HETEROGENEITY OF RESIDUAL STRAINS IN PLASTICALLY DEFORMED ZIRCONIUM ALLOYS

N. Letouzé[1], R. Brenner[1], J. L. Béchade[2], M.H. Mathon[3], O. Castelnau[1]

[1]LPMTM, UPR 901, Université Paris 13, Av. J.B. Clément, 93230 Villetaneuse, France
[2]DEN/SRMA, CEA-Saclay, 91191 Gif-sur-Yvette, France
[3]Laboratoire Léon Brillouin (CEA-CNRS), CEA-Saclay, 91191 Gif-sur-Yvette, France

Zirconium polycrystalline alloys widely used in the nuclear industry, especially as cladding tubes and guide tubes for Pressurized Water Reactors (PWR), behave like an heterogeneous material during plastic deformation, because they are made of grains with soft and hard crystallographic orientations. This behaviour is mainly due to the hexagonal close-packed (h.c.p) structure which induces a very large local plastic anisotropy [1].
Two complementary ways are undertaken to investigate the heterogeneity of residual strains in plastically deformed zirconium alloys: experimentally using diffraction techniques (X-ray and neutron diffraction), and numerically with a modelling approach using homogenisation techniques.

✓ On one hand, diffraction gives a statistical analysis of average elastic residual strains and of their fluctuations in the investigated volume (the whole sample volume in the case of neutron diffraction). These mechanical parameters can be extracted respectively from the position and the shape of the peak.

✓ On the other hand, volumic residual strains can also be predicted by homogenisation techniques, providing that the (non-linear) local mechanical behaviour and the microstructure of the material is known. For polycrystals, the self-consistent scheme (the stresses and the strains are not considered as homogeneous between all the phases) is well adapted owing to the approximate random microstructure [2]. However, the extension of the self-consistent scheme to non-linear behaviour is only approximate.

Comparison between elastic strain maps obtained by neutron diffraction experiments performed on 6T1 at the LLB and by a thermo-elasto-visco-plastic self-consistent model have been performed. An example of (0002) pole figure for a Zircaloy-4 specimen deformed by creep at 400°C in tension up to 5% is given Figure 1. One can see on Figure 2 the good agreement between the experimentally determined residual strains obtained for different orientations in the (0002) pole figure defined by their tilt angle χ and rotation angle φ (open circles) and the micromechanical modelling calculation (affine self-consistent scheme, continuous line)

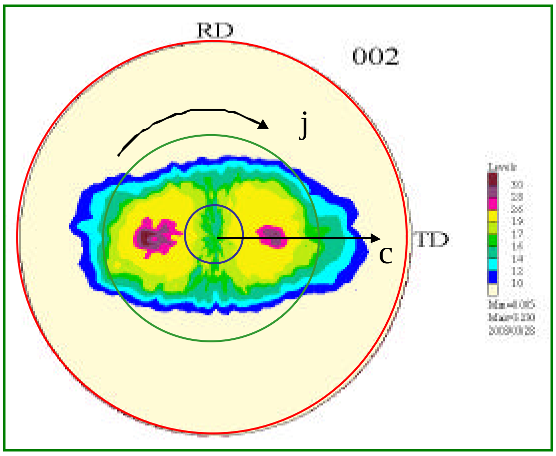

Figure 1. (0002) pole figure measured on a Zircaloy-4 sample deformed by creep at 400°C in tension up to 5% (RD is the rolling direction and TD is the transverse direction)

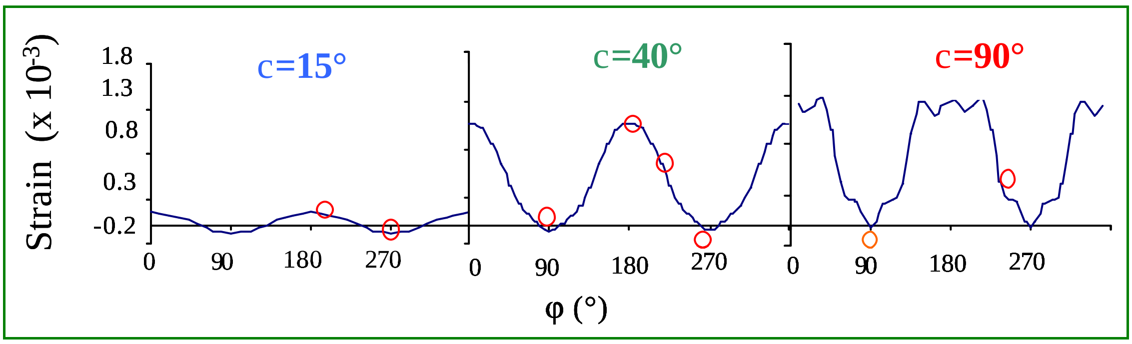

Figure 2. Strain map after thermal creep for different χ angles.

