Equivalent True Stress Strain to Failure in Eurofer97 Small-Scale Tensile Tests

R. Spencer[a1], A. Marsh[1], H. Nolles[1], P. Earp[1], D. Andres[1], M. Gorley[1], A. Harte[1], S. Gonzalez De Vicente[2]
[1]UKAEA, Culham Science Centre, Abingdon, Oxfordshire, OX14 3DB, [2]IAEA, Vienna International Centre,
PO Box 100, 1400 Vienna, Austria
[a]Rory.Spencer@UKAEA.UK

Abstract

Small-scale testing is required for materials qualification after exposure to the extreme environment within a nuclear reactor to limit the volumes of hazardous radioactive material under test. Contact extensometry is typically impossible for these small-scale geometries and is undesirable from a radioactive contamination perspective. Therefore, non-contact methods are needed to obtain constitutive parameters necessary for component design codes. Finite Element Model Updating (FEM-U) and Digital Image Correlation (DIC) has been used to determine true stress-strain to failure during tensile tests for three small-scale tensile testing geometries. Results show reasonable agreement for true stress strain between the different specimen geometries and provide materials properties in agreement with those from standard-scale specimens used for validation of component design rules.

Introduction

Eurofer97 is a reduced activation ferritic/martensitic (RAFM) tempered steel with a grain size of 5-10 µm, developed as the reference material for the European DEMOnstration reactor blanket structure. These structures will operate at 350-550 °C and experience high energy irradiation from the thermal-to-14MeV neutron spectrum produced during nuclear reactions in the fusion plasma. RAFM steels were developed to have a lower residual activity after service compared to standard FM steels. Material properties for these materials are necessary to inform component design and lifetime predictions. However, handling large quantities of active material poses considerable challenges. It is therefore essential to develop small scale techniques to limit the volume of active material under test. Recent focus has been on miniature standard tests, which require non-contact methods for quantification of deformation behaviour due to their small size.

DIC is a non-contact measurement technique that tracks the displacements of the surface of a specimen to derive the full-field strain. Specimen surface displacements from DIC can be used to update FE models of the test to derive the stress state.

Method

Three different small-scale tensile specimen geometries were tested: LCF, SSJ-3 and DONES, shown in Fig.1. The 3 DONES and 3 SSJ-3 specimens were from the same batch of Eurofer97, whereas the LCF specimen was from a different batch. The DONES and SSJ-3s were tested in displacement control at a nominal strain rate of 0.06s^{-1}, the LCF at 0.025s^{-1}. An airbrushed speckle pattern was applied to the specimen to facilitate DIC measurements.

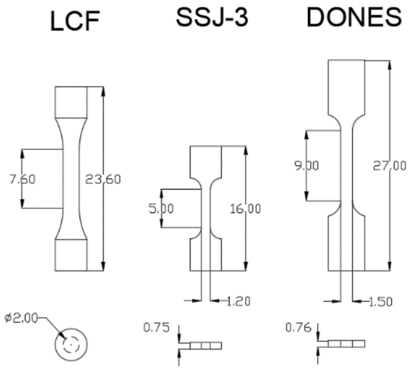

Figure 1 - The three specimen geometries used in this work. Dimensions in mm.

During each test, images were captured of the specimen at 6Hz using a 3D stereo microscope DIC system (*Zeiss, LaVision*). The images were processed in DaVis 10.1. using a 25 pixel subset to extract the displacement and strain fields. A virtual extensometer was used to extract the strain of the gauge length.

A FEM-U routine was developed using Python and ANSYS. A piecewise approach similar to Knitel et al [1] was used. Displacements were incrementally applied to a quarter size model of each specimen and the equivalent true stress of a multilinear isotropic hardening model updated until the disagreement between the model and experimental engineering stress was less than 0.5% for a given strain value.

Additionally, for the LCF specimen, a coordinate transform was performed to translate the data from cartesian to cylindrical coordinates. The radius of the neck a was measured and the curvature R was determined by fitting to the neck geometry in each image. These parameters were used to calculate the Bridgman correction factor [2] and hence determine the equivalent true stress.

