Experiment Report Form

The double page inside this form is to be filled in by all users or groups of users who have had access to beam time for measurements at the ESRF.

Once completed, the report should be submitted electronically to the User Office via the User Portal:

https://wwws.esrf.fr/misapps/SMISWebClient/protected/welcome.do

Reports supporting requests for additional beam time

Reports can be submitted independently of new proposals – it is necessary simply to indicate the number of the report(s) supporting a new proposal on the proposal form.

The Review Committees reserve the right to reject new proposals from groups who have not reported on the use of beam time allocated previously.

Reports on experiments relating to long term projects

Proposers awarded beam time for a long term project are required to submit an interim report at the end of each year, irrespective of the number of shifts of beam time they have used.

Published papers

All users must give proper credit to ESRF staff members and proper mention to ESRF facilities which were essential for the results described in any ensuing publication. Further, they are obliged to send to the Joint ESRF/ ILL library the complete reference and the abstract of all papers appearing in print, and resulting from the use of the ESRF.

Should you wish to make more general comments on the experiment, please note them on the User Evaluation Form, and send both the Report and the Evaluation Form to the User Office.

Deadlines for submission of Experimental Reports

- 1st March for experiments carried out up until June of the previous year;
- 1st September for experiments carried out up until January of the same year.

Instructions for preparing your Report

- fill in a separate form for each project or series of measurements.
- type your report, in English.
- include the reference number of the proposal to which the report refers.
- make sure that the text, tables and figures fit into the space available.
- if your work is published or is in press, you may prefer to paste in the abstract, and add full reference details. If the abstract is in a language other than English, please include an English translation.

ESRF	**Experiment title:** Mapping of Residual Strains Around Cold-expanded Holes	**Experiment number**: ME1378
Beamline: ID22	**Date of experiment**: from: 08/05/2015 to: 11/05/2015	**Date of report**: 11/08/2015
Shifts: 9	**Local contact(s)**: Andy Fitch	

Names and affiliations of applicants (* indicates experimentalists):

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Introduction:

Cold expansion is a well-established technique used in the aerospace industry to enhance the fatigue life of fastener holes in aircraft structures. One of the most widely used cold expansion processes called 'split-sleeve cold expansion' (FTI. Seattle, USA) involves passing a hardened steel mandrel with an oversized head through an initially undersized fastener hole which creates a ring of compressive residual stresses around the expanded hole. 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. The investigation presented in this report utilised the high resolution powder diffraction beamline, ID22 at ESRF, to evaluate the impact of fatigue crack initiation from a cold-expanded hole on the beneficial compressive residual stresses around it.

Experiment Procedures

Two rectangular coupons, with a geometry shown in Figure 1, were manufactured from a 6.35mm thick 2024-T351 Aluminium plate. A central hole was drilled and reamed to a final diameter of 6.36mm in both the coupons. The cold expansion of the holes was performed using a FTI cold expansion kit. The nominal diameter of the cold-exanded holes was measured to be 6.58mm, providing a retained expansion of 3.6%. One of the coupons after cold expansion was loaded under constant amplitude fatigue loading (σ_{max}=170MPa, R=0.1) for a total period of about 150k cycles at a frequency of 19Hz. The crack initiation was monitored during fatigue loading on both the coupon faces and a crack growth of 2mm was observed on either sides of the hole edge (along 90° & 270° directions from the sleeve split) at the mandrel entry face of the coupon. The mandrel entry and the mandrel exit faces are referred to the coupon faces from where the mandrel enters or leaves the coupon respectively, during cold expansion.

The prior full-field strain measurements using digital image correlation showed that the total strain (elastic + plastic) field developed around the cold-expanded hole was symmetric about an axis coincident with a diameter through the location of the split sleeve. This piece of knowledge was very helpful in identifying a region around a small portion of the hole (see blue shaded area in Figure 1) for the residual strain mapping

