ANALYSIS OF TOTAL RESIDUAL STRAINS AROUND COLD-EXPANDED HOLES

K. Amjad[1a], E.A. Patterson[1] and W.C. Wang[2]

[1]School of Engineering, University of Liverpool, The Quadrangle, Brownlow Hill, Liverpool L69 3GH, UK
[2]Department of Power Mechanical Engineering, National Tsing Hua University, 101, Section 2, Kuang-Fu Road, Hsinchu, Taiwan 30013, R.O.C.

[a]khurram.amjad@liverpool.ac.uk

Abstract. Split-sleeve cold expansion was performed on a fastener hole in an Aluminium plate and the full-field total residual strains were measured around the expanded hole using a digital image correlation stereo vision system. The results show that the hole expansion is not axisymmetric and the residual strains are highest in the region where sleeve split was positioned. An unexpected trend of decreasing minimum principal strain gradient close to the hole edge was also observed which has not been reported elsewhere in the published literature.

Introduction

Thousands of fastener holes are used in the assembly of aircraft structures. It is a routine practice in the aerospace industry to cold-work such fastener holes to enhance the fatigue life of new and existing aerospace structures. Cold-working or cold expansion is normally performed by passing a mandrel through a fastener hole to expand it plastically. This creates a ring of residual compressive stresses around the cold-expanded (CX) hole which is believed to inhibit the fatigue crack growth. Researchers in the past have applied different experimental mechanics techniques such as moiré photography [1], moiré interferometry [2] and the grid method [3] to measure total residual strains (elastic + plastic) around holes resulting from cold expansion. More recently digital image correlation (DIC) [4] has been used to measure full-field total residual strains around CX holes. This paper presents an experimental analysis of the total residual strain field which develops around the CX hole, using a DIC stereo vision system.

Experimental Procedure

Cold Expansion Test setup. The most widely used cold expansion process called 'split-sleeve cold expansion' (FTI. Seattle, USA) involves passing a hardened steel mandrel with an oversized head through an initially undersized fastener hole. A schematic of this process is shown in Figure 1. There is an internally lubricated sleeve, with a split in it, which resides on the mandrel shank. The purpose of this sleeve is to avoid direct contact of the mandrel head with the internal hole edge in order to keep hole distortion to minimum during the hole expansion. In this work, split-sleeve cold expansion was performed on a rectangular specimen containing a centrally drilled hole of 6.35mm diameter. The specimen was cut from 1.6mm thick ALCLAD 2024-T3 Aluminium sheet. The specimen dimensions are provided in Figure 2. During the expansion process, the orientation of the sleeve split was along the 3 o'clock direction as shown in Figure 2. The nominal diameter of the expanded hole was 6.58mm, providing the final hole expansion of about 3.6%.

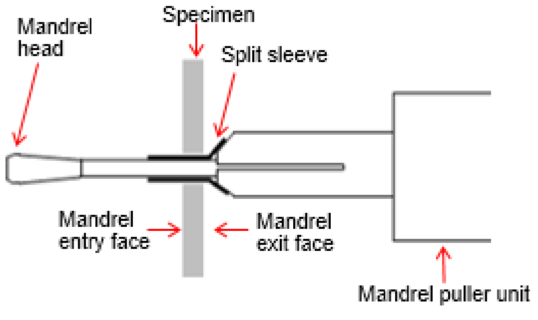

Fig 1. Schematic of split-sleeve cold expansion

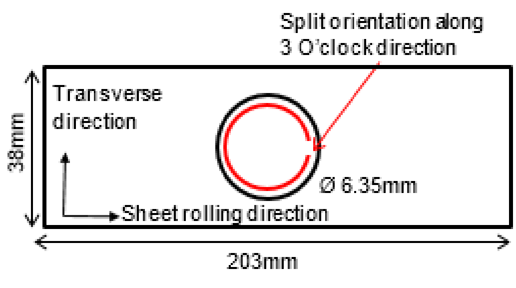

Fig 2. Aluminium specimen dimensions

Measurement of total residual strains. A DIC stereo vision system (Dantec Dynamics GmbH, Germany) was used to measure total residual strains around the hole, on the mandrel entry face of the specimen, resulting from split-sleeve cold expansion. The stereo vision setup comprised of two identical digital video cameras (Guppy PRO F-125, Allied Vision Technologies, Germany) with resolutions of 1292×964 pixels. The two cameras were mounted with a matched pair of compact 50mm focal length lenses (Schneider Kreuznach, Germany) which provided a common field of view (FOV) of about 26mm×19mm from a working distance of approximately 300mm from the specimen surface. For the FOV used in this optical setup, the spatial resolution of 0.02mm/pixel was achieved. A series of images, recorded by the two cameras, at different loading steps during hole expansion, were processed using a DIC software, ISTRA (Dantec Dynamics GmbH). This DIC software performs the evaluation by discretizing the undeformed (reference) image into small square regions called facets. Each facet in the reference image is located in the deformed image using correlation algorithms to determine a displacement vector.

Experiment Results

Image correlation was performed using a facet size of 35 pixels and a grid spacing of 5 pixels, which is simply a distance between the centers of the adjacent facets in the reference image. The evaluated total residual maximum (ε_1) and minimum (ε_2) principal strain maps are shown in Figure 3a and 3b respectively. In order to analyse the deviation of split-sleeve hole expansion from the ideal (axisymmetric) hole expansion, a map of shear strain ($\varepsilon_{r\theta}$) in polar coordinates was evaluated using the strain transformation equations (Fig 3c). The line plots of principal strains were also produced along six radial directions, as shown in Figure 4.

