



The Application of Hole Drilling Method Integrated with 2D and 3D Digital Image Correlation for Estimating Residual Stresses

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Abstract

Accurate measurement of residual stress is crucial for assessing structural integrity and predicting fatigue life. Although significant work has been documented on applying two-dimensional (2D) and three-dimensional (3D) digital image correlation (DIC) independently to the hole drilling process, a direct comparison of their accuracy and performance under the same conditions (most importantly, with plastic deformation) has not yet been published. This work conducted the first explicit comparison between 2D and 3D-DIC combined with the hole drilling method for residual stress measurement using finite element (FE) analysis as a validation standard. Residual stresses were induced through plastic bending of a square beam made of aluminum alloy 7075-T651. The findings indicate that the 3D-DIC is more accurate (93%) compared to the 2D-DIC (88%), objectively tested against FE solutions, even on a flat surface, which is theoretically ideal for 2D-DIC. This difference in accuracy is attributed to the higher sensitivity of the 2D-DIC to out-of-plane deformation and camera misalignment. These results support the effectiveness of 3D-DIC in measuring residual stress and explain that there is a trade-off between the practical accuracy of 2D and 3D versions of the hole-drilling technique.

Keywords: *Digital Image Correlation, Residual Stresses, Hole Drilling Method, Finite Element Analysis.*

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1. Introduction

Residual stresses are self-equilibrating internal stresses locked within a material after manufacturing or processing. They play a critical role in the mechanical performance of materials and structural members by significantly influencing their stability, fatigue life, corrosion resistance, and overall structural integrity, making their accurate measurement essential for reliable engineering design and failure prevention [1][2]. Residual stresses can be quantified using different techniques, which can in turn be broadly classified as either non-destructive or destructive procedures. The hole-drilling technique falls in between because it is a semi-destructive procedure [3].

Previous studies have examined various optical measurement methods. Ya et al [4] and Pisarev et al [5] proposed combining hole drilling with moiré interferometry, a high-resolution, full-field, noncontact measuring method. However, the sophisticated setup limits the in situ applicability of the method. Reflection hologram interferometry is highly accurate but necessitates vibration-isolated, precision setups that deter practical application [6]. Lord et al [7] showed 3D-DIC integrated with blind hole drilling, having a within 5% theoretical accuracy calculation without vibration isolation necessity. Chen et al [8] progressed the technology with 2D-DIC and incremental hole drilling application for through-thickness stress profiling. Brynk and Baishya [9] took the 3D-DIC application further to quantify in-plane and out-of-plane displacements better than conventional strain gauges. Peng [10] developed an innovative approach combining 3D-DIC with the hole drilling method to measure residual stresses in structural steel components. The

research identified an optimal measurement zone located between 2 to 2.5 times the hole radius from the hole center, where displacement field measurements provided the most reliable stress calculations.

Blödorn et al [11] contrasted the effect of real hole geometry on calibration coefficients in the hole-drilling method. They demonstrated through experiments and FEM simulations that chamfered bottom holes cause errors, especially in first depth increments, requiring geometry-dependent coefficients to determine residual stresses correctly in materials such as steel, stainless steel, and aluminium. Alegre et al [12] performed research on the effect of workpiece thickness and diameter of hole on calibration coefficients using the hole-drilling method and extending ASTM E837-13a to application using FEM simulations. The research verified coefficients in the case of thin samples and non-conventional hole sizes, with evidence of deviation from ASTM's correction factor for diameter, and suggesting new matrices for precise residual stress calculation in such a situation. Halabuk and Návrát [13] created a new approach to residual stress evaluation of cylindrical parts by the hole-drilling method. They applied internal loading of forces through thermal and torsional stresses in finite element models instead of direct loading through holes. Their method of four sets of calibration coefficients minimized errors significantly, particularly for small radii, with higher precision in applications. Lakey and Hill [14] confirmed the ASTM E837-20 thickness-dependent method for measurement of residual stress by hole-drilling in thin and intermediate specimens. Through shot-peened aluminium coupons and finite element analysis, they proved enhanced precision over calculations of thick workpieces, with differences remaining in

thinner specimens. Their results verify applicability to different thicknesses of the new standard.