The results obtained show also how diffraction data can be used for the validation of the scale transition model [3] used in the frame of homogenisation methods.

These methods make it possible to estimate or bound the effective behaviour of heterogeneous materials starting from the statistical description of the microstructure (texture) and the knowledge of the mechanical behaviour of the constituents (in this work, we label "phase" a set of grains with the same orientation). They also allow to estimate the intra- and inter-phase fluctuations of the mechanical fields. So the comparison of experimental and calculated strain maps using different non linear approaches, is a promising way for determining the best linearisation procedure.

Figure 3 gives an example of the influence of the linearisation procedure on the prediction of the residual elastic strain for different orientations. In this case, viscoplastic simulation has been performed, using Zircaloy-4 real texture with thermal creep loading in tension at 127 MPa stress level. We used the secant and affine Self Consistent schemes (2 ways of linearization assuming both inhomogeneity of stress and strain) as well as Reuss (stress homogeneity) and Taylor (strain homogeneity) bounds to calculate the phase average stress. Focusing for a particular orientation, here for example at χ=55°, significant differences between several polycrystals models are shown.

One main result is that the Reuss model does not predict any residual strain around the principal orientation (at χ=55°), which is absolutely not realistic. The secant formulation is closer to the prediction of the Taylor bound, whatever χ angle is, the Taylor formulation showing a strain level 10 times higher, for example at χ=55°, and the affine one a strain level 2 times lower compared to the secant formulation. Finally these large discrepancies between different linéarisation procedures would be enough to select the best one when experimental data will be acquired and compared too.

In conclusion, we have shown that neutron scattering provides a volume measurement of the elastic strain distribution in polycrystals on a plastically deformed Zircaloy-4 specimen. Taking into account that the experimental data can be compared rigorously to the results of homogenisation schemes, they may be used for a reliable determination of the local constitutive relation ; this process is a good way for determining the best linearisation procedure in the case of non linear behaviour.

An application to creep loading shows an excellent agreement with the prediction of the **affine self-consistent scheme** for non linear elasto-viscoplasticity (see figure 2). To our knowledge, this result is the first validation of the affine linearisation procedure at a ?nest scale than the macroscopic one.

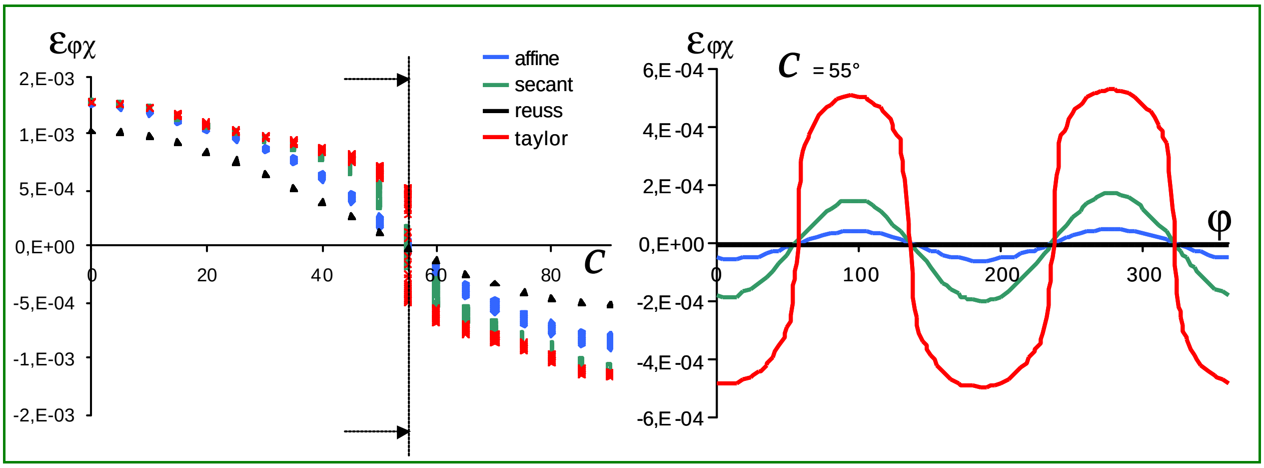

Figure 3. Evolution of the residual strains calculated with several polycrystal models and comparisons for a particular orientation at χ=55°.

References

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