A Proposed Indentation Scheme for Investigating Elasto-viscoplastic Behaviour of Materials at Elevated Temperatures

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Summary An indentation scheme is proposed for investigating high-temperature elasto-viscoplastic behaviour of metallic materials based on a unified constitutive model. A multi-step loading history is chosen to separate the rate independent (plastic) part of the indentation loading response from the time/rate dependent (viscous) part. To extract valuable mechanical parameters from the indentation data, an identification method based on artificial neural networks is developed and an inverse analysis software is implemented.

Introduction

With significant recent advances in instrumented indentation testing, it has become possible to routinely measure the mechanical properties of bulk materials, small-volume materials and thin film structures. Considering many systems are operating under hot conditions (for example, blades of jet turbines, cladding alloys of nuclear reactors), high-temperature indentation systems have recently been developed by customizing commercial indentation devices with hot cells and thermal-shielding systems [1,2]. However, due to the significant viscoplastic deformation induced during high-temperature testing, the conventional indentation schemes proposed for room-temperature testing are not applicable any more and an indentation scheme suitable for investigating high-temperature elasto-viscoplasticity is required. This paper aims to develop an indentation scheme for metallic materials which can separate the rate independent (plastic) part of the indentation loading response from the time/rate dependent (viscous) part during hot testing. An indentation method to extract valuable mechanical parameters from the indentation data is discussed.

A unified elasto-viscoplastic model for metallic materials at high temperature

For metallic materials at high temperature, complex elasto-viscoplastic deformations occur under indentation loading. To describe both the rate independent (elasto-plastic) part and the rate dependent (visco-plastic) part of the mechanical response, a unified constitutive model (Fig.1) with the following set of constitutive equations is proposed:

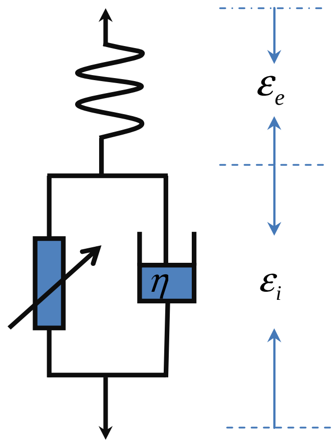

Fig.1 Schematic of the unified mechanical model

$$
\begin{aligned}
&\varepsilon = \varepsilon_e + \varepsilon_i \\
&\sigma = E\varepsilon_e \\
&\dot{\varepsilon}_i = \frac{\langle F \rangle^m}{\eta} \\
&F = |\sigma - \alpha| - Y \\
&Y = Y_0 + \frac{H}{\beta}\left(1 - e^{\beta s}\right) \\
&\dot{\alpha} = \frac{3}{2} c\dot{\varepsilon}_i - b\dot{s}\alpha \\
&s = \int_0^t \dot{\varepsilon}_i(\tau)\, d\tau
\end{aligned}
\tag{1}
$$

where $\varepsilon, \varepsilon_e$ and ε_i denote the total strain, elastic strain and the inelastic strain. The stress is given by Hook's law with Young's modulus *E*. The inelastic strain is calculated from an overstress *F* and the operator $<F>=F$ for $F>0$ (viscoplastic loading) and $<F>=0$ otherwise (elastic loading/unloading).The overstress combines both the isotropic hardening *Y* and the kinematic hardening α . *H* is the initial slope of work hardening and β is the work hardeing parameter.

Compared to frequently used power-law type hardening models, the unified constitutive model has several advantages [3] in that the model can describe the hardening behaviour of a wide range of materials very well and the same model can be used over a wide range of temperatures using temperature dependent material parameters. In addition, the material response for more complex loading histories, e.g. including cyclic loading, dwell-times and time dependent loading rate, can be well predicted. The model has been implemented as a user subroutine VUMAT in ABAQUS.

