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ASSESSMENT OF THE CONSTITUTIVE PROPERTIES OF REACTOR STEEL USING AN INVERSE ANALYSIS ON THE SMALL PUNCH TEST

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Abstract: *This paper presents a method for parameter identification based on the small punch test and inverse analysis. During the small punch test a miniaturized disk specimen was deformed by a spherical punch in a manner similar to deep drawing. The experimental outcome was a force – displacement curve, which indirectly contains information concerning the mechanical properties of the tested material. The parameter identification was carried out by means of an inverse analysis which was based on the finite element modeling of the small punch test. The finite element models have to maintain the required accuracy with reasonable computational costs. The inverse analysis consists of an iterative method which minimizes error between the experimental load – displacement curve and the curves obtained via finite element modeling. The identification procedure was applied to 15Ch2MFA steel in order to estimate the true stress – true strain relationship. The identified curve was compared with the one obtained from the standard tensile test.*

Keywords: Small punch test, Inverse analysis, Finite elements, Parameter identification.

1. Introduction

Parameter estimation of irradiated materials based on small-scale specimen techniques is currently a subject of interest worldwide. Despite the fact that the small-scale specimen brings with it certain difficulties, its use is required for several reasons. Firstly, there are severe limitations on specimen size in irradiated-material testing facilities. Secondly, the small specimen can be extracted from in-service components in a semi-destructive way, i.e. the component can be kept operative without a need for sampling place repair. This allows for an estimation of the residual life of a component and keeping it in-service beyond its designed life.

Over recent decades a number of different techniques applied onto non-standard small specimens have been developed in order to assess material properties. Among them the small punches test (SPT) has been shown to be an extremely attractive and promising technique. In small punch testing a disk sample (usually 0.5 mm thick and 8 mm diameter) is clamped between dies and punched with a spherical indenter in a miniaturized deep drawing test. The experimental outcome is the relationship between the applied force and the tip displacement of the sample – load-displacement curve (LDC). SPT was developed by Manahan et al. (1982) for postirradiation mechanical behavior determination. SPT has been used thus far in order to extract the true stress – true strain relationship, the ductile-brittle transition temperature, tensile strength, fracture toughness, creep properties and others (Chang, 2008).

The aim of this paper is to invent the parameter estimation procedure based on an inverse analysis of the small punch test. The function and validity of the procedure is demonstrated by estimating the true stress – true strain relationship of the 15Ch2MFA steel.

2. Experimental Tests

The material under investigation was 15Ch2MFA steel which is used as a base material for pressure vessels in a nuclear reactor VVER-440. Young's modulus $E = 213 \pm 3$ GPa and the yield strength

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$R_p0.2 = 499 \pm 5$ MPa was measured with a standard tensile test. The true stress – true strain relationship is plotted in Fig. 4.

The SPTs was performed on a tensile testing machine Inspekt 100 kN, Hegewald & Peschke. The tests were carried out at room temperature. The schematic of the small punch testing device is shown in Fig. 1. The specimen is a small disk with dimensions 8 mm in diameter and 0.5 mm in thickness which was clamped to a die by means of a down-holder with the force F ~ 14.5 kN. The final specimen surface was grinded with sand paper (grit size P1200) and no lubrication between the punch and the specimen was used. Over the course of the test, the punch with a spherical head was pushed downward with a constant speed v = 0.5 mm/min. The test was completed when a sudden force drop caused by a crack extension occurred. The disk was symmetrically deformed in a deep drawing manner. Using the down holder, the specimen was prevented from cupping upward and therefore, the plastic deformation was concentrated into the region below the punch. Further information about the specimen preparation, testing device and test procedure can be found in Janča (2013).

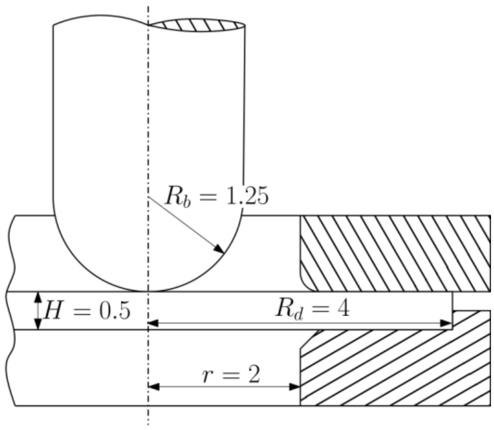


Fig. 1: Schematic illustration of the SPT device.

