped to 16200×11880 pixels. This pattern was printed onto sublimation paper as shown in Fig. 4 below.



Fig. 4 Specimen with Goodman generated speckle pattern sublimated onto its surface

The sublimation paper is then adhered to the heated build plate of a Prusa Mk4S so that the specimen can be printed on top of the sublimation paper. A Prusa Mk4S was used due to its adaptive bed leveling procedure, which is capable of adjusting to any existing surface on the build plate to manufacture the specimen. As the printer deposits the heated PLA onto the paper, the ink is sublimated onto the surface of the first layer. A microscope image of the Goodman pattern on the specimen is shown in Fig. 5 a, with the sublimation paper shown after use in Fig. 5 b.

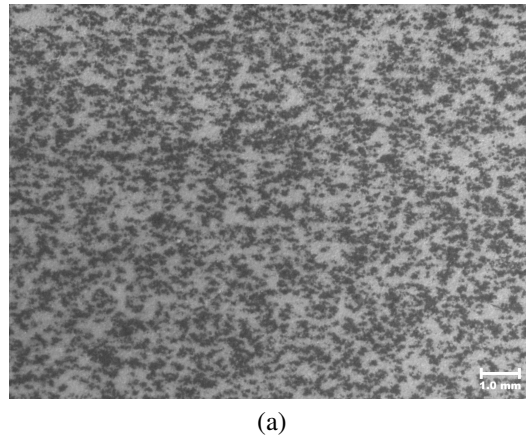
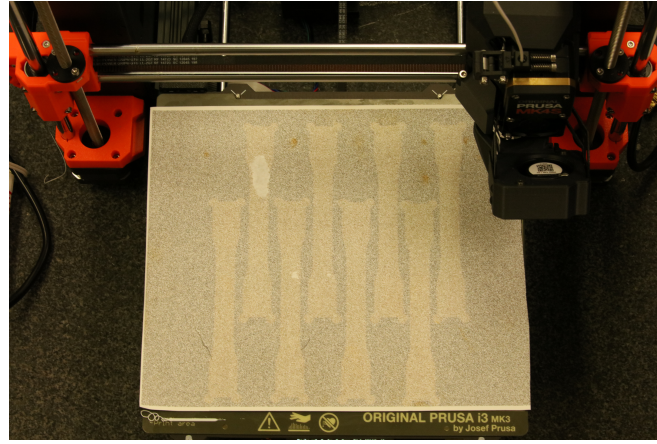


Fig. 5 *Continued.*



(b)

Fig. 5 (a) Microscope image of speckle pattern on printed specimen (b) Sublimation paper on printer after specimens were removed

Experimental Procedure and Analysis

Each specimen was affixed into a universal testing machine, and loaded in tension with a displacement control of 0.5 mm/min. Each specimen was imaged with a Canon EOS 5DSR to be analyzed. The CASI results are presented in Fig. 6 and the resulting force-displacement plots of blank, and sublimated speckled specimens are shown in Fig. 7 below.

