Non-Uniform Residual Stress Measurement Using Incremental Hole-Drilling Method and Digital Image Correlation

D. Halabuk[1a] and M. Vajdák[2]

[1] Institute of Solid Mechanics, Mechatronics and Biomechanics, Brno University of Technology, Technická 2896/2, 616 69 Brno, Czech Republic,

[2] X-Sight s.r.o., Staňkova 557/18a, 602 00 Brno, Czech Republic

[a] david.halabuk@vutbr.cz

Abstract. The hole-drilling method is a widely used technique for residual stress measurement, traditionally relying on strain gauge rosettes to detect deformation from material removal. Optical methods, such as Digital Image Correlation (DIC), offer several advantages, including full-field deformation measurements and simplified experimental procedures by eliminating complex strain gauge installation and alignment requirements. This study explores the application of DIC for measuring residual stresses in steel specimens under non-uniform stress conditions. Incremental hole-drilling experiments were conducted, employing DIC to capture full-field deformation data. Controlled stresses were introduced using a four-point bending fixture, enabling comparison between measured and applied stresses. The results indicate that combining DIC with the hole-drilling method is a promising alternative to conventional strain gauge approaches.

Introduction

The hole-drilling method is a widely used technique for measuring near-surface residual stresses due to its versatility and applicability to various materials and geometries. Traditionally, this method employs strain gauge rosettes to measure deformation resulting from stress relaxation as a small hole is incrementally drilled into the material's surface. However, strain gauge rosettes provide limited information, collecting data only at discrete points. Moreover, precise surface preparation without inducing additional stresses, accurate alignment of the rosette relative to the hole, and secure bonding of the strain gauges are critical for obtaining reliable measurements. An alternative to strain gauge-based measurement is optical methods, such as Moiré Interferometry, Holographic Interferometry, Electronic Speckle Pattern Interferometry, and Digital Image Correlation (DIC) [1]. These techniques offer non-contact, full-field measurements of surface deformations. While interferometric methods provide high precision, they require specialized equipment and controlled environments. In contrast, DIC is easier to implement, less sensitive to environmental conditions, and applicable across a wider range of materials and practical applications [2-4].

Method

The applicability of DIC for measuring residual stresses in steel specimens subjected to non-uniform stress distributions was investigated in this study. Specimens were loaded using a bending fixture, simulating residual stresses through controlled applied stresses (Fig.1). A fine, random speckle pattern was applied to each specimen's surface, serving as a unique "fingerprint" for tracking surface displacements. Incremental hole drilling was performed in 20 steps, creating a hole approximately 2 mm in diameter. After each incremental drilling step, images of the area surrounding the drilled hole were captured using a telecentric lens combined with a high-resolution machine vision camera. The images were post-processed using Alpha (X-Sight) software to quantify surface displacements resulting from stress relaxation.

To evaluate residual stresses from measured displacement fields, calibration coefficients are required. While analytical solutions exist for thin plates with through-holes, finite element simulations are necessary for accurately determining calibration coefficients in complex, three-dimensional stress states associated with blind holes. Therefore, a finite element model was developed using ANSYS to calculate these coefficients.

Since the number of displacement measurement points significantly exceeded the number of unknown parameters, a least squares method was employed to evaluate stresses. In addition to the stresses at each depth of the drilled hole, rigid-body motion artefacts were identified and separated from the measured displacement data [5].

