# Residual stress evaluation of laser powder bed fusion benchmarks using the contour method

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## Abstract

Additive manufacturing offers significant advantages over traditional methods; however, its application has been challenged by processing induced residual stress. This study aims at investigating the effectiveness of the contour method of residual stress measurement on laser-based powder-bed fusion fabricated benchmarks with a complicated geometry, which is challenging as its departure from a conventional application of the contour method based on rectangular specimens. A series of contour method analyses employing sacrificial parts was arranged, with different measurement originations and cutting configurations considered. Preliminary result showed successful mitigation of cutting artefacts due to geometrical irregularities, with appreciable agreement to existing measurements obtained using diffraction-based techniques in previous studies. The presence of cutting-induced plasticity was observed, which will be further investigated with different cutting arrangements.

## Key words

Additive manufacturing; laser powder bed fusion; Residual stress; Contour method; Sacrificial parts

## Possible Sessions

Residual Stresses; Testing of Additive Materials;

## Introduction

Additive manufacturing (AM) has seen wider application in manufacturing[1] and in-situ repair[2] of functional, high-value components in automobile, aerospace, energy, and medical device industries. However, the large, layer-by-layer thermal gradients often lead to anisotropic residual stress (RS) that can affect dimensional accuracy, fatigue behaviour and structural integrity[3]. The contour method (CM)[4] is a destructive technique to provide a 2-D stress map, reconstructing the stresses that have been elastically released on a cut plane, usually achieved with wire-electrical-discharge-machining (WEDM) process. WEDM is sensitive to cutting thickness, which can introduce cutting-related artefacts when cutting through a varying cross-section[5] that widely exists in AM fabricated parts. These artefacts can further be misinterpreted as artificial stresses in final result that require careful mitigation in a CM setup by applying sacrificial parts or through post-corrections[6].

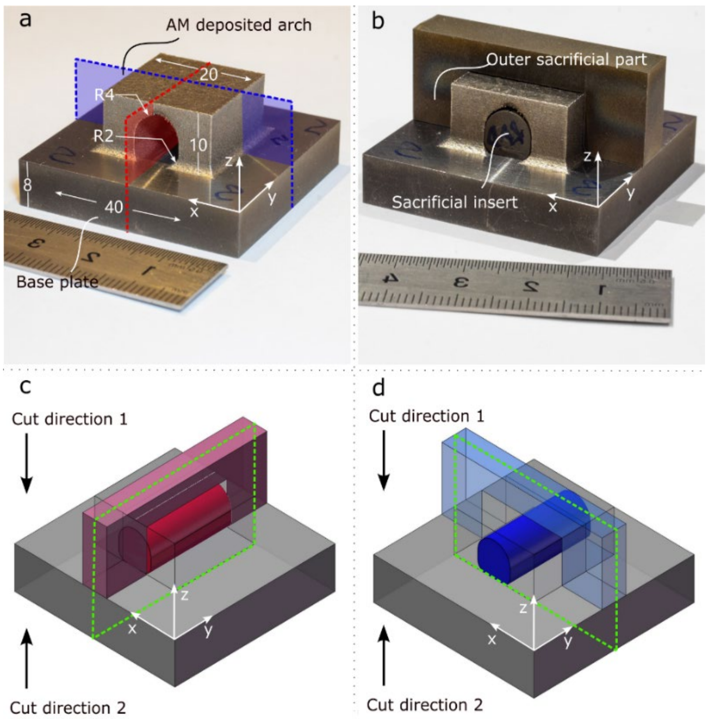


Fig. 1 Illustration of (a) as-deposited with two measurement plane shaded in red(y-z plane) and blue(x-z plane) and (b) example of sacrificial assembly(dry fit); two different cutting arrangements (cutting plane marked in green dashed line) with their corresponding sacrificial parts layout are plotted in (c) blue and (d) red, with inner sacrificial inserts in deeper colour and outer sacrificial parts in semi-translucent for better illustration.

## Methodology and experiments

The effectiveness of CM measurements employing sacrificial parts was investigated on benchmarks fabricated with laser powder bed fusion machine at the Henry Royce institute, as part of the follow-up of the EASI-STRESS round-robin exercise. The benchmark specimen shown in Fig. 1a incorporates an arch concept with a centre void that serves a good geometric candidate for RS evaluation in AM parts, which can be a challenge in conventional CM analysis largely based on more regular components with a rectangular or tubular cross-section.

Eight arches were deposited on an 8mm base plate in one batch, of which four were subjected to heat-treatment of 700°C for 2 hours, followed by furnace cooling to room temperature. A sacrificial layout consists of an insert and enclosure (Fig.1b) was designed to render a rectangular cutting path, mitigating the complexity of the geometry. Silver doped conductive epoxy was applied between the sacrificial parts and the arch to maintain conductivity as required by WEDM and to prevent the sacrificial assembly from separating during a contour cut. Two different measurement planes following the axial (x-y plane, shaded with red in Fig.1a) and radial (x-z plane, shaded with blue in Fig.1a) directions of the inner void were examined in this study, with the corresponding sacrificial layout shown in Fig. 1c and Fig. 1d. Each measurement plane has two cutting directions employed to investigate the effect of cutting induced plasticity(CIP) [7], with the direction from the crown of arch to base plate designated as direction 1, and direction 2 in reversed order.