Hagara et al [15] established basic rules for applying standard stereo-DIC equipment and showed that an error of a single camera of as little as 0.125° generates highly erroneous values (14-21%), whereas a well-configured stereo system maintains accuracy below 5%. Yuksel et al [16] used the method to examine heterogeneous materials, recording a central tensile stress of 6.1 MPa in a pultruded composite and detecting a drilling-affected zone of 2 mm. Additional refinements in the method were implemented by Brynk et al [17] who improved residual stress measurement by proposing a three-dimensional digital image correlation-assisted inverse process. Among the improvements was employing finite element modelling to obtain fifth-order polynomial correction coefficients, thus expanding the valid range of measurement to hole depth to diameter ratios of 0.2 to 1.2. This facilitated high-resolution stress profiling, and a stunning gradient was uncovered in a hydrostatically extruded bar: longitudinal stress varied from +400 MPa tension on the edge to -300 MPa compression in the center. The technique was also successfully translated to curved surfaces, proving versatility. Correa et al [18] later improved precision by applying enhanced finite element modelling by means of a high-definition mesh to minimize the calculation error of average stress from 9.7% to 3.9% for a linear gradient of +117.2 MPa to -117.2 MPa. The experimental feasibility of these advancements was demonstrated by Chatterjee et al [19], who made DIC a viable, contactless substitute for strain gauges by being able to record transverse compressive (-100 MPa) and longitudinal tensile (118 MPa) stresses in weld joints.

The methods of residual stress measurements can be divided into diffraction-based, mechanical and optical methods, and each of them was designed to suit specific materials and geometrical features. Table 1 summarizes the concrete characteristics of methods commonly used, their principal advantages, and limitations. Following this comparison, the current study illustrates that 3D-DIC is more accurate and quantifies the trade-off between its accuracy and experimental complexity.

Engineering-wise, under plastic deformation, accurate measurement of residual stress is still a challenge. The traditional strain-gauge-based hole-drilling techniques have a low spatial resolution and sensitivity to installation, and optical techniques cause uncertainty with respect to surface alignment and out-of-plane deformation. Specifically, the distinction between the accuracy and applicability of 2D and 3D-DIC with hole drilling has not been clearly quantified under the same experimental conditions.

Accordingly, the main aim of the study is to conduct experimental and numerical analysis of the performance, accuracy and practical constraints of 2D-DIC and 3D-DIC combined with the hole-drilling technique for measuring residual stress under plastic deformation. Finite element analysis is used as an independent benchmark to quantitatively evaluate the reliability of each process.

The novelty of the current work is that it is the first systematic and side-by-side experimental comparison of 2D- and 3D-DIC-based methods of hole-drilling under the same loading, drilling, and measurement conditions. The combination of controlled experiments and finite element validation provides practical guidance on selecting methods based on accuracy, experiment complexity, and usability.

2. Methodology

This work combines experimental and numerical methods to analyze residual stresses with the help of the hole-drilling technique and digital image correlation methods. 2D and 3D-DIC are used under the same conditions to measure strain relief resulting from drilling. Figure 2 gives an overview of the adopted workflow, and the finite

element analysis is considered as a reference framework to evaluate the quality of experimental measurements.

