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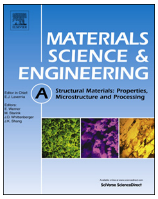

# Identification of the hardening law of materials with spherical indentation using the average representative strain for several penetration depths

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ABSTRACT

The identification of plastic properties with spherical indentation has been the subject of many studies in the last decades. In the present work, a new method for the determination of the hardening law of materials using the load–displacement curve of a spherical indentation test is proposed. This method is based on the use of an average representative strain. The advantage of the proposed average representative strain is that it is strictly obtained from the material in response to the indentation test. By using various values of penetration depth, the proposed method gives the range of strain for which the hardening law is precisely identified and allows determining a confidence domain that takes into account experimental imprecision and material heterogeneity. The influence of penetration depth and the error formula on the identified Hollomon hardening law are discussed in the present study. The present study clarifies many problems that were observed in previous studies such as the uniqueness of solution and the sensitivity of the indentation test to the plastic parameters of the Hollomon hardening law.

## 1. Introduction

Knowledge of the hardening law is fundamental in design and formation of metal products. This mechanical property is commonly obtained from tensile test. For cases such as plastically and functionally graded materials, biomedical materials, welded components and thin films, the tensile test cannot be applied. The instrumented indentation test is an excellent substitute in such cases for the standard tensile test [1–9]. Identification of plastic hardening parameters from a load–penetration depth spherical indentation curve ($F$–$h$ curve) is mostly used and the methods based on the representative strain and stress approach are widely proposed [10–20].

Several methods consist to directly correlate the representative stress and strain to the stress–strain point in the uniaxial tensile test [10,13–15]. Other methods consist to determine the parameters of the Hollomon hardening law from a closed-form expression of the $F$–$h$ curve as a function of material properties [11,12,16–18,20,21]. For the second group of methods, the full stress–strain response is commonly estimated from the following piecewise power law assumption:

$$\begin{cases} \sigma = E\varepsilon & \text{if} \quad \sigma \le \sigma_y \\ \sigma = E^n \sigma_y^{(1-n)} \varepsilon^n & \text{if} \quad \sigma \ge \sigma_y \end{cases} \tag{1}$$

where $\sigma_y$ is the yield stress, $n$ is the work hardening exponent and $E$ is Young's modulus.

While the framework for determining the hardening law of materials by considering the $F$–$h$ curve has been demonstrated to work well for metals, issues of uniqueness [17,22,23] and sensitivity [23–25] have also been identified. Moreover, none of the studies concerning the mechanical characterization using the $F$–$h$ curve [11,12,16–18,20,21] gave a clear answer on the range of strain for which the hardening law is precisely identified. In some studies, no physical justification was given to explain the reason why the proposed strain can be considered as a representative of spherical indentation [10,16]. In other studies, the use of the representative strain serves as a mathematical trick having no physical basis [11,12,18,20,21].

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In a recent study [26], an investigation of the domain in which the solution exists while identifying the hardening law of a material with spherical indentation using the *F*–*h* curve was performed. A definition of an average representative strain only based on the material response to the indentation test, i.e. the *F*–*h* curve, was also proposed in this study. Based on the use of this average representative strain, a new identification method that allows identifying the hardening law of materials for a well-known range of strain is proposed in the present study. Also, the influence of the penetration depth and the choice of the error formula used in the identification process is investigated and overtaken in the proposed method.

## 2. Material presentation and experimental results

The studied material denoted 20MnB5 steel (European Standard EN 10083-3, Steelgrade no. 1.5530) is a commercial hot-rolled boron-alloyed case-hardening and heat-treatable steel, provided by Hoesch Hohenlimburg GmbH. The chemical composition in weight is 0.191% C, 1.14% Mn, 0.362% Si, 0.0158% P, 0.0008% S, 0.25% Cr, 0.0014% B, 0.039% Al, 0.027% Ti, 0.017% Mo, 0.025% Cu and 0.06% Ni. The steel has been hot rolled to a thickness of 4.5 mm. All investigations have been performed on the material in the as received condition.

The micrograph in Fig. 1 shows, as a result of the hot rolling, a fine and homogeneous distribution of spheroidized carbides in a ferritic matrix. This microstructure gives excellent properties in the as rolled condition for cold forming, slitting and machining without additional annealing processes. For our study, this type of steel was selected because of this fine, homogeneous microstructure, which leads to a good reproducibility of the indentation tests.

The tensile test and indentation specimens were carefully sectioned with a Precision Cut-Off Machine from the hot rolled sheet. The Vickers hardness (10 Kgf) measurements gave $HV_{10}=155$ for the surface and $HV_{10}=160$ for the core. The true tensile curves obtained for 20MnB5 steel before necking are represented in Fig. 2. The experimental conditions and measurement method for the tensile test were presented in a previous study [6]. Fig. 2 shows that the studied material exhibits a yield stress of about 340 MPa and a non-negligible work hardening. This figure also shows that the Hollomon equation does not describe the entire flow curve for the 20MnB5 steels

The spherical indentation tests were carried out with a tungsten carbide ball of radius 0.5 mm. The indentation bench and the experimental conditions used for the indentation tests were detailed in a previous study [6]. Four spherical indentation curves were obtained from the material. Fig. 3 shows that a satisfying reproducibility of the indentation tests was obtained.

