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INFERRING SUPERELASTICITY PARAMETERS OF NITI SMA FROM INSTRUMENTED INDENTATION DATA

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Abstract. *Among the most important Shape Memory Alloys (SMA), NiTi have been widely investigated because of their outstanding Shape Memory Effect (SME) and Superelasticity (SE), damping capacity and biocompatibility. Given the importance of NiTi SMA, this work will describe uniaxial stress-strain testing of a NiTi shape memory alloy, obtaining best-fit values of the parameters in an FEM model describing this behaviour over a suitable strain range (up to about 10%) and then inverse procedures for inferring these parameters by searching for combinations that maximise the value of g associated with experimental load-displacement plots during indentation. As with plasticity parameters, it is found that use of more than one indenter shape assists in converging on the best-fit solution and optimal "g-scanning" procedures are identified.*

Keywords: *Superelasticity, NiTi, Indentation, Methodology.*

1. INTRODUCTION

Indentation testing is a simple procedure that can be applied to small samples, with minimal preparation. It can also be used to map point-to-point variations in properties over a surface.

Unfortunately, apart from the simple property of stiffness, and the poorly-defined "pseudo-property" of hardness (Oliver and Pharr 1992, Oliver and Pharr 2004), there are no widely-accepted methodologies for obtaining property parameter values from indentation data. This work is oriented towards the development of a procedure for obtaining superelasticity parameters of NiTi SMA in this way.

The work is part of a larger programme aimed at establishing such procedures, and writing associated software packages, for plasticity (including strain rate sensitivity parameters) (Dean and Clyne 2017) and creep (Dean, Campbell et al. 2014). In all cases, the methodology involves iterative FEM simulation of the indentation process, attempting to converge on the set of property parameter values that gives the best fit between predicted and measured indentation outcomes. In the case of superelasticity, the stress-strain relationship that is being sought is a relatively complex one (Duerig, Melton et al. 1990, Otsuka and Wayman 1998, Otsuka and Kakeshita 2002, Otsuka and Ren 2005), involving seven parameter values, although two of these concern the stiffness of the two phases, which are likely to be known.

2. EXPERIMENTAL PROCEDURE

The experimental procedures employed in this work are very straightforward. Indentation was carried out under displacement control, using a large diameter (mm dimensions) sphere. This minimises difficulties associated with surface roughness, oxide films and also ensures that representative (large) sample volumes are interrogated. In addition, use of such an indenter tends to keep the magnitude of the strains in the sample relatively low, which is essential if all of the "plastic" deformation is to take place (reversibly) via phase transformations, rather than dislocation motion. Conventional uniaxial (compression) testing was also carried out. The material used was a standard NiTi shape memory alloy. A typical stress-strain plot for this alloy is shown in Fig. 2a, together with the values of the seven parameters used to characterise this type of plot. These parameters are used within an ABAQUS routine (ABAQUS 2009) that is available for simulation of superelastic deformation.