using x-ray diffraction measurements, which could provide information about the overall residual strain field around the whole cold-expanded hole. All the x-ray diffraction measurements were performed in a transmission geometery using a beam size of 0.3×0.3 mm^2 at a beam energy of 60keV. At this beam energy, the (311) diffraction in Aluminium was obtained at $2\theta \approx 9.7^o$, giving the longitudional gauge volume dimension of approximately 3.55mm. For the purpose of evaluating residual strains, the unstrained Aluminium (311) lattice spacing was determined by taking several measurements on a sample from the same 2024-T351 Aluminium plate that has been machined into a comb teeth structure.
In the un-cracked coupon, x (longitudinal) and y (transverse) direction residual strains were measured over a region represented by the blue area in Figure 1, defined at a depth of 2mm from the mandrel entry face. The matrix of measurement points in the blue area had a uniform spacing of 0.4mm. In order to determine the through-thickness variation of residual strains, the x and y direction strain maps were also produced from regions represented by the green and the red areas in Figure 1, at a depth of 2mm from the mandrel exit face. The matrices of measurement points in the red and the green areas were the subsets of a larger matrix of measurement points in the blue area. For the cracked coupon, the longitudinal and transverse residual strains were measured in a region around the hole from where one of the fatigue cracks was initiated i.e. the red area in Figure 1, at the depths of 2mm from the both the mandrel entry and the mandtrel exit faces of the coupon. After performing the originally planned scans described above, a small amount of remaining beamtime was utilised to scan the green area again in the un-cracked coupon at a depth of 2mm from the mandrel entry face, this time, using a measurement point spacing of 0.2mm. The purpose of this scan was to establish the reproducibilty of residual strain values to gain more confidence over the measurements performed and also to determine the steepness of the stress gradients by increasing the density of measurement points in the scan area.

Results and Discussions
The corresponding longitudinal and transverse residual strain maps were converted into residual stress maps by applying the Hooke`s law assuming plane stress conditions. Figure 2 shows the x and y direction stress maps for the un-cracked coupon at depths of 2mm from both the coupon faces. It can be observed that the magnitude of stresses, in particular the compressive stresses, are higher close to the mandrel exit face. This indicates the three-dimensional nature of the cold expansion process. For a more quantitative comparision, line plots of x and y direction stresses (corresponding to radial and hoop stresses) along 0^o and 270^o directions are presented in Figure 3. It is well established that at the location of the sleeve split, there is a negligible expansion of the hole during cold expansion process, therefore, the residual stresses along the split orientation direction (0^o) are expected to be lower in magnitude. It can be observed from Figure 3 that the 0^o hoop stresses are about 50MPa lower than the 270^o hoop stresses close to the hole edge. Considering the negligible hole expansion at the sleeve split location, the hoop stresses are still significantly compressive which indicates that the sleeve split does not cause a severe discontinuity in the beneficial compressive stress field around the cold-expanded hole. As mentioned earlier, the red zone around the cold-expanded hole, shown in Figure 1, contains a fatigue crack of about 2mm (along 270^o direction) in the cracked coupon. The maps of a component of stress perpendicular to the direction of a fatigue crack (y direction), obtained from the red zone at depths of 2mm from both the mandrel entry and the mandrel exit faces, are compared in Figure 4 for the cracked and the un-cracked coupons. No sign of residual stress relaxation could be noticed as a result of fatigue crack growth of 2mm; in fact the residual stresses appear to be slightly more compressive for the cracked coupon in comparison of the un-cracked coupon. One plausible explanation for this could be the process variability of the cold expansion process i.e. there can be a slight variation in the residual stress field developed around the expanded hole for two identical hole expansions. The increase in magnitude of the residual stresses in the cracked coupon could also be due to the interaction of the plastic zone ahead of the crack tip with the surrounding residual compressive stresses, causing them to be more compressive. A key conclusion that can be drawn with certainty from these results is that the beneficial compressive residual stresses, on a macro scale, do not relax as a result of fatigue crack initiation. The effective stress intensity factor at a growing crack tip and thus the remaining fatigue life of the cold-expanded hole could therefore be evaluated quite accurately by superimposing the local compressive residual stresses along a crack over the remote fatigue stresses.

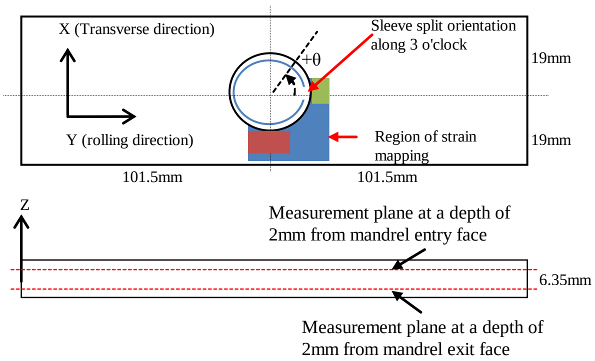

Figure 1. Schematic of specimen geometry

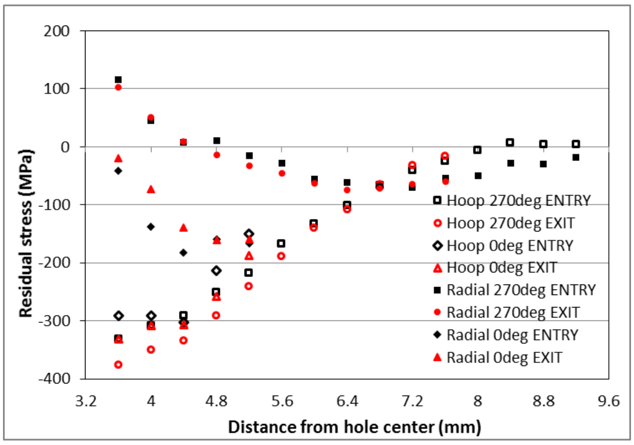

Figure 3. Line plots of radial and tangential residual stresses along 0° & 270° directions from the sleeve split.

