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On quasi-non-destructive strength and toughness testing of elastic–plastic materials

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Abstract

Non-destructive evaluation of mechanical material properties, like strength and fracture toughness, is impossible for principal reasons. However, there are possibilities of quasi-non-destructive estimation methods, which can be quite useful in practice. Instrumented indentation tests are often suitable to get information about the elastic–plastic behaviour, where the indentation depth is measured as a function of indentation force. By approximate analytical methods, key parameters like ultimate tensile strength, work-hardening exponent or even yield stress can be derived from these measurements. A mobile indenter is presented here and its use in ambulant testing is described. To obtain the uniaxial stress–strain curve more directly and more exactly, the same instrument can be used for a miniature compression test, where a small pin is machined out from the surface of the material. Furthermore, to get information about the toughness of materials, a carving instrument has been developed, which allows the energy required to introduce a defined furrow to be measured and correlated with toughness parameters.

Keywords: Quasi-non-destructive testing; Instrumented indentation; In-situ; Fracture toughness; Carving; Scratching; Miniature pin compression; Ambulant

1. Introduction

For quality control of materials, or to provide data for safety analysis of existing structural components, non-destructive testing methods are needed. Actually, determination of strength and toughness no-destructively is nearly impossible for principle reasons. The only way to obtain parameters related to these properties is by approximate quasi-non-destructive methods. Well-known for this purpose are hardness tests like

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Brinell or Vickers, which allow the ultimate tensile strength (UTS) to be estimated by semi-empirical correlations. Despite of their limited accuracy they are still the most popular quasi-non-destructive tests to estimate the tensile strength. Instrumented indentation testing (IIT), as recently standardized by EN ISO 14557, now opens further possibilities to obtain better and additional information about elastic–plastic material behaviour from tests as simple and as little destructive as hardness tests. Compared with the classical hardness test, the advantages are obvious: Firstly, the test procedure is well suited to be applied not only on specimens in the laboratory, but also ambulant on components, secondly, the information content of the measured data is much higher than in classical hardness tests, and, thirdly, it is universal concerning materials. Furthermore, these tests can be performed relatively easy at different temperatures or loading rates.

Various material parameters can be obtained from the measured indentation curves, including some of the classical hardness parameters, E-modulus and UTS. In principle, as shown by several authors like He et al. (2002), Boucaille et al. (in press) or Haggag (2001), it is even possible to identify the constitutive law (i.e. the true stress–strain curve) of the material in a certain range of strains. However, this requires, in general, either a rather sophisticated mathematical procedures like inverse finite element analysis, or indentation tests with numerous unloading cycles.

The present paper deals with some recent developments concerning simplified ambulant application of IIT and related procedures, to estimate tensile and toughness properties of the material. A new mobile indenter is presented, which allows ambulant (in situ) IIT to be performed on components. Concerning the evaluation, it is focussed on relatively simple analytical means. As a further step towards measuring directly the uniaxial stress–strain behaviour in a quasi-non-destructive way, a new miniature compression test is suggested, which can be performed with the same instrument as the IIT. Both, the IIT and the pin compression test, deliver information about the plastic flow behaviour, but not about fracture behaviour and toughness. For quasi-non-destructive toughness testing, a carving test is suggested where a well-defined small furrow is introduced into the surface of the specimen or component, and the dissipated energy is measured. These data correlate with toughness. For ambulant testing, a mobile test apparatus, that allows measurement of the energy required to produce a defined furrow of unit length, is developed.

Note that all the subjects and results reported herein concern work in progress, so the presented equations and described procedures are likely to be subjected to future modifications, refinements, optimisations and extensions. The main purpose of this paper is just to show and discuss some preliminary aspects of these tests in order to stimulate further research on these topics.

2. Ambulant instrumented indentation testing

The term instrumented indentation testing (IIT) means pressing a hard indenter into the surface of the test piece by an increasing force F and monitoring this process by measuring the relative displacement v of the indenter with respect to the surface (or the indentation depth $h = v - v_0$, respectively) as a function of the applied force F (Fig. 1). From the F–v or F–h diagram various hardness-related parameters can be derived, like the Martens-hardness HM as standardised in the new international standard EN ISO 14577. HM has some important advantageous features compared with the classical hardness parameters such as Brinell- or Vickers, including its universality concerning material, simplicity of application and the possibility to get the distribution of hardness HM as a function of load or indentation depth by a single test.