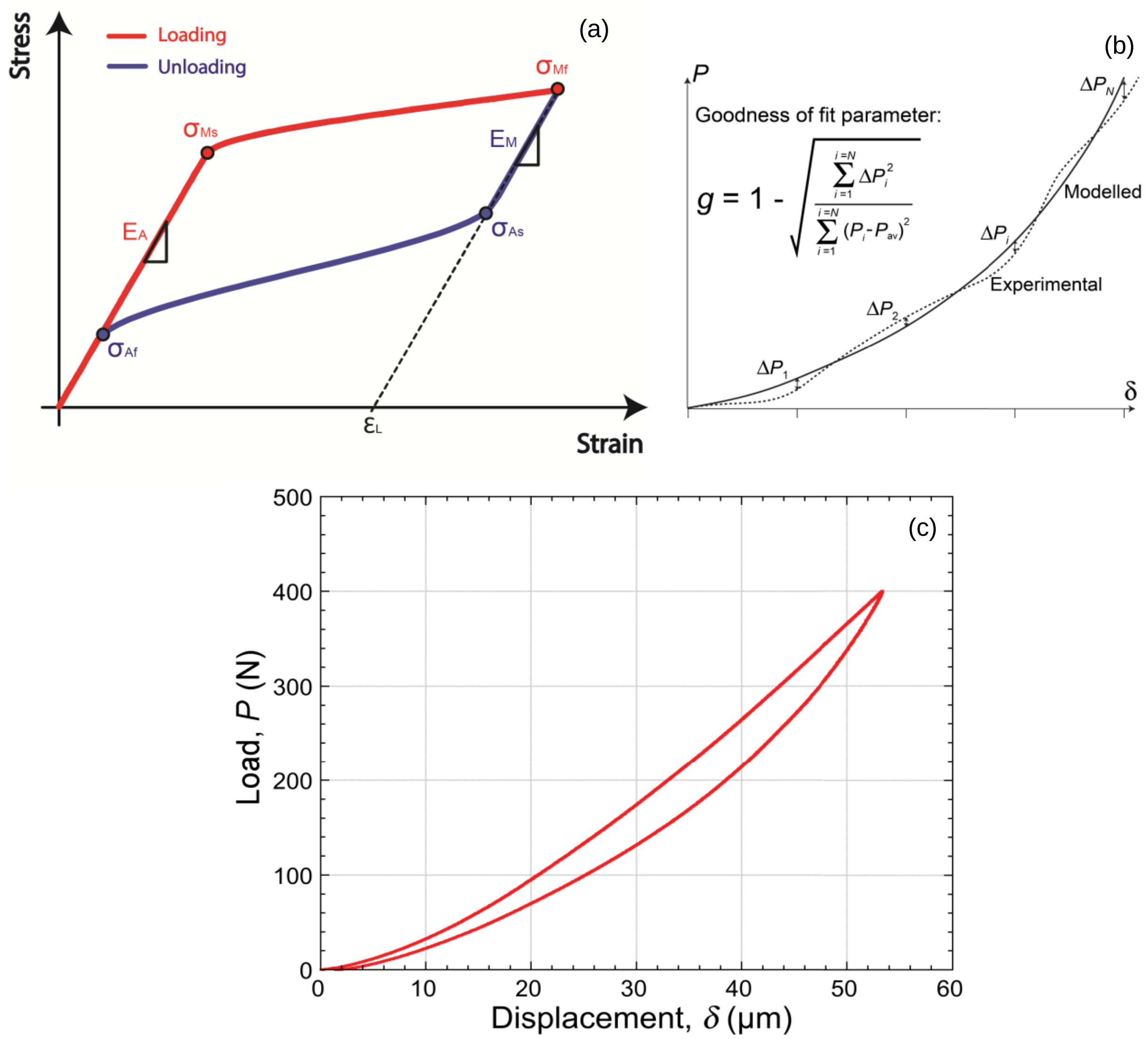


Figure 1. (a) Superelasticity parameters required for simulation of the NiTi behaviour; (b) definition of goodness of fit parameter (g), plus model prediction; (c) Load-displacement plot obtained during indentation of the NiTi alloy.

As with the uniaxial testing, the unloading part of the plot is important, and it can be seen that, for both types of test, there was virtually no residual strain - i.e. no permanent compression of the uniaxial sample and no residual impression after indentation.

If superelasticity parameter values are known, the indentation response is readily predicted. However, the inverse problem (using the indentation response to obtain the parameter values) is the objective here. Iterative FEM to find the set of values giving the best fit with experimental indentation data is impractical without an efficient methodology for converging on the "best-fit" set, and also for evaluating the reliability and uniqueness of this solution. This requires a "goodness of fit" parameter, g, representing the fidelity between predicted and observed outcomes (load-displacement plots in this case). A formulation has been adopted giving $g = 1$ for perfect agreement and $g = 0$ for no correspondence (Dean and Clyne 2017).

Simulation of the indentation process was carried out using the ABAQUS package. The mesh employed for these runs, and a typical strain field at full penetration (i.e. a depth of about 50 μm) are shown in Fig. 2. It can be seen that the peak strains generated with the sample are only about 4%. This is well below the limit for superelastic deformation, which in this alloy is about 7%. This is consistent with the experimental observation of no residual deformation, shown in Fig. 1c.

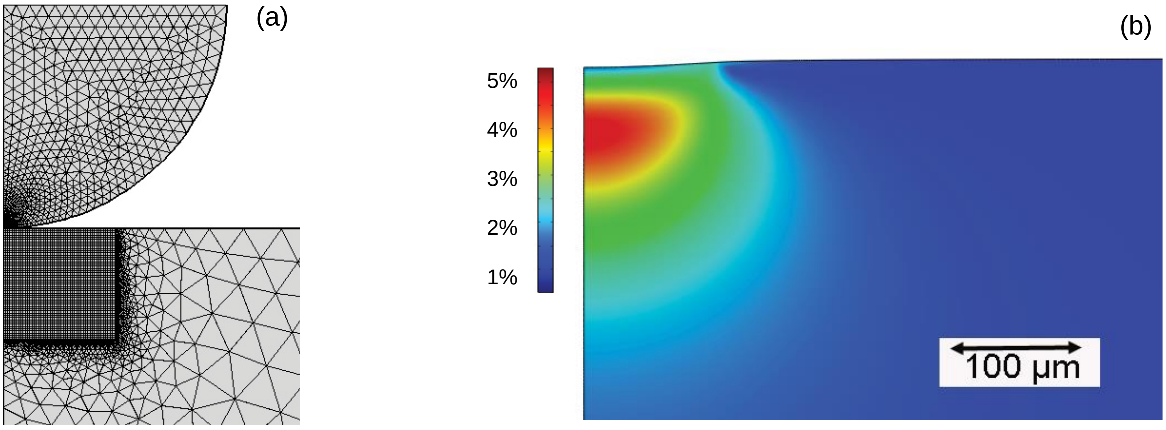


Figure 2. (a) Finite element mesh; (b) predicted strain field for indentation with a sphere of diameter 4 mm, to a depth of 50 µm, obtained using the parameter values in Fig.1.