Table 1. Comparison of residual stress measurement methods and their applicability to specific characteristics

Technique	Concrete characteristic addressed	Advantages	Restrictions
X-ray diffraction	Near-surface stress, crystalline materials	Non-destructive, high accuracy	Significant shallow depths, susceptible to surface state
Neutron diffraction	Macroscopic residual stresses, thick-walled structures	Depth-Resolved Stress profiling, 3D stress analysis	Specialized access requirements, Significant cost
Traditional strain gauge	In-plane strains	Established and uncomplicated	Discrete point measurement, semi-destructive
2D-DIC with hole drilling	In-plane strains, planar surfaces	Full-field measurement, cost-effective	Sensitive to camera misalignment and out-of-plane deformation
3D-DIC with hole drilling	Out-of-plane deformation, non-planar geometries	High precision, full-area mapping	Require initial calibration and higher computational time
Moiré holography with hole drilling	High-resolution	excellent sensitivity	Need vibration isolation and a complex setup

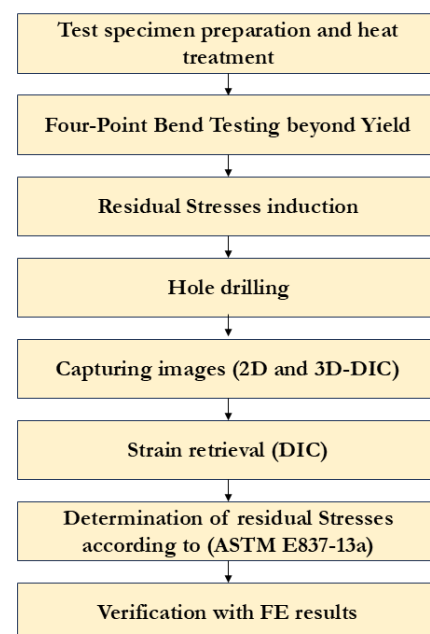


Figure 1. Flow chart illustrating the experimental procedure of residual stress measurement with 2D and 3D-DIC

2.1 Concept of Calculation

The measure of residual stresses is based on the hole-drilling technique, which measures strain relief in the adjacent material after drilling. The strain field released was quantified using the DIC techniques and then transformed to the residual stress components under the analytical framework of ASTM E837. Fully-field 2D and 3D-DIC measurements have been used in place of conventional strain gauges in this research, making it possible to obtain both in-plane and out-of-plane displacement fields non-contactually. In the

case of isotropic, linear elastic material behavior, the strains relieved at three angular locations about the hole drilled were calibrated using the ASTM E837 coefficients against the in-plane residual stress components. The same coefficients were used in both DIC methods to have a direct and fair comparison. Figure 2 illustrates a schematic of the hole drilling strain gauge rosette geometry, as specified in ASTM E837. The figure indicates a top view of a nominal three-element rosette (Type A), Hole diameter D and mean radius R_m to the strain gauge centers are shown.

For uniform residual stresses, the following relationship from ASTM E837-13a [20] applies:

$$\varepsilon = \frac{1+\nu}{E} \bar{a} \frac{\sigma_x + \sigma_y}{2} + \frac{1}{E} \bar{b} \frac{\sigma_x - \sigma_y}{2} \cos 2\theta + \frac{1}{E} \bar{b} \tau_{xy} \sin 2\theta \quad \dots(1)$$

where ν is the Poisson's ratio, E is the Young's modulus, σ_x and σ_y are the normal stresses in x and y directions, τ_{xy} is the shear stress, $\bar{a}$ and $\bar{b}$ are the calibration coefficients, and θ is the angle of the strain gage with respect to the x -axis. By applying Equation (1) at the specified three positions, a system of linear equations is obtained that can be solved for σ_x , σ_y and τ_{xy} .