To obtain the Martens-hardness HM of homogeneous materials, or the hardness distribution HM (F) of non-homogeneous materials, respectively, cone- or pyramid-shaped indenters are preferable. They produce self-similar indents, so the hardness value is constant independent of the indentation depth. Thus, a variation of HM as a function of depth indicates a non-homogeneous material behaviour. Each shape of the indentor tip corresponds to just one elastic–plastic deformation state, i.e. just one representative point on

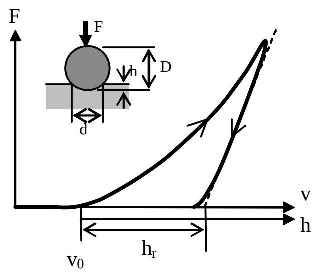

Fig. 1. Force F as a function of displacement relative to the surface, v, or indentation depth, h, obtained from an instrumented indentation test cycle including loading and unloading (schematic). h_r denotes the approximate indentation depth remaining after unloading.

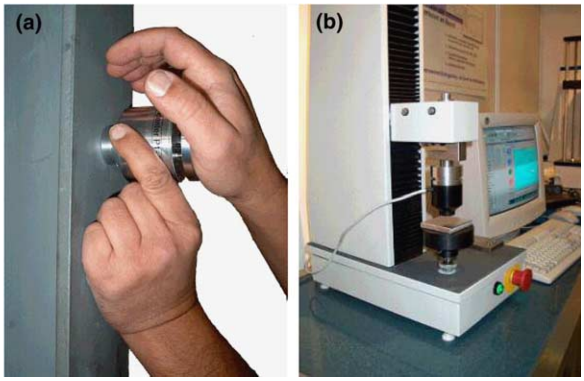

Fig. 2. Indenter Mat-Tec Unihard applied in the free manual mode (a) and as a hardness testing module used in a universal testing machine (b).

the true stress–strain curve. To obtain stress–strain data in a wider range of strain by one single test, a ball indenter should preferably be used. A relatively simple evaluation method for ball indentation tests is presented in the following section.

Quasi-non-destructive testing requires the possibility of ambulant testing of existing components. The mobile indenter Mat-Tec Unihard, shown in Fig. 2, was developed for ambulant IIT according to EN ISO 14577, as well as for the pin compression test as described below. Besides its compact form and size, its characteristic feature is the modular design, which allows it, among other loading modes, to be used either in the free mode by applying the force manually or in the stationary mode by attaching it to a universal testing machine (see Fig. 2 right). This apparatus delivers characteristic parameters according to EN ISO 14577 as well as the force-indentation diagram that is required for the evaluation described in the following section.

3. Constitutive law from ball indentation test

3.1. General

If a sphere indenter is pressed against the surface of an elastic–plastic body by an increasing force F, then the plastic strains in the contact region increase with increasing indentation depth h. Thus, the measured indentation curve $F(h)$ can serve to determine the stress–strain curve by an inverse FEM analysis like He et al. (2002) and Boucaille et al. (in press). However, this is a relatively complex task. In the present paper some possibilities of simpler engineering estimation procedures are explored.

As a first attempt, in Tipping et al. (2003) the original Meyer–Tabor procedure was adapted to the instrumented indentation test. From the measured force F as a function of indentation h the diameter of the indent, d, was calculated as a function of F, assuming the most simple case of a fully plastic behaviour. As shown by Tipping et al. (2003), the material parameters C and n for a constitutive law of the of the type

$$\sigma = C \cdot \varepsilon^n \tag{1}$$

can be readily obtained, by the approximate relations. The main elements of this method are estimation of the reference strain and stress as found semi-empirically by Tabor (1951)

$$\sigma_r(d) = \frac{9.81 \bullet \mathrm{MH}(d)}{2.8} \tag{2a}$$

$$\varepsilon_r(d) = 0.2 \cdot d/D \tag{2b}$$

where MH is Meyers's Hardness as defined by Meyer (1908) (in kp/mm^2) and d is the diameter of the indent calculated from the indentation depth h as shown in Fig. 1 (see below).