The displacement of the central point on the bottom side is monitored as a function of applied force during the test. This load-displacement curve (LDC) contains information about the material properties of the sample. The typical LDC for the ductile material can be divided into several regions based on the main deformation process (Baik et al., 1986): elastic bending (I), plastic bending (II), plastic membrane stretching (III) and plastic instability (IV). The linear elastic deformation in region I is followed by an expansion of the plastic deformation from the punch tip to the entire specimen in region II. In region III the deformation mechanism changes from bending to biaxial stretching. The local reduction of thickness in region IV causes a micro-cracking and load decrease followed by a final rupture.

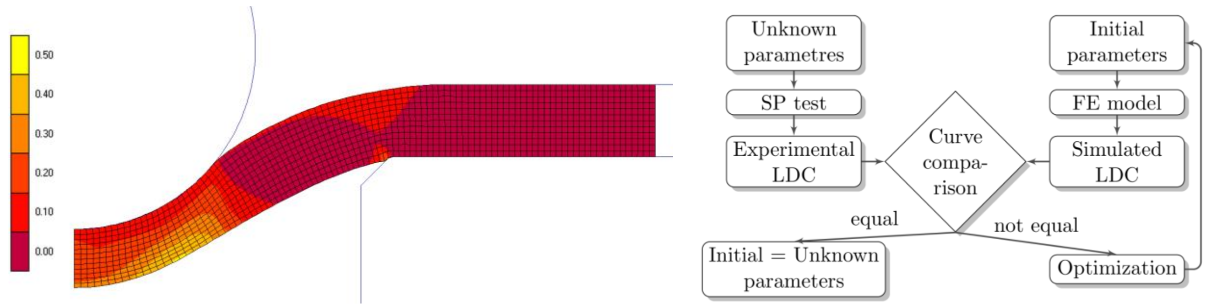
3. Parameter Estimation

LDC contains information indirectly concerning the elasto-plastic deformation behavior and about the strength and fracture properties of the material. There are two basic ways to extract unknown material parameters from LDC: (I.) determine the empirical relationship in order to relate the results from SPT and unknown parameter for a given class of materials; (II.) perform an inverse analysis based on finite element simulations. The latter is presented in this paper to obtain a true stress – true strain curve.

3.1. Finite element modeling of SPT

FE simulations have become an inseparable tool for parameter estimation by means of inverse analysis. During the inverse analysis, tens or even hundreds of finite element models have to be evaluated, thus models should maintain the required accuracy with a reasonable computation costs.

Since the test geometry, loading, deformation and damage evolution up to the crack initiation are axisymmetric, a 2D FE model is sufficient to calculate the LDC. A typical finite element mesh is plotted in Fig. 2a, four node axisymmetric elements of full integration with an edge 0.04 mm in length were used. The contact between the specimen, punch and dies was modeled with a friction coefficient $\mu = 0.1$. The punch and dies were modeled as rigid bodies. Neither damage nor failure were taken into account in the FE model, thus LDC is only valid in first three regions before micro-cracking occurs.



a) *b)*

Fig. 2: a) Typical FE mesh used in the simulations. The scale shows the equivalent logarithmic strain. b) Scheme of inverse analysis.

3.2. Inverse Analysis

Obtaining a true stress – true strain relationship by SPT requires an inverse analysis. The principal scheme of the parameter estimation procedure is shown in Fig. 2b. The iterative procedure compares the experimental and simulated LDC by means of the cost function

$$err(x) = \frac{1}{N} \sum_{i=1}^{N} [F^{MKP}(x, u_i) - F^{EXP}(u_i)]^2 \quad (1)$$

in which N is the number of points considered in the optimization. $F^{MKP}(x, u_i)$ is the force value at displacement u_i calculated by the FE model which is dependent on unknown parameters x. $F^{EXP}(u_i)$ is the force value at displacement u_i from the experimental SPT. The cost function is minimized by means of a gradient-based algorithm, namely the Levenberg–Marquardt method (Andrade-Campos et al., 2007).

The unknown parameters (x) represent in this case the true stress – true strain curve defined as a piecewise function

$$\sigma_{true} = \begin{cases} K\varepsilon_{true}^{n} + \sigma_0 & \varepsilon_{true} \leq \varepsilon_0 \\ A(\varepsilon_{true} - \varepsilon_0) + K\varepsilon_0^{n} + \sigma_0 & \varepsilon_{true} > \varepsilon_0 \end{cases} \quad (2)$$

in which there are four unknown parameters K, n, σ_0, B and parameter ε_0 is kept fixed at value 0.29.