3. RESULTS AND DISCUSSION

The "g-screening" process, illustrated in Fig. 3, for (a) loading and (b) unloading parts of the $P(\delta)$ plot, is thus central to the methodology.

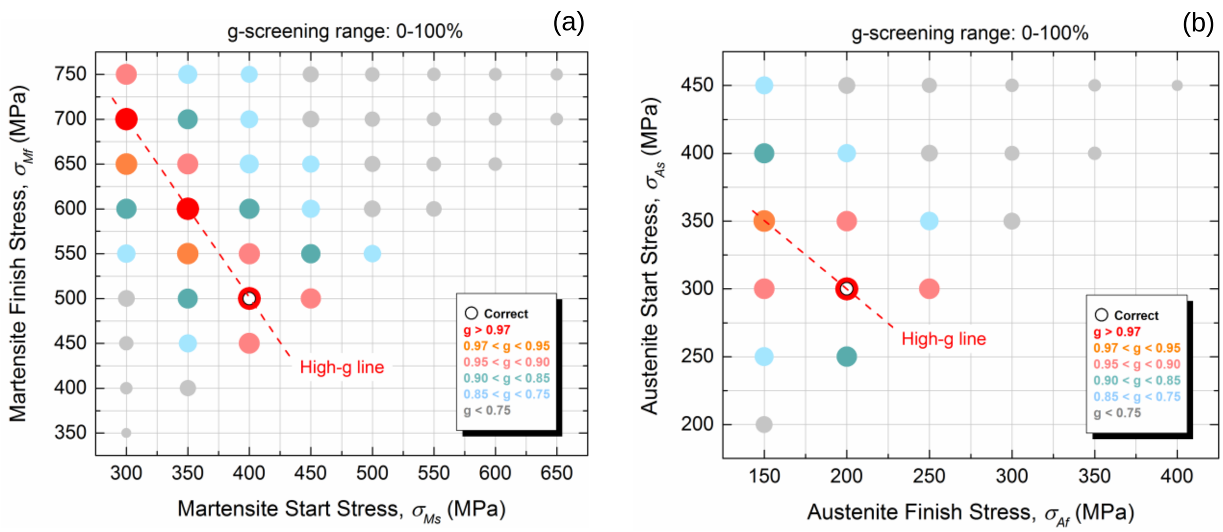
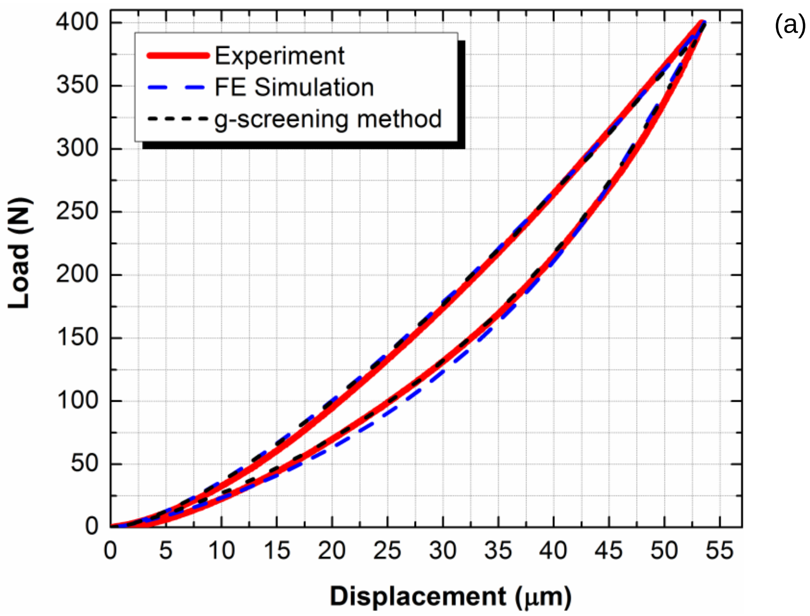


Figure 3. Two g-maps for comparisons between the FEM predicted $P(\delta)$ plot obtained using the reference case set of parameter values with those for cases in which individual values were systematically varied.