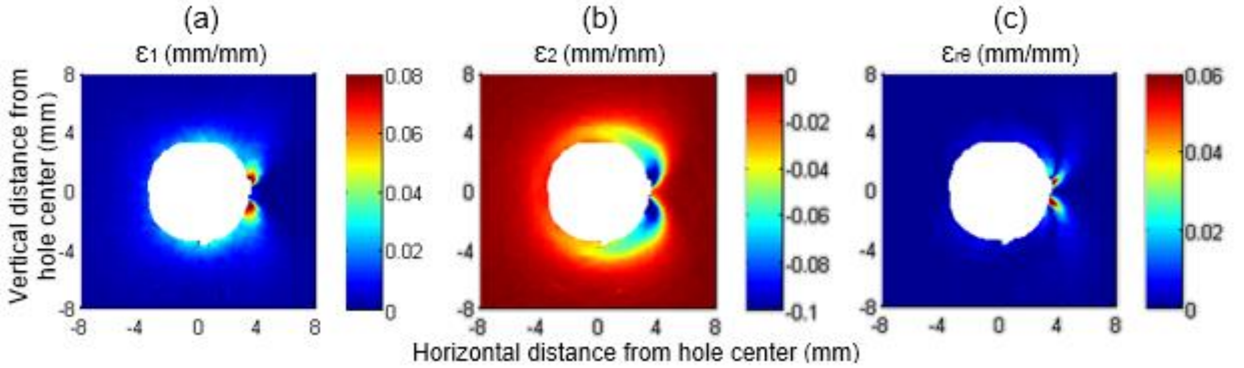

Fig 3. Total residual strain maps

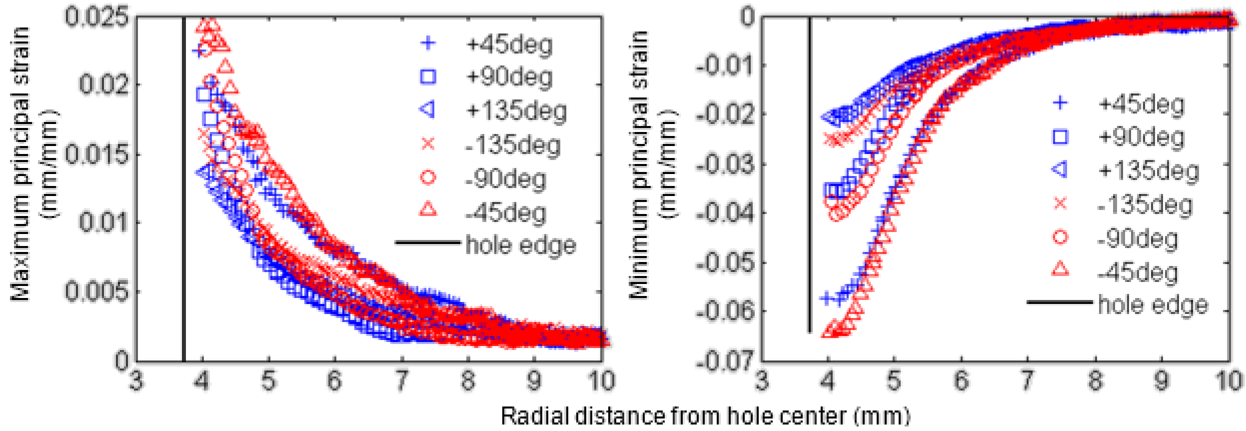

Fig 4. Line plots of principal strains along six radial directions (θ +ve CCW from split orientation)

Discussion and Conclusions

In case of axisymmetric hole expansion, hoop and radial strains are equivalent to the maximum and minimum principal strains respectively which is not true for the split-sleeve cold expansion. As shown in Figure 3c, there is a component of polar shear strain ($\varepsilon_{r\theta}$) close to the hole edge and it is particularly significant in magnitude in the region around sleeve split position. The radial line plots of total residual principal strains in Figure 4 clearly indicate that the hole deformation is most severe near to the sleeve split position (see ±45° plots) and the deformation decreases away from it (±135° plots). An interesting and unexpected trend of decreasing minimum principal strain gradient close to the hole edge can be observed for all six radial line plots. According to author`s knowledge, this trend has not been reported so far in the published literature. Future work will focus on understanding and identifying the cause of this trend. This knowledge will be potentially very significant in making improvements in the analytical and/or computational modelling of the split-sleeve cold expansion process which will in turn lead to better predictive capability for the fatigue life of CX holes.

References

[1] G.L. Cloud: *Measurement of Strain Fields Near Coldworked Holes*, Experimental Mechanics, Vol. 20 (1980) p 9-16.

[2] R.E. Link and R.J. Sanford: *Residual Strains Surrounding Split Sleeve Cold Expanded Holes in 7075-T651 Aluminium*, Journal of Aircraft, Vol. 27 (1990) p 599-604.

[3] D.L. Ball and D.R. Lowry: *Experimental Investigation on the Effects of Cold Expansion of Fastener Holes*, Fatigue and Fracture of Engineering Materials and Structures, Vol. 21 (1998) p 17-34.

[4] D. Backman, M. Liao, L. Yanishevsky and E.A. Patterson: *The use of digital image correlation in a parametric study on the effect of edge distance and thickness on residual strains after hole cold expansion*, Journal of Strain Analysis for Engineering Design, Vol. 43 (2008) p 781-789.