However, by experimental comparisons and by FEM-simulations, it was found that Eqs. (2) work sufficiently well only in cases of materials which follow more or less the power law assumed in (1). To improve the accuracy of the estimation for more general cases, appropriate modifications have to be considered. Some key issues are discussed in the following. The effects are demonstrated by an illustrative experimental example in Fig. 3.

3.2. Elements of analytical evaluation

3.2.1. Reference strain and stress

From physical reasons it is quite obvious that Eq. (2b) to estimate the plastic strain due to indentation of a ball of diameter D is not universal, but dependent on the material, particularly on its hardening behaviour. An improved assumption for the reference plastic strain is

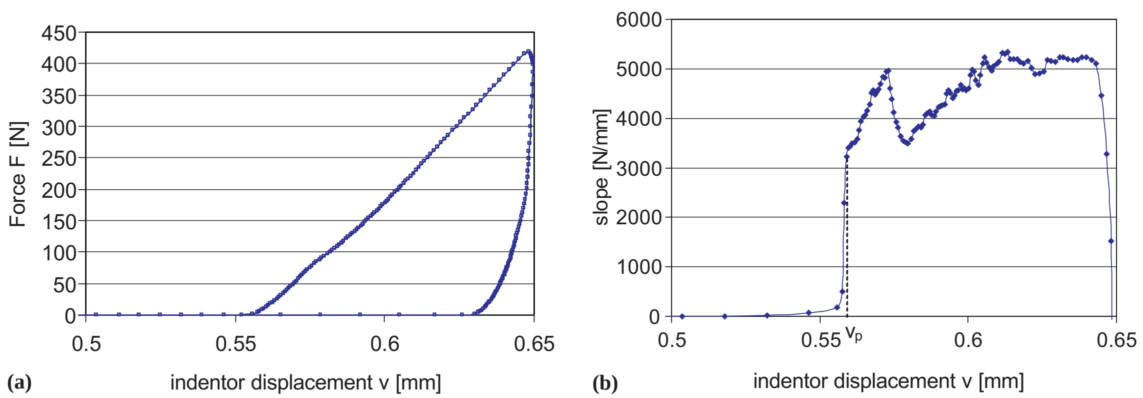

Fig. 3. Example of an indentation curve obtained by a ball indentation test on stainless steel 316L using a sapphire ball with $D = 1.0$ mm (a) and the corresponding slope with definition of v_p (b).

$$\varepsilon_{\mathrm{r}}(F) = c_{\varepsilon}(n) \cdot \frac{d_{\mathrm{p}}(F)}{D} \tag{3}$$

where $d_{\mathrm{p}} = d - d_{\mathrm{el}}$ denotes the increase in the indent diameter with respect to the elastic plastic transition, which is assumed to take place at $v = v_{\mathrm{p}}$ and $d = d_{\mathrm{el}}$. Assuming a fully plastic behaviour, it can be obtained in a first approximation as

$$d_{\mathrm{p}}(F) = 2 \cdot \sqrt{D \cdot (v - v_{\mathrm{p}}) - (v - v_{\mathrm{p}})^2} \tag{4}$$

A method to determine v_{p} is shown below.

From comparison of experimental data obtained for austenitic and ferritic structural steel, c_{ε} was found to be

$$c_{\varepsilon} = 0.25 \tag{5}$$

rather than 0.2 as used in (2b). This is in agreement with the result obtained by a simplified analytical derivation of Clough et al. (2003). However, for physical reasons c_{ε} is expected to be not a constant but to depend on the hardening behaviour of the material. Based on a few preliminary finite element computations (see Schindler, 2003, for more details) the proportionality factor c_{ε} was obtained to be about

$$c_{\varepsilon}(n) \cong 0.7 \cdot (1 - n)^4 \tag{6}$$

where the hardening exponent n as defined in (1) is obtained by the Meyer–Tabor procedure from

$$\log F = \log K + (n + 2) \cdot \log d/D \tag{7}$$

(see Tipping et al., 2003). The main problem of determining c_{ε} by (6) is the high sensitivity of (7) to determine n. Thus, rather than using an inaccurate n in (6), it is often preferable to use the approximate fixed value (5).