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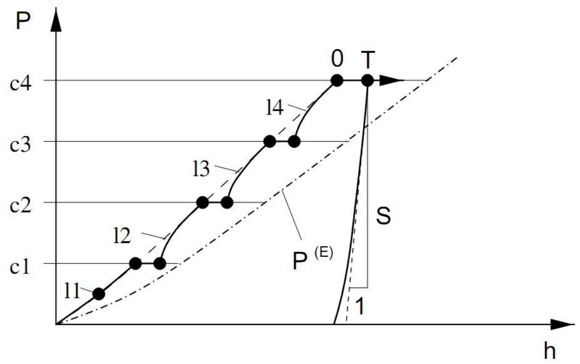
An indentation scheme for elasto-viscoplastic materials

Based on a simple empirical model, a loading history containing multiple steps as shown in Fig. 2 (a) was proposed in [4]. It allows for separating the rate independent (plastic) part of the indentation loading response from the time/rate dependent (viscous) part by introducing three intermediate creep phases c1–c3, each of 100s at equidistant force intervals. A final creep phase c4 at maximum load and of 600 s duration provides the necessary data for the identification of the viscosity parameters. In this paper we followed the loading history and calculated the load-depth curve by using FEM with known constitutive parameters (Fig.2(b)).



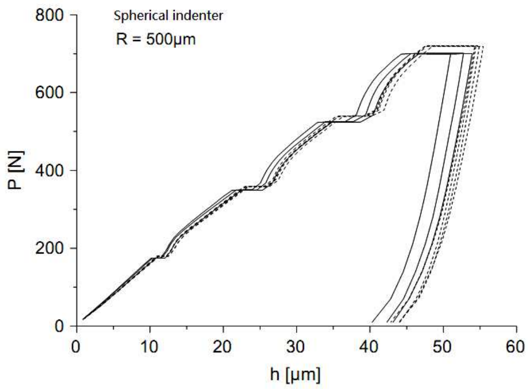


Fig.2 (a) Multi-step loading history (b) Calculated load-depth curves

Identification of the constitutive parameters from the indentation data was achieved by combing neural networks and the FE calculations. A number of Finite Element simulations of the spherical indentation test were performed by randomly chosen sets of material parameters. The inputs are defined by the load-depth and depth-time response while the desired outputs are the material parameters of the material model. The indentation curves generated by the extracted parameters and by the exact parameters were compared in Fig.3.

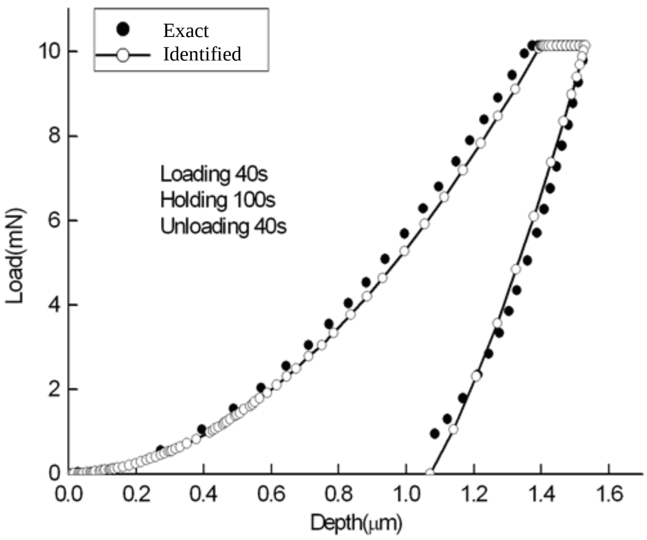


Fig.3 Comparison between the curves generated from the identified parameters and the exact parameters

Conclusion

The present work has shown that by using the tools of the finite element method together with neural networks, it is possible to extract the elasto-viscoplastic parameters of metallic materials at elevated temperatures by using hot indentation testing.

References

[1] C.A. Schuh, C. E. Packard, and A. C. Lund: Nanoindentation and contact-mode imaging at high temperatures. J. Mater. Res. **21**(3): 725-736, 2006.

[2] V. Bhakhri, R.J. Klassen:. Investigation of high-temperature plastic deformation using instrumented microindentation tests. J. Mater. Sci. **41** :2259–2270,2006.

[3] N. Huber, Ch. Tsakmakis: A neural network tool for identifying the material para-meters of a finite deformation viscoplasticity model with static recovery. Comput. Meth. Appl. Mech. Eng. 191: 353-384,2001.

[4] N. Huber, E. Tyulyukovskiy: A new loading history for identification of viscoplastic properties by spherical indentation J. Mater. Res. 19: 101-113,2004