It can be seen that the agreement is good. In general, the "*g*-screening" method requires more than one indenter shape to assist convergence on a unique solution. This is due to the compensation effect caused by the change in the material parameters. An example is shown in Fig. 3, where it can be seen that the ambiguity associated with the indenter shape (high-g line). For this case, the *g*-map was obtained by creating a "master cloud" of random values for the forward and reverse transformation stresses, obtained, respectively, from the loading and unloading portions of the plot (see Fig.3).

The outcome of such process is shown in Fig. 4b, which compares the experimental stress-strain curves with one that was obtained solely from the indentation data, after a *g*-screening operation on the $P(\delta)$ plot in Fig. 4a. After the convergence process (not shown), the *g*-value for the correct parameter combination was 0.97.



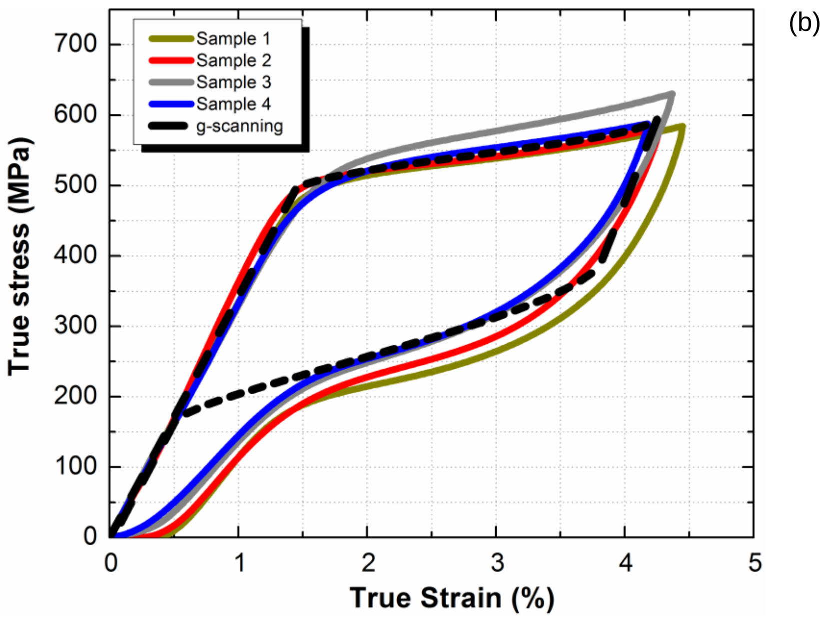


Figure 4. Experimental stress-strain curves superimposed on one was obtained solely from indentation data.

4. CONCLUSION

The FE-inverse methodology used in this work has proved to be reliable for inferring superelasticity properties of NiTi alloys from indentation data. The technique, however, is sensitive to the data quality obtained from indentation testing. This represents a breakthrough in the field, given that the current literature in the topic is neither clear nor widely used by researchers/companies.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

ABAQUS (2009). *ABAQUS User Manuals*, Version 6.9.

Dean, J., J. Campbell, G. Aldrich-Smith and T. W. Clyne (2014). "*A Critical Assessment of the "Stable Indenter Velocity" Method for Obtaining the Creep Stress Exponent from Indentation Data*." Acta Materialia 80: 56-66.

Dean, J. and T. W. Clyne (2017). "*Extraction of Plasticity Parameters from a Single Test using a Spherical Indenter and FEM Modelling.*" Mechanics of Materials 105: 112-122.

Duerig, T., K. N. Melton, D. Stöckel and C. M. Wayman, Eds. (1990). *Engineering aspects of shape memory alloys*, Butterworth-Heinemann.

Oliver, W. C. and G. M. Pharr (1992). "*An Improved Technique for Determining Hardness and Elastic Modulus Using Load and Displacement Sensing Indentation Experiments*." Journal of Materials Research 7(6): 1564-1583.

Oliver, W. C. and G. M. Pharr (2004). "*Measurement of hardness and elastic modulus by instrumented indentation: Advances in understanding and refinements to methodology*." Journal of Materials Research 19: 3-20.

Otsuka, K. and T. Kakeshita (2002). "*Science and Technology of Shape-Memory Alloys: New Developments.*" MRS Bulletin 27: 91-100.

Otsuka, K. and X. Ren (2005). "*Physical metallurgy of Ti–Ni-based shape memory alloys.*" Progress in Materials Science 50(5): 511-678.

Otsuka, K. and C. M. Wayman (1998). *Mechanism of shape memory effect and superelasticity. Shape Memory Materials*. K. Otsuka and C. M. Wayman. Cambridge, CUP: 27-48.

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