The reference stress σ_{r} corresponding to the reference strain given in (3) is

$$\sigma_{\mathrm{r}}(F) = \frac{4 \cdot F}{c_t \cdot \pi \cdot d^2(F)} = \frac{F}{c_t \cdot \pi \cdot [D \cdot (v - v_0) - (v - v_0)^2]} \tag{8}$$

where c_t is a factor accounting for the over-all triaxiality of the region below the contact area. Based on a few FEM-simulation (see Schindler, 2003) it was estimated to be

$$c_t \approx 3.1 - n \tag{9}$$

The second equation in (8) holds only beyond the elastic range of the contact, i.e. for $v > v_{\mathrm{p}}$. The expressions (3) and (8) represent the true stress–true strain curve in the corresponding range without any assumption concerning the constitutive law.

3.2.2. Stress from the slope of the indentation curve

In order to calculate the stress by Eq. (8), the "zero-point" $v = v_0$ (Fig. 1) has to be determined. This is a basic problem in IIT, since the instant of first contact is poorly defined, physically as well as mathematically. A promising approach to overcome this problem is to consider the relation between σ_{r} and the slope of the F–v curve. Assuming a perfectly plastic indentation one easily finds from (8) and (4)

$$\sigma_{\mathrm{r}}(F) = \frac{1}{c_t \cdot \pi \cdot D} \cdot \frac{\mathrm{d}F}{\mathrm{d}v} \tag{10}$$

Eq. (10) can be used as an alternative to (8) to determine the reference stress. However, since the assumption of a fully plastic behaviour is an idealistic simplification, Eq. (10) applied to a real indentation curve delivers only an approximation of the reference stress. The "waves" that appear in the corresponding curve

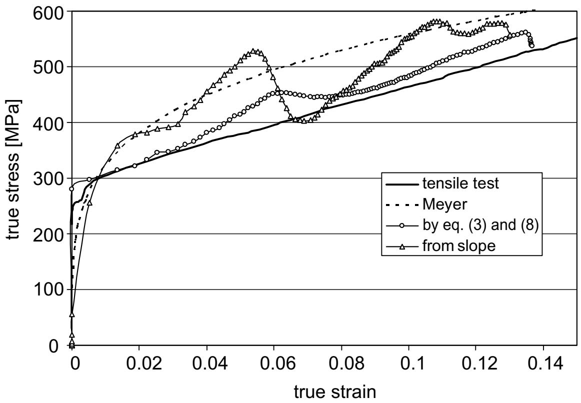

Fig. 4. Results of evaluation methods discussed in the text applied to the example shown in Fig. 3.

in Fig. 4, i.e. the exaggerated initial steepness of the curve followed by a drop at about 5% strain, can be attributed to the transition from the "sink-in" to the "pile-up" behaviour.

3.2.3. Determination of elastic–plastic transition

According to the elastic theory of Hertzian contact (see Fischer-Cripps, 2000), Eq. (10) holds essentially also for the elastic range that precedes the elastic–plastic one, disregarding an additional factor of 2. The elastic regime is characterized by a pronounced increase of σ_r with increasing v, whereas it is rather decreasing in the plastic regime. Thus, the transition between elastic and plastic behaviour, which is defined in (4) to occur at $v = v_p$, may be defined as the point where

$$\frac{d^2F}{dv^2}(v = v_p) = 0 \tag{11}$$

This is shown in Fig. 3 by an example. The displacement $v = v_p$, where the second derivative of the indentation curve changes its sign as indivated by (11), can be detected in the curve $dF(v)/dv$ very clearly (see example in Fig. 3b).

By a linear extrapolation of $\sigma_r(v)$ as given by (8) or (11), respectively, to $v = v_p$ as obtained by (11), the yield stress can be estimated. The preliminary experimental results are promising, as shown by the examples in Fig. 4.