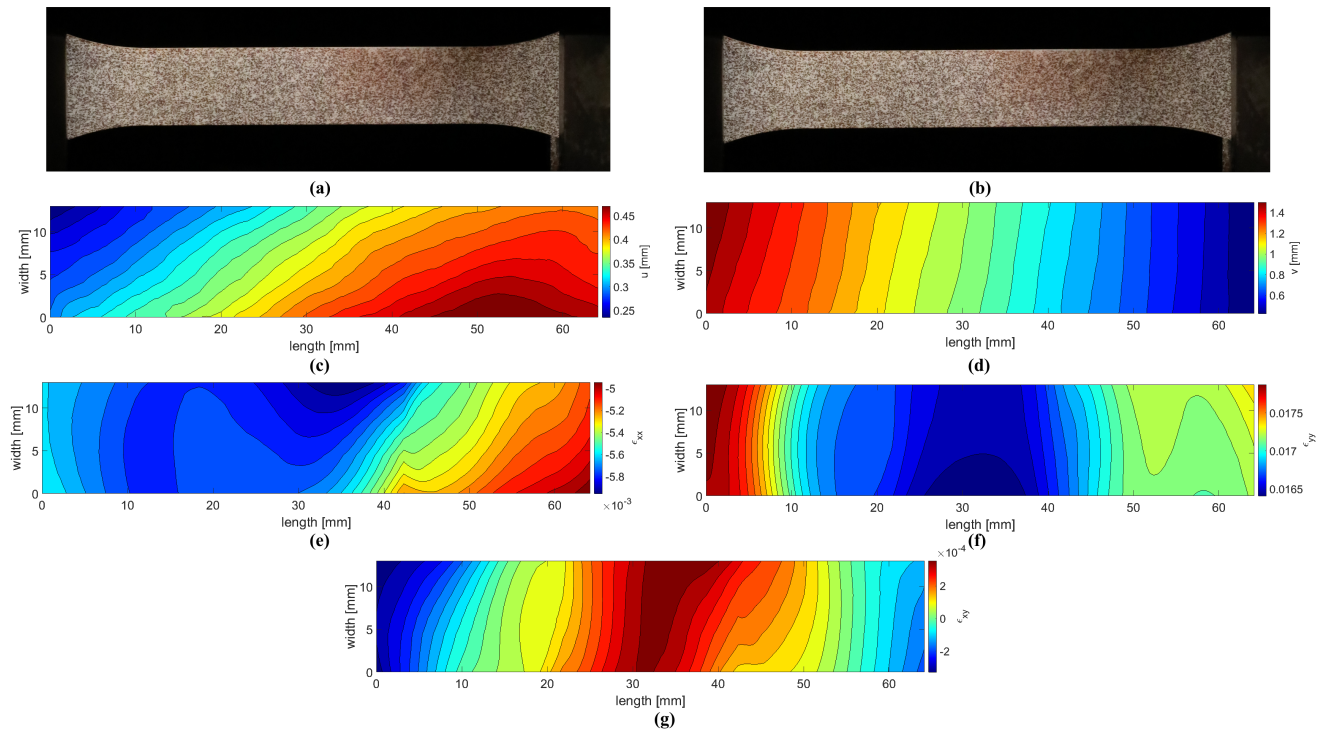


Fig. 6 (a) Undeformed specimen, (b) deformed specimen, (c) u -displacement field, (d) v -displacement field, (e) ϵ_{xx} field, (f) ϵ_{yy} field, (g) ϵ_{xy} field.