4. Application and Results

The aforementioned procedure was implemented via Matlab which governed the optimization procedure as well as the FE simulations carried out with the MSC.Marc software. An inverse analysis has been performed in order to estimate the four unknown parameters of the true stress – true strain curve defined by equation (2) for the 15Ch2MFA steel.

The LDC obtained during the inverse analysis are plotted in Fig. 3 and compared with the experimental one. Only regions I–III of the LDC are used for the parameter identification. It is apparent that the iterations steadily converge towards the experimental curve. The convergence was reached in 13 iterations and 103 FE models in all were calculated. The entire curve is approximated quite well with a slight misalignment remaining in the early stages of deformation.

The corresponding true stress – true strain curves are shown in Fig. 4. The predicted curve underestimated the value of the yield strength, although it on the whole provided close agreement with the curve obtained by the classic tensile test which was corrected after necking by Bridgman's correction method.

5. Conclusions

The characterization of material for the pressure vessel in the nuclear reactor has been carried out in this paper by means of an inverse analysis on a small punch test. Both the experimental tests as well as the optimization routine with finite element simulations have been carried out in order to validate the parameter estimation based on an inverse analysis.

The developed identification routine was applied to extract the true stress – true strain curve from the outcome of the SP test (load-displacement curve). The estimated curve provided a satisfactory approximation of the curve from the standard tensile test with a maximum deviation 6%.

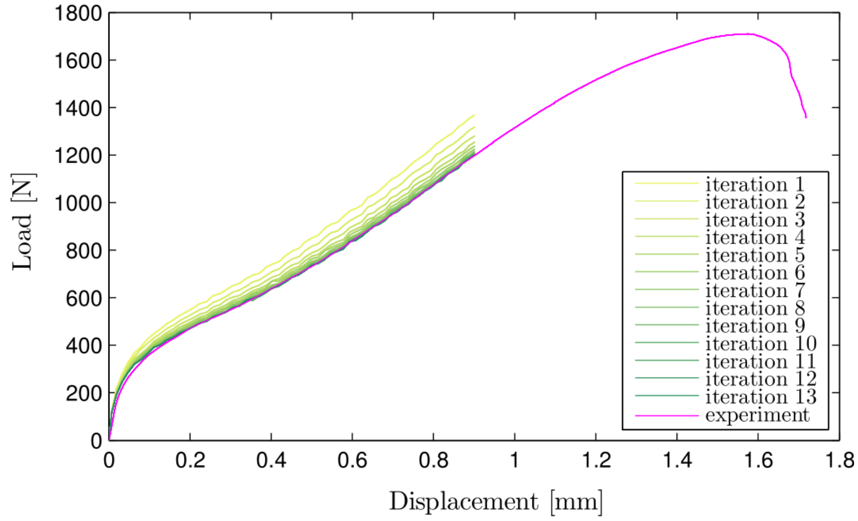


Fig. 3: Experimental LDC and numerically estimated curves during the inverse analysis.

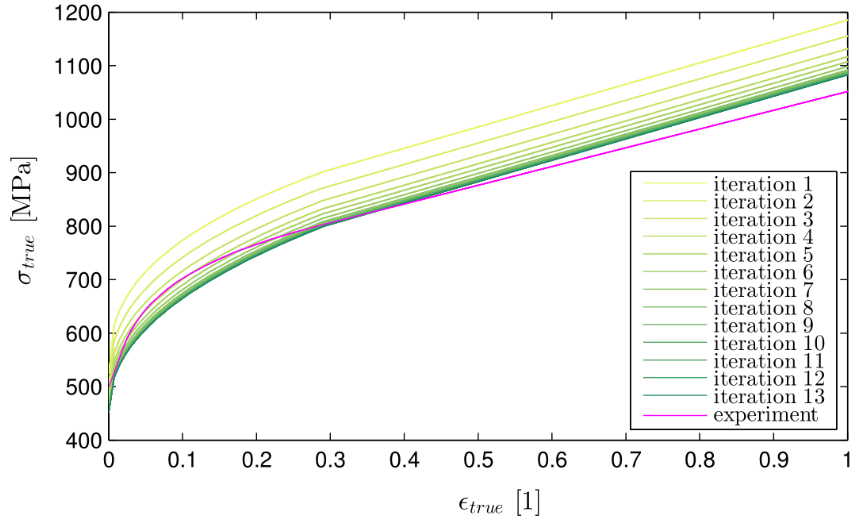


Fig. 4: Hardening curves corresponding to LDC in Fig. 3.

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