The CM measurements were arranged following the practice guide detailed in EASI-STRESS deliverable report[8]. The data analysis was performed using pyCM[9] open source software following its instruction.

### Preliminary results and discussion

Fig. 2a shows a preliminary result a CM analysis following the configuration showed in Fig. 1c direction 1. Noticeable effect of CIP near the end of the cut at upper ligament was observed. The disruption of geometrical complexity was not prominent, which can be contributed to the use of sacrificial parts in this application. This could also potentially be due to less variance in cutting length along this orientation. Further investigation will be carried out with cuts along z-x plane in a later stage. A comparison of the preliminary CM result with existing neutron diffraction (ND), lab X-ray diffraction (LXRD), as well as RS determined by synchrotron X-ray diffraction (SXRD)[10] is presented in Fig. 2b, showing a reasonable agreement among each technique, particularly towards centre region, which credits the effectiveness of CM in this study.

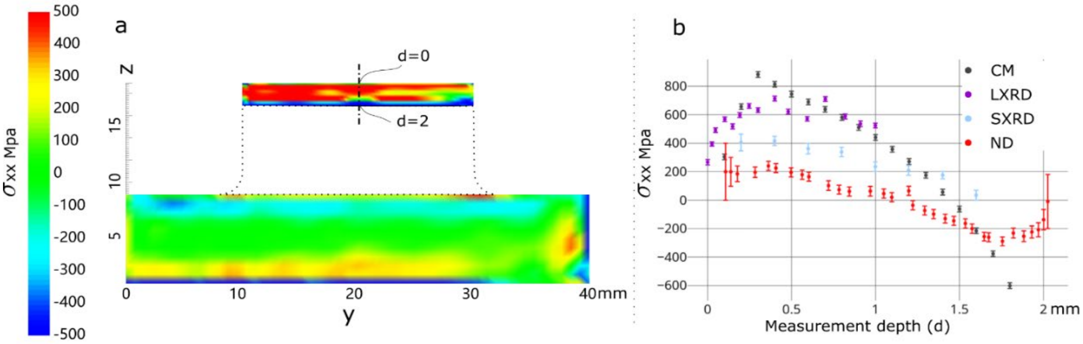


Fig. 2 (a) CM results showing the $\sigma_{xx}$ of as-built sample cutting from top to bottom and (b) comparision of CM (black) to LXRD (purple), SXRD (blue) and ND (red) results acquired from EASI-STRESS round-robin results.

### References

[1] G. N. Levy, R. Schindel, and J. P. Kruth, "Rapid manufacturing and rapid tooling with layer manufacturing (LM) technologies, state of the art and future perspectives," *CIRP Ann. - Manuf. Technol.*, vol. 52, no. 2, pp. 589–609, 2003, doi: 10.1016/S0007-8506(07)60206-6.

[2] K. Kanishka and B. Acherjee, "A systematic review of additive manufacturing-based remanufacturing techniques for component repair and restoration," *J. Manuf. Process.*, vol. 89, pp. 220–283, 2023, doi: 10.1016/j.jmapro.2023.01.034.

[3] L. Mugwagwa, I. Yadroitsava, N. W. Makoana, and I. Yadroitsev, "Residual stress in laser powder bed fusion," in *Fundamentals of Laser Powder Bed Fusion of Metals*, Elsevier, 2021, pp. 245–276. doi: 10.1016/B978-0-12-824090-8.00014-7.

[4] M. B. Prime and A. T. DeWald, "The Contour Method," in *Practical Residual Stress Measurement Methods*, G. S. Schajer, Ed. John Wiley & Sons Ltd, 2013, pp. 109–138. doi: 10.1002/9781118402832.

[5] M. B. Prime and A. L. Kastengren, "The Contour Method Cutting Assumption: Error Minimization and Correction," in *Experimental and Applied Mechanics, Volume 6*, 2011, pp. 233–250.

[6] Z. Cai, T. Sun, and M. J. Roy, "Mitigation of Cutting-Induced Artificial Stresses in Contour Method Analysis of Irregular Components," *J. Mater. Eng. Perform.*, no. Ref 10, 2024, doi: 10.1007/s11665-023-09072-0.

[7] Y. L. Sun, M. J. Roy, A. N. Vasileiou, M. C. Smith, J. A. Francis, and F. Hosseinzadeh, "Evaluation of Errors Associated with Cutting-Induced Plasticity in Residual Stress Measurements Using the Contour Method," *Exp. Mech.*, vol. 57, no. 5, 2017, doi: 10.1007/s11340-017-0255-5.

[8] M. Roy *et al.*, "Easi-Stress European Activity for Standardization of Industrial Residual Stress Characterization Deliverable Report: D2.2 Best practice guidelines," 2022.

[9] M. J. Roy, N. Stoyanov, R. J. Moat, and P. J. Withers, "pyCM: An open-source computational framework for residual stress analysis employing the Contour Method," *SoftwareX*, vol. 11, p. 100458, 2020, doi: https://doi.org/10.1016/j.softx.2020.100458.

[10] M. J. Roy *et al.*, "Easi-Stress European Activity for Standardization of Industrial Residual Stress Characterization Deliverable Report: D2.3 Round-robin results," 2022.