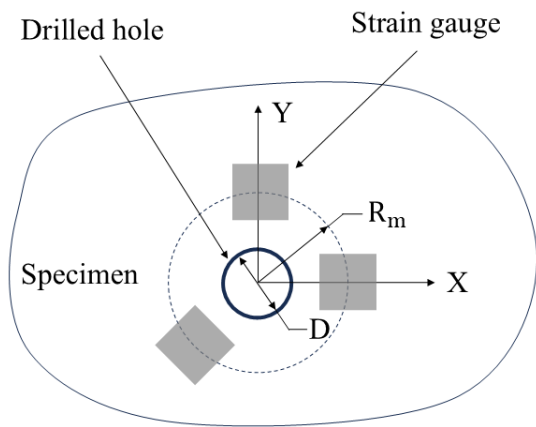


Figure 2. Hole geometry and strain gauge layout

2.2 Experimental Setup and Procedure

The experimental study was done through a solid square cross-section beam, which was produced using aluminum alloy 7075-T651. Before testing, the test specimen was annealed to reduce the pre-existing residual stresses. The four-point bending set-up shown in Figure 3 was used to impose a systematic residual stress field. The total applied force was 93 kN, which is greater than the yield strength of the beam material to guarantee that plastic deformation was developed and self-equilibrating residual stresses formed after unloading. The area between the inner loading points was chosen to be a hole drilled and DIC measurements done because this region is devoid of any boundary effects and external loading effect and hence a representative residual stress state is recorded.

2.3 DIC Measurement

Both 3D and 2D-DIC techniques were used to obtain full-field deformation measurements under the same experimental conditions. The surface of the specimen was covered with a random speckle pattern to facilitate the easy tracking of displacement and strain. In 3D-DIC measurements, a two-camera system (each with a 20-megapixel sensor) was fitted on a rigid tripod. The drilling was done at the measurement points and stereo image pairs were obtained before and after the drilling. The sets of recorded images were analyzed with the help of DuoDIC, which is a MATLAB digital image correlation toolbox that allowed reconstructing 3D displacement fields to estimate the strain relief due to hole drilling.

In the case of 2D-DIC measurements, a planar image was obtained by a single camera of the stereo system before and after drilling. The obtained pairs of images were analyzed with the help of the Ncorr software that provided the in-plane displacement and strain fields. DIC measurements depend highly on the parameters used for the correlation. Specifically, the spatial resolution and measurement stability trade-off are controlled by the size of the subset and its spacing. In this study, a subset radius of 15 pixels and a distance of 5 pixels are selected to provide a reliable strain measurement with enough spatial resolution around the hole that is drilled. The same conditions of illumination, camera optics, and the quality of the speckle were used in all the DIC approaches to obtain consistency and to compare the two methods directly. The entire experimental setup, cameras and drilling unit are depicted in Figure 4.



Figure 3. Experimental setup for the four-point bending test

2.4 Hole Drilling Configuration

In line with ASTM E837-13a, stress relief was caused by drilling flat-bottomed holes with an end mill. An electric drill was firmly attached to a bidirectional movable table so that the drill could be precisely positioned and kept still whilst drilling. Coolant was applied to mitigate heat build-up and thermally induced distortions. The drilling process was achieved using flat-bottomed holes, which create a consistent cylindrical hole that facilitates axisymmetric strain relief and fulfills the analytical assumptions of the ASTM standard. The chosen hole geometry was 2 mm in diameter and 1 mm in depth. These parameters were selected based on recommendations of ASTM E837-13a to make the field of stress-relief homogeneous with minimal plasticity caused by drilling. This depth-to-diameter ratio allows the direct use of standard calibration coefficients without further numerical scaling and offers an acceptable trade-off between sensitivity to measurement and the spatial resolution needs of each 2D- and 3D-DIC system. Nine holes were drilled in the area between the two inner loading points. Three holes were drilled on each of the top, bottom, and side surfaces of the beam. Figures 5 and 6 depict the beam specimen and a close-up of the holes drilled on the top surface, respectively, and Figure 7 is a schematic diagram of the locations of holes on all the measured surfaces. Table 1 provides a summary of the coordinates and positions of the holes that were drilled.

2.5 Residual Stress Determination

The longitudinal axis of the beam was used as the X-axis and normal to it, as the Y-axis. The point of reference on the coordinate system was the lower-left corner of every measured surface. The DIC analysis was done to obtain strain components, which were then applied in calculating the residual stress according to the ASTM E837 analytical formulation, allowing the consistent assessment of residual stresses of both 2D and 3D-DIC measurements.