4. Miniature pin compression test

One of the main disadvantages of IIT is that only a small surface layer of the material is subjected to the test. Thus, in case of surface layers, the bulk material properties are not obtained, unless the former are removed by grinding. A further step towards quasi-non-destructive evaluation of the uniaxial stress–strain curve is the miniature pin test as sketched in Fig. 5. Using a special core-drilling device, as developed by the author, it is possible to machine a small pin, typically about 1 mm in diameter and 2 mm in length in the surface of the test piece. By using a flat indenter, the mobile apparatus for indentation testing presented above can be used to load this pin in essentially uniaxial compression, and to measure the corresponding displacement h. From the force–displacement diagram, the stress–strain curve is readily obtained by the usual evaluation procedure of a uniaxial compression test. The disturbance of the uniaxial stress state near

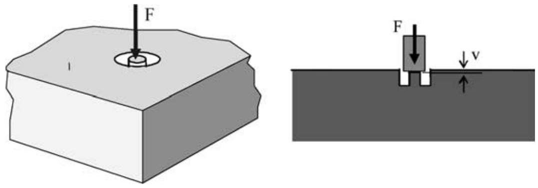

Fig. 5. Mechanical system of the pin compression test.

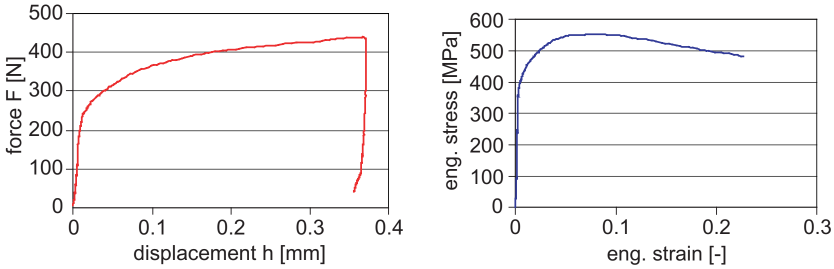

Fig. 6. Example (Steel Fe 510, pin-diameter 0.88 mm, pin length 2.3 mm) of a force–displacement diagram of a pin compression test and the corresponding stress–strain diagram.

the base of the pin can be accounted for by a suitable correction of its effective length. Fig. 6 shows an example of a measured force–displacement and the corresponding stress–strain curve.

5. Toughness testing by carving

IIT as well as the pin compression tests are not capable to deliver information about fracture strain or fracture toughness. Thus, the true stress–strain curves determined by the procedure discussed above are only valid up to the fracture strain. Correspondingly, estimation of the engineering ultimate tensile strength based on indentation data is only justified if the fracture strain is higher than the uniform fracture strain, which is approximately equal to the hardening exponent n. There is no way to estimate the fracture strain or fracture toughness from either indentation or compression tests.

In order to fill this gap in quasi-non-destructive testing, the Mat-Tec Carver shown in Fig. 7 was developed. This apparatus, which is clamped onto the surface of the test piece, enables a shallow, well defined furrow to be cut into the surface of the test specimen or the component. Typically, the furrow is V- or U-shaped with a depth of about 0.1 mm. Although metal cutting or machining in general is a very complex process and depends on many parameters, fracture processes in the vicinity of the cutting edge are always involved, so the energy required to cut such a defined furrow is likely to correlate with fracture toughness.

In order to measure the cutting energy, the component F_x (where x denotes the carving direction) of the force acting on the cutting tool is measured by the instrument as a function of the actual length of the produced furrow. Obviously, F_x is identical to the required cutting energy per unit furrow length.

Fig. 8 shows two measured curves $F_x(x)$ as examples. As explained above, these curves contain information about the toughness, which can be extracted by empirical correlations. Usually, the shape of these curves is characterized by a certain mean value F_{mean} and stochastic oscillations, which can be quantified as the standard deviation ΔF_s. The experiments performed so far and their comparison with fracture toughness or Charpy fracture energy indicate that increasing toughness causes an increasing mean force F_{mean} and decreasing ΔF_s. For this reason, a characteristic parameter C is tentatively defined as