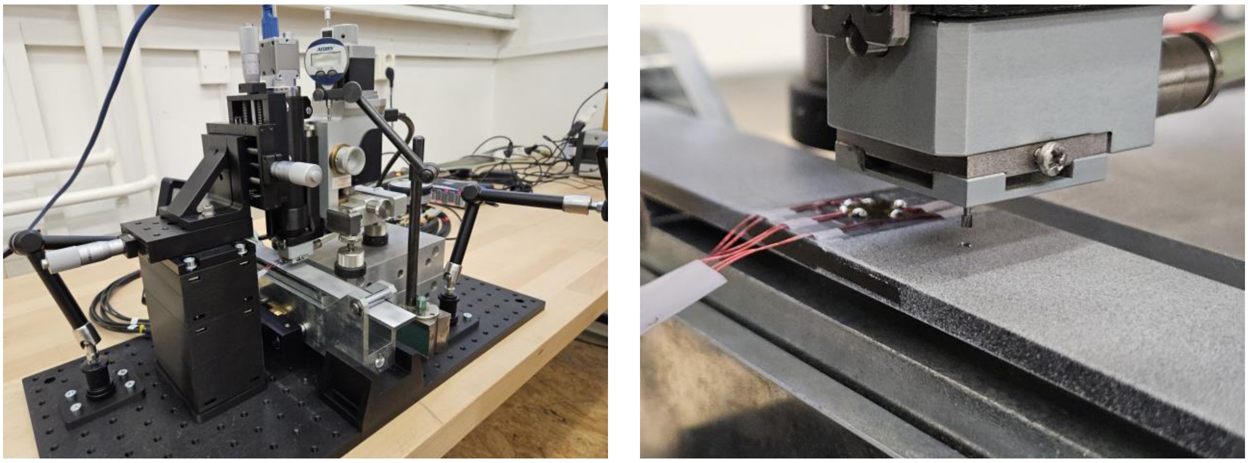

Fig. 1 Experimental setup (left) and detailed view of the drilling head (right)

Result and Discussion

Examples of measured displacement fields around the drilled hole at the 5th and 20th depth increments are shown in Fig. 2. At the initial depth increments, the signal-to-noise ratio was relatively low, making the displacement gradient caused by the drilled hole barely distinguishable. However, fitting an analytical model to the measured data allowed for accurate determination of the applied stresses while mitigating the impact of measurement noise. As the drilling depth increased, the magnitude of measured displacements significantly exceeded the noise level, resulting in displacement fields that closely matched theoretical predictions.

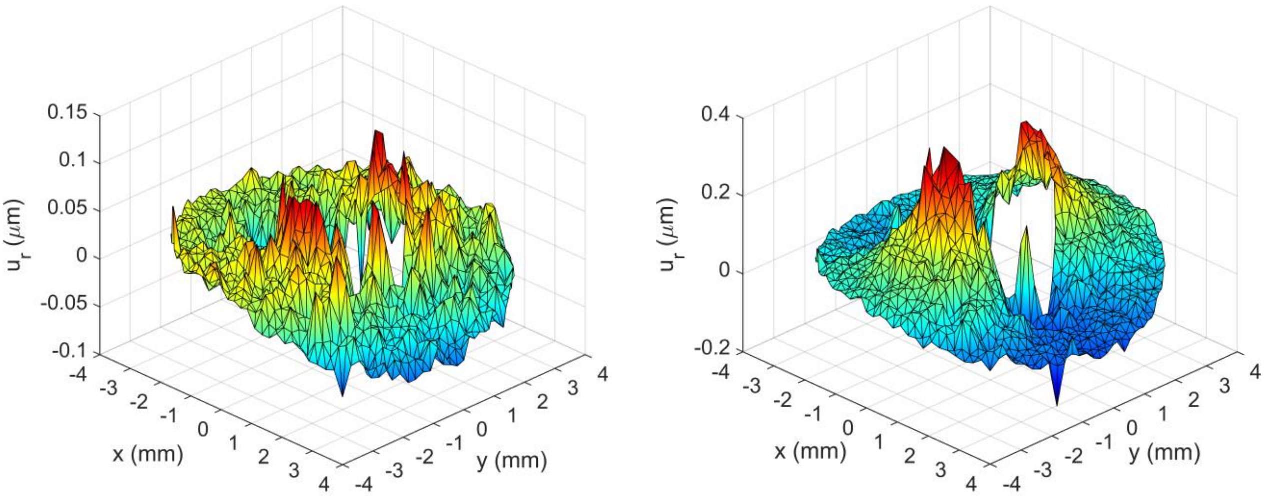

Fig. 2 Measured radial displacements around the drilled hole at the 5th depth increment (left) and the 20th depth increment (right), with rigid-body motion artefacts removed

Conclusion

Since stresses were introduced using a four-point bending fixture, direct comparisons between measured and applied stresses were possible. The results indicate that combining the hole-drilling method with DIC is a promising alternative to traditional strain gauge-based residual stress measurement.

References

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