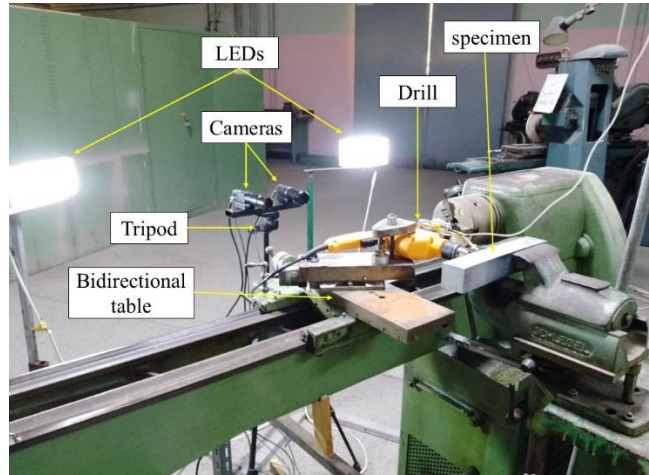


Figure 4. 3D-DIC experimental setup



Figure 5. Beam specimen



Figure 6. Holes drilled on the top surface

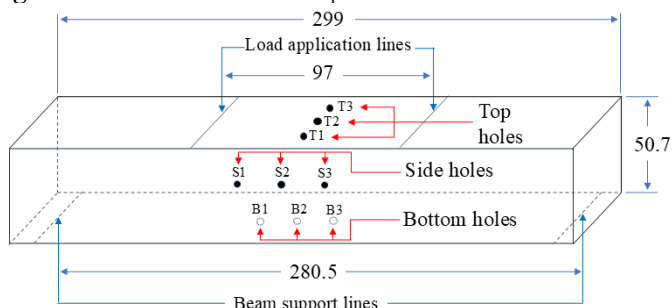


Figure 7. Hole locations on the top, bottom, and side surfaces of the beam (dimensions in mm)

2.6 Finite Element Analysis

To accurately compute residual stresses based on actual loading and boundary conditions, a finite element model was developed by using Ansys 18. Plane stress element type 182 was used for the analysis. The element edge size was set to 0.5 mm, resulting in a total of 60398 square elements with 61098 nodes. It is noted that

further reduction of element size didn't result in any change in the results. Loading was applied in two steps. In step one, a 93 kN downward load was applied, which led to plastic deformation of the beam. The second operation consisted of the unloading of loads and permitted springback deformation. Figures 8 and 9 represent the residual stress and strain distribution resulting from FE analysis along the axial axis of the beam, respectively, in the midpoint section, where both the influence of support constraints and outside loads are zero. Table 3 summarizes the results at the midpoint section of the beam of selected nodes and their respective values.

Table 2. Holes positions and coordinates on the top, bottom and side surfaces of the beam

Surface	Hole	X (mm)	Y (mm)
Top	T1	146.8	10.9
	T2	148.6	22.1
	T3	149.2	36.3
Side	S1	129.6	17.4
	S2	148	17.5
	S3	166	18.4
Bottom	B1	143.8	18.1
	B2	167.1	18.7
	B3	186	20.6

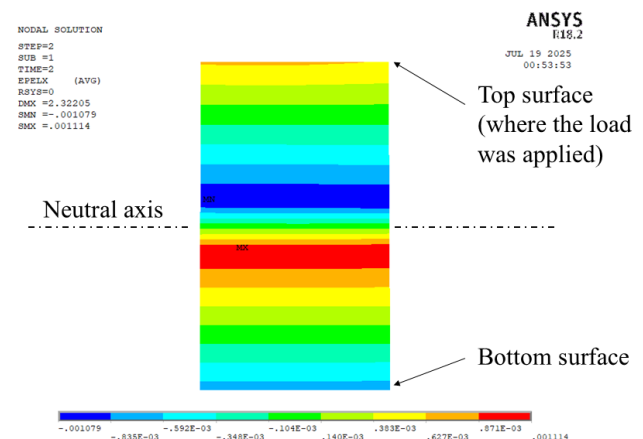


Figure 8. Residual stresses (from FEM) in the axial direction of the beam at the mid-section