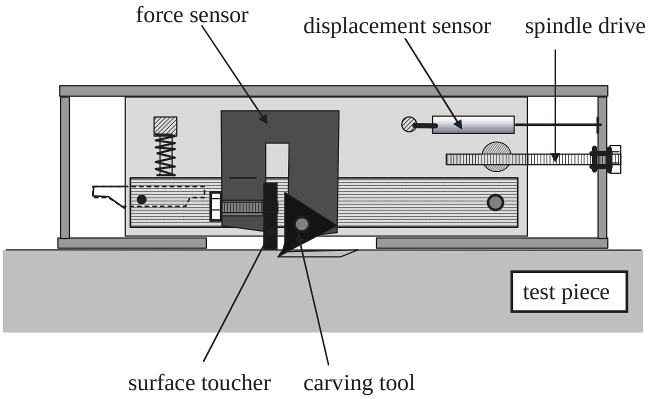

Fig. 7. Principle of the Mat-Tec carver.

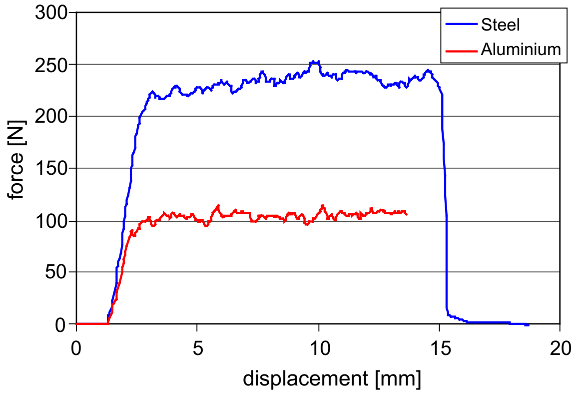

Fig. 8. Examples of measured force–displacement curves.

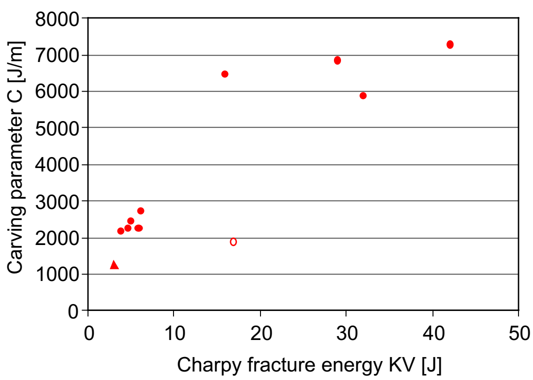

Fig. 9. Correlation between the parameter C extracted thereof with Charpy fracture energy obtained by several tests on various types of bronze alloys.

$$C = F_{x\text{mean}}/\Delta F_{xs}^2 \tag{12}$$

Fig. 9 shows the correlation between the Charpy fracture energy and the tentative parameter C. It confirms the correlation between C and toughness.

6. Conclusions

Although non-destructive determination of mechanical material properties is principally impossible, there are some methods to obtain estimates of reasonable accuracy by quasi-non-destructive testing. The procedures and results described in the present paper were part of a feasibility study to evaluate the possibilities of such methods. A few promising possibilities have been shown and discussed: Ambulant instrumented indentation tests to determine a reference stress–strain curve, miniature pin compression tests that allow uniaxial compression tests in situ, and carving tests to estimate fracture toughness. Quasi-non-destructive testing only makes sense if a mobile test apparatus is available to perform ambulant tests on a component. The corresponding equipment is shown.

A relatively simple analytical evaluation procedure for instrumented indentation tests is shown. It enables one to derive stress–strain curves from an IIT of just one loading cycle. The accuracy is in the order of 10–20%, which in many practical cases is sufficient to avoid standard destructing testing. To increase the accuracy, strain range, and depth of the volume, a miniature pin compression test is suggested, which can be performed in situ on the surface of a component essentially by the same instrument as IIT. Furthermore, taking credit from the well-known relation between cutting energy and fracture toughness, a possibility to get information about fracture toughness based on carving is shown. However, determining absolute toughness values is probably a too ambitious aim, but for comparisons it already has proven to be suited.

All the described tests can be performed relatively easily. Particularly, they also can be performed at high or low temperatures. However, a lot of further research and experience is necessary to explore the possibilities and limitations of such tests.

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