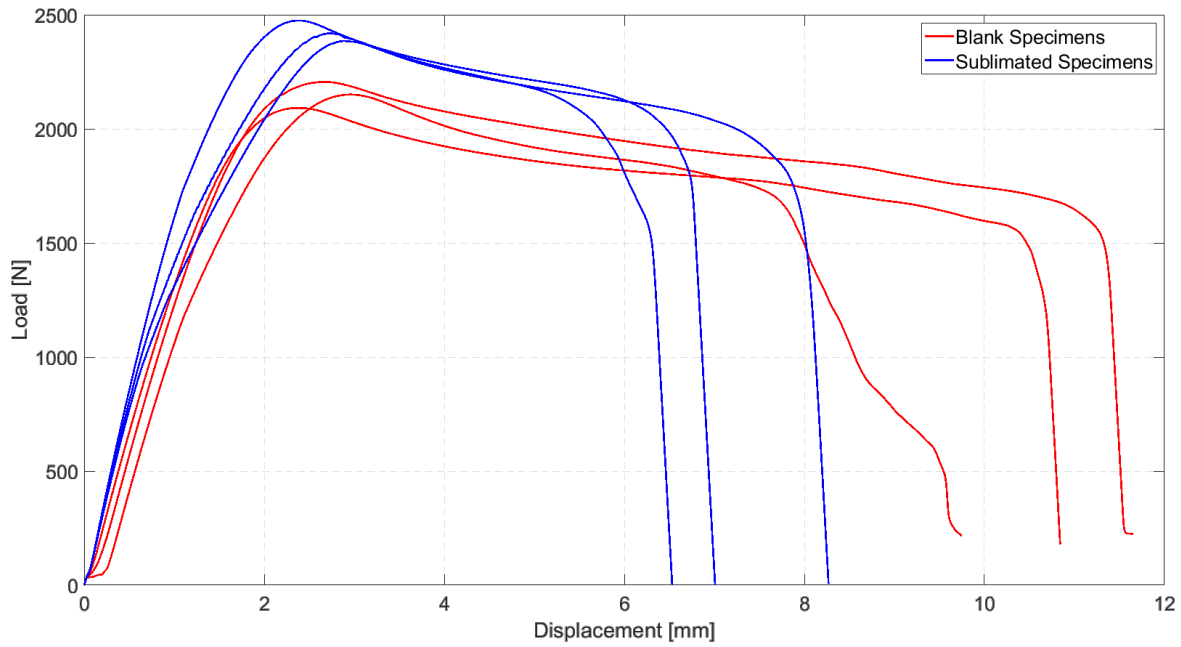


Fig. 7 Force-displacement graph of specimens with sublimated speckles compared to blank specimens

Conclusion

We have produced accurate displacement fields from CASI analysis of additively manufactured specimens with sublimated speckles. We find that speckled specimens produce similar results in the force-displacement when compared to blank specimens. In previous work [10], it was seen that printing a speckle pattern using a multi-material printing technique lead to limit plasticity of the specimen, the technique present in this work does not have that drawback. This work can be extended by utilizing the technique shown to produce a moiré pattern which will enable analyze via the sampling moiré method [11]. Further work needs to be done to determine the viability of the experimental technique shown, but from these initial results, producing specimens with sublimated patterns for deformation analysis appears to be promising.

References

1. Grand View Research, "Additive Manufacturing Market Size & Trends," 2024. [Online]. Available: <https://www.grandviewresearch.com/industry-analysis/additive-manufacturing-market>
2. Z. Zhu, P. Pradel, R. Bibb, and J. Moultrie, "A Framework for Designing End Use Products for Direct Manufacturing Using Additive Manufacturing Technologies," Aug. 2017.
3. D. Syrlybayev, B. Zharylkassyn, A. Seisekulova, M. Akhmetov, A. Perveen, and D. Talamona, "Optimisation of strength properties of FDM printed parts—A critical review," May 01, 2021, *MDPI AG*. doi: 10.3390/polym13101587.
4. E. Toshikj and B. Prangoski, "Textile Sublimation Printing: Impact of Total Ink Limiting Level and Sublimation Transfer Paper on Black Print Quality," *Tekstil ve Konfeksiyon*, vol. 33, no. 4, pp. 366–374, Dec. 2023, doi: 10.32710/tekstilvekonfeksiyon.1145260.
5. D. J. Chen, F. P. Chiang, Y. S. Tan, and H. S. Don, "Digital speckle-displacement measurement using a complex spectrum method," 1993.
6. J. Blaber, B. Adair, and A. Antoniou, "Ncorr: Open-Source 2D Digital Image Correlation Matlab Software," *Exp Mech*, vol. 55, no. 6, pp. 1105–1122, Jul. 2015, doi: 10.1007/s11340-015-0009-1.
7. L. Keene, "A Range and Performance Optimized Version of the Computer-Aided Speckle Interferometry Algorithm for Real-Time Displacement-Strain Field Monitoring," *Exp Tech*, vol. 46, no. 6, pp. 1027–1048, Oct. 2022, doi: 10.1007/s40799-021-00520-x.
8. The MathWorks Inc, "Uniformly Distributed Random Numbers," mathworks.com. Accessed: Feb. 17, 2024. [Online]. Available: <https://www.mathworks.com/help/matlab/ref/rand.html>.
9. J. W. Goodman and Society of Photo-Optical Instrumentation Engineers, *Speckle phenomena in optics: theory and applications*.
10. N. Yusim, A. Giordano, and F. P. Chiang (2024) An Additively Manufactured Pattern Generation Technique for Deformation Analysis of Additively Manufactured Specimens. Advancement of Optical Methods in Experimental Mechanics, 2024 Annual Conference of the Society for Experimental Mechanics; 2024 June 3-6; Vancouver, WA.
11. S. Ri, M. Fujigaki, and Y. Morimoto, "Sampling Moiré Method for Accurate Small Deformation Distribution Measurement," *Exp Mech*, vol. 50, no. 4, pp. 501–508, Apr. 2010, doi: 10.1007/s11340-009-9239-4.