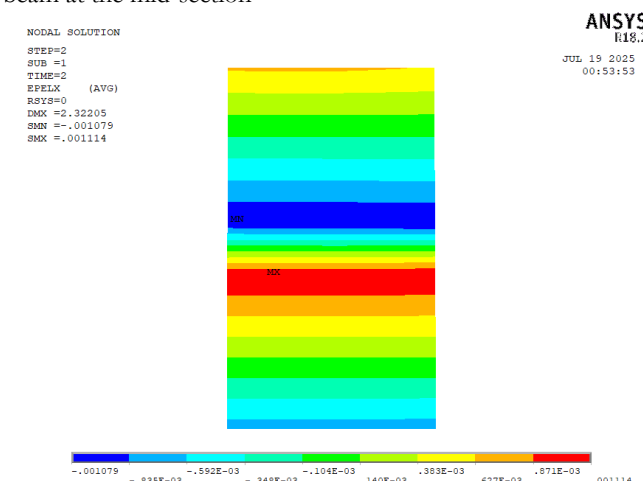


Figure 9. Residual strains (from FEM) in the axial direction of the beam at the mid-section

Table 3. FEM results at the midpoint section of the beam of selected nodes and their respective values

Node No	X (mm)	Y (mm)	Residual stress (MPa)	Residual strain
20300	150	0	-48.28	-6.90E-04
30888	150	2	-37.4	-5.34E-04
30892	150	4	-25.705	-3.67E-04
30896	150	6	-13.971	-1.99E-04
30900	150	8	-2.2112	-3.12E-05
30904	150	10	9.5593	1.37E-04
30908	150	12	21.329	3.05E-04
30912	150	14	33.086	4.74E-04
30916	150	16	44.823	6.42E-04
30920	150	18	56.53	8.09E-04
30924	150	20	68.197	9.76E-04
30928	150	22	71.202	1.02E-03
30932	150	24	27.33	3.93E-04
30936	150	26	-15.285	-2.16E-04
30940	150	28	-57.935	-8.25E-04
30944	150	30	-69.249	-9.86E-04
30948	150	32	-57.876	-8.24E-04
30952	150	34	-46.546	-6.62E-04
30956	150	36	-35.256	-5.01E-04
30960	150	38	-24	-3.41E-04
30964	150	40	-12.765	-1.80E-04
30968	150	42	-1.5394	-2.05E-05
30972	150	44	9.6926	1.39E-04
30976	150	46	20.95	3.00E-04
30980	150	48	32.253	4.61E-04
30984	150	50	43.626	6.23E-04
20582	150	50.5	45.731	6.54E-04

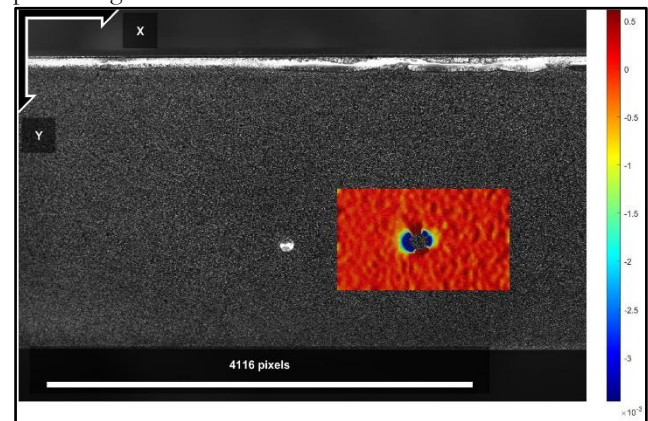
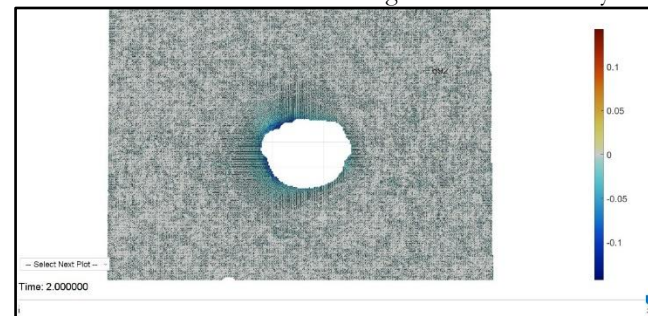
3. Results and Discussion