Results

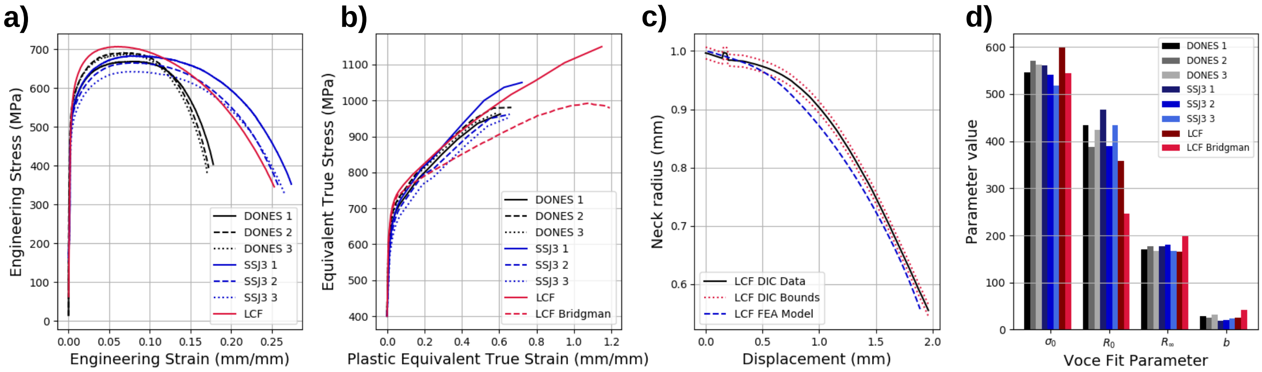

Figure 2 - Engineering stress strain curves (a), calculated equivalent true stress-strain curves to failure (b), change in neck radius for the LCF data (c) and Voce fit parameters (d).

Proof stress calculated from the engineering stress strain curves in Fig 2. are in agreement (within the range of scatter) with values from standard-scale specimens in the Eurofer material property handbook [3].

The results of the FEM-U process gave similar equivalent true stress-strain curves for the three specimen designs, despite the differences in engineering stress-strain curves. Using the Bridgman correction factor results in an under-estimation of the equivalent stress after necking. There is a difference of ~3% between the neck radius as measured via DIC and the neck radius output from the converged model. The model is outside the 95% confidence bounds (±10µm) of the DIC radius measurements.

$$\sigma_Y = \sigma_0 + R_0\varepsilon^{pl} + R_\infty\left(1 - e^{-b\varepsilon^{pl}}\right) \tag{1}$$

A Voce strain hardening model, Eq. 1, has been fit to all true stress strain curves with $R^2 > 0.98$, the results shown on the right of Fig. 2. Such data shows the reproducibility of materials parameters from different geometry specimens when using DIC and FEM-U. This greater confidence in data can be used to reduce conservatism in component design and analysis of performance.

Conclusions

True stress-strain curves have been determined using DIC and FEM-U for Eurofer97 in three small-scale tensile testing geometries. The converged model for the cylindrical LCF specimen shows agreement with experimental DIC geometry measurements prior to failure. True stress-strain calculated using DIC geometry data and the Bridgman correction factor was found to under-estimate the true stress relative to FEM-U. Further work is on-going to robustly validate the modelling approach for each geometry and extend the modelling to high temperature by including a void damage model to account for the increased ductility.

Acknowledgements

The authors would like to acknowledge EPSRC grant EP/T012250/1. This work was also carried out within the framework of the IAEA Coordinated Research Project F13017 “Towards the Standardization of Small Specimen Test Techniques For Fusion Applications”. The views and opinions expressed herein do not necessarily reflect those of the International Atomic Energy Agency.

References

[1] S. Knitel, P. Spätig, and H. P. Seifert, “An inverse method based on finite element model to derive the plastic flow properties from non-standard tensile specimens of Eurofer97 steel,” *Nucl. Mater. Energy*, vol. 9, pp. 311–316, Dec. 2016.
[2] P. W. Bridgman, *Studies in Large Plastic Flow and Fracture*. New York: McGraw Hill, 1952.
[3] E. Gaganidze, F. Gillemot, I. Szenthe, M. Gorley, M. Rieth, and E. Diegele, “Development of EUROFER97 database and material property handbook,” *Fusion Eng. Des.*, vol. 135, no. February, pp. 9–14, 2018.