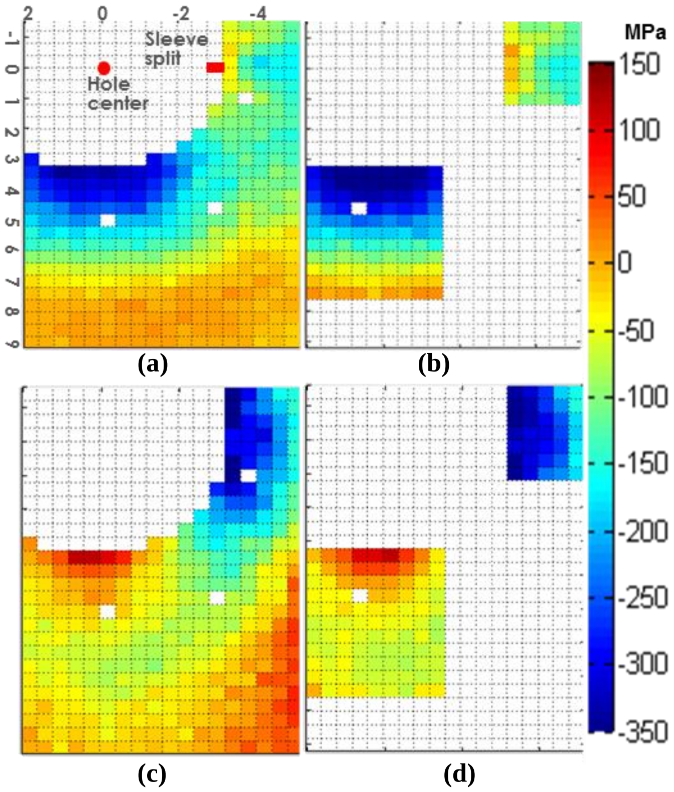

Figure 2. Residual stress maps around the cold-expanded hole in an un-cracked coupon:
(a) Near mandrel entry face Y direction stress map,
(b) Near mandrel exit face Y direction stress map ,
(c) Near mandrel entry face X direction stress map &
(d)Near mandrel exit face X direction stress map.
The spatial dimensions of the maps are in mm, defined from the hole center.

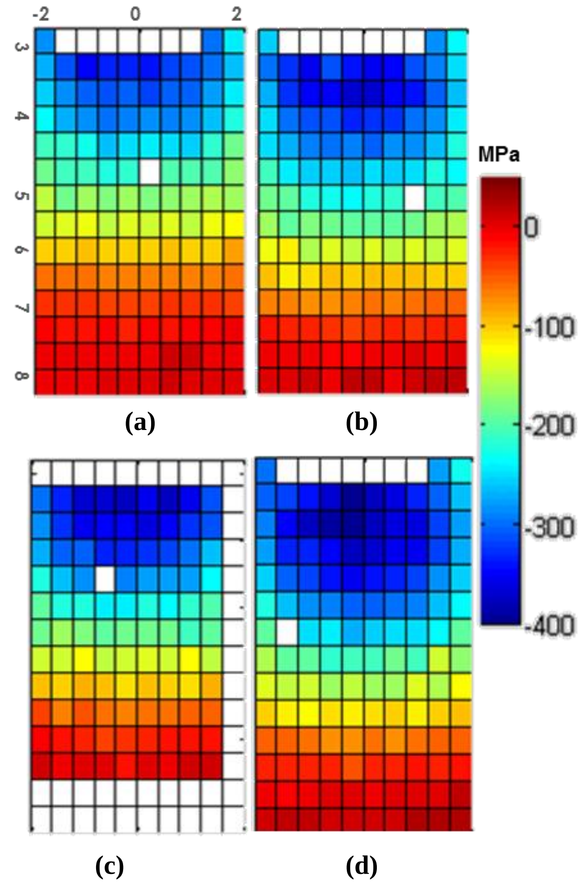

Figure 4. Comparison between the un-cracked and the cracked coupon Y direction stress maps obtained from the scan area shaded in red (see Figure 1):
(a) Un-cracked coupon - near mandrel entry face stress map,
(b) Un-cracked coupon – near mandrel exit face stress map,
(c) Cracked coupon- near mandrel entry face stress map &
(d) Cracked coupon, near mandrel exit face stress map.
The spatial dimensions of the maps are in mm, defined from the hole center.