3.1 2D-DIC Versus 3D-DIC Measurements

Figure 10 illustrates the strain field around the drilled hole (S2) on the side surface of the beam, which was obtained through 2D-DIC analysis via Ncorr while Figure 11 presents the strain field around the same hole resulting from 3D-DIC analysis via DuoDIC. The hole-drilling procedure given in ASTM E837-13a was modified to use full-field digital image correlation measurements instead of the traditional strain gauges. The strain relief was measured in an annular area between 2- 2.5 times the radius of the hole center, avoiding strain gradient regions around the hole edge. The strain components were extracted at three angular positions (0° , 90° , and 225°) with respect to the beam longitudinal axis. The components of residual stress were obtained by substituting the extracted strain components in Equation (1) to obtain a system of three linear equations, which was solved to obtain the σ_x , σ_y and τ_{xy} . Tables 4-6 summarize the measurement of the residual stress of 2D-DIC, 3D-DIC, and finite element (FE) analysis of the top, bottom, and side surfaces of the beam, respectively. The average agreement between 2D-DIC and FE predictions was between (87 - 90 %) and (91 – 94%) for 3D-DIC. These results indicate that both DIC methods are capable of measuring tensile and compressive residual stresses under the same experimental conditions, with a trend of greater correspondence between 3D-DIC and numerical approximations.

3.2 Accuracy Variance Assessment

Although the geometry of the beam surface was flat, a perfect scenario to apply 2D-DIC, the average agreement ratio of 3D-DIC with FE predictions (93%) was higher than that of 2D-DIC (88%). This is mainly due to the capability of 3D-DIC to measure out-of-plane displacements and also, it eliminates the sensitivity to the surface tilt and misalignment of the camera. Conversely, 2D-DIC is by nature sensitive to in-plane deformations, and thus it is more susceptible to inaccuracies caused by minor misalignments or out-of-plane movement. Previously, the camera misalignment sensitivity of 2D-DIC is quantitative. Indeed, in 2D-DIC measurements, Hagara et al. [15] found that a 0.125° camera tilt can cause strain errors of between 14-21%. Although direct camera tilt measurements were not conducted in this study, this aspect is acknowledged and provides a reasonable explanation for the reduced concordance of 2D-DIC compared to 3D-DIC. On practical considerations, enhanced accuracy of 3D-DIC is coupled with complexity in the system. Stereo cameras should be thoroughly calibrated and have a series of processing steps, including the camera calibration, 2D correlation, stereo reconstruction and post-processing. Whereas 3D-DIC would be beneficial when considering complex geometries or large out-of-plane deformation, 2D-DIC is also a viable option when quick in-plane measurements and less processing time are the criteria.

**Figure 10.** Strain distribution $[\epsilon]_{xx}$ around the hole S2 on the side surface of the beam resulting from 2D-DIC analysis**Figure 11.** 1st principal strain distribution around the hole S2 on the side surface of the beam resulting from 3D-DIC analysis**Table 4.** Residual stress measurements and agreement ratios relative to FEA for the top surface

Hole	FEA Result (MPa)	2D-DIC Result (MPa)	Agreement ratio (%)	3D-DIC Result (MPa)	Agreement ratio (%)
T1	43.37	38.32	88.356	40.34	93.0136
T2	43.37	37.77	87.0878	39.94	92.0913
T3	43.37	37.53	86.5345	40.87	94.2356

Table 5. Residual stress measurements and agreement ratios relative to FEA for the bottom surface

Hole	FEA Result (MPa)	2D-DIC Result (MPa)	Agreement ratio (%)	3D-DIC Result (MPa)	Agreement ratio (%)
B1	-45.88	-39.8	86.748	-43.69	95.2267
B2	-45.88	-41.03	89.4289	-40.92	89.1892
B3	-45.88	-41.45	90.3444	-41.37	90.17

Table 6. Residual stress measurements and agreement ratios relative to FEA for the side surface

Hole No.	FEA Result (MPa)	2D-DIC Result (MPa)	Agreement ratio (%)	3D-DIC Result (MPa)	Agreement ratio (%)
S1	50.681	46.89	92.5199	47.96	94.6311
S2	51.12	45.07	88.1651	48.85	95.5595
S3	62.37	57.02	91.4222	58.04	93.0576

3.3 Proposed Technique Limitations

The limitations of this study include:

- The validation finite element model is developed based on a two-dimensional plane-stress assumption. Although this method offers a clear and viable benchmark of comparative analysis, it would not be responsive enough to three-dimensional stress-relief effects due to hole drilling, namely, out-of-plane deformation and through-thickness stress redistribution. It is a limitation that is taken into account when analyzing the discrepancies between 3D-DIC measurements and numerical predictions, and it encourages future research that uses fully three-dimensional finite element simulations.
 - In this study, the calibration coefficients used in ASTM E837 were used as an approximation. Plastic bending produces a non-uniform residual stress field across the thickness of the beam, and the ASTM formulation assumes uniform stress. This discrepancy is known to be one of the factors leading to differences between finite element predictions and experimental results.
 - The use of incremental drilling was also not done because of the high demand for highly accurate depth management that requires the appropriate quality of drilling tools and a sophisticated positioning system. Lack of depth accuracy may create significant uncertainty in the assessment of stress. This practical limitation is thus cited as a limitation of the current study and a focus point of concern in future studies to ensure that non-uniform residual stress distributions are addressed more precisely.
 - The single hole geometry (2 mm diameter and 1 mm depth) was chosen based on the ASTM E837 guidelines to reduce the number of additional experimental variables and use standard calibration coefficients directly. The lack of a parametric study of the effects of the diameter-to-depth ratio is admitted as a weakness and suggested as a future research direction.
 - The stresses induced by drilling were assumed to be small compared to the existing residual stress field. However, the possibility of the effects of drilling is not disregarded and it is suggested that correction models or incremental drilling plans be included in future research.
- Even with these constraints, the suggested methodology is not confined to aluminum 7075-T651. It can also be generalized to other metallic materials and other sources of residual stress like welding, shot peening as well as machining, as long as material isotropy and mainly elastic stress relief assumptions hold. In the case of materials that are strongly anisotropic or have extremely non-uniform stress

distributions, complex calibration methods and 3D numerical models may be needed.

4. Conclusions

This paper has provided a direct experimental comparison between 2D and 3D-DIC integrated with the hole-drilling method for measuring residual stress under plastic deformation conditions. The two methods successfully measured tensile and compressive residual stresses under the same experimental conditions, which displays their potential in practical use. A comparison with finite element predictions revealed that 3D-DIC was more accurate than 2D-DIC (93% vs 88% agreement), on flat surfaces where 2D-DIC should be highly appropriate. This improvement is attributed to the fact that 3D-DIC is able to consider the out-of-plane deformation and is less sensitive to camera misalignment. The findings reveal a concession between the accuracy of measurements and the complexity of the system. Although 3D-DIC is more accurate, 2D-DIC can still be used as an option that is efficient and reliable in in-plane measurements, where simplicity and lower processing time are essential factors. Future studies are supposed to be directed towards applying the methodology to non-linear or curved geometries, adopting incremental drilling operations, and adopting fully 3D FEA to enhance the assessment of non-uniform residual stress fields.

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