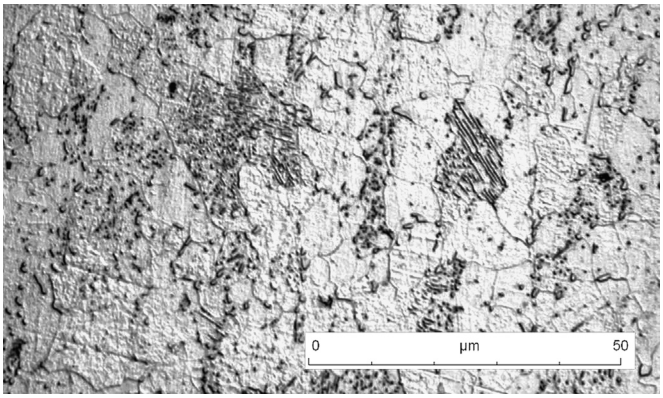

**Fig. 1.** Microstructure of the 20MnB5 steel alloy.

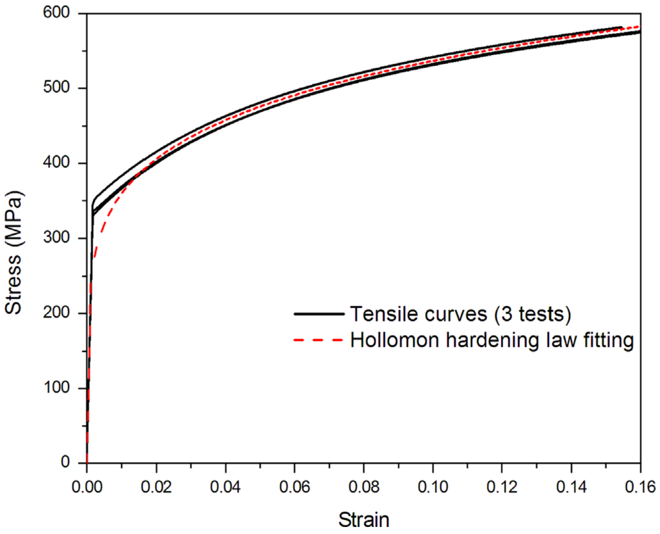

**Fig. 2.** Uniaxial tensile test curves for 20MnB5 steel alloy [26].

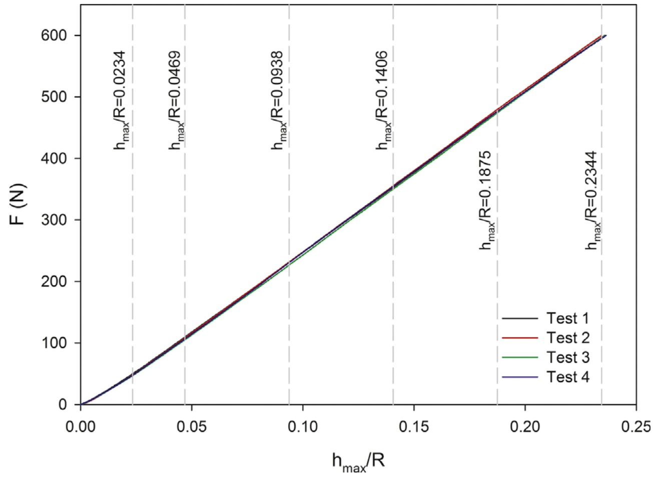

**Fig. 3.** Spherical indentation curves for 20MnB5 steel alloy.

## 3. Evaluation of the tensile properties from one value of $h_{max}/R$ ratio

Using the four experimental indentation curves (see Fig. 3), the average curve is determined (average load for every penetration depth). In the present study, only the average curve is used to characterize the material. In order to quantify the gap between two indentation curves, the root mean square error, the following equation, was used

$$E_{RMS}(h_{max}/R)=\sqrt{\frac{1}{h_{max}}\int_0^{h_{max}}(F_1-F_2)^2dh} \tag{2}$$

where $R$ is the spherical indenter radius (0.5 mm), $h$ is the penetration depth, $h_{max}$ is the maximal penetration depth and $F_1$ and $F_2$ are the load for the two considered curves. In this section one penetration depth is treated ($h_{max}/R=0.2344$). The characterization procedure consists of calculating the gap, using $E_{RMS}$ (Eq. (2)), between an experimental *F*–*h* curve and a number of *F*–*h* curves obtained from Finite Element simulations for different Hollomon hardening law parameters. The finite elements (FE) model was presented in a previous study [26]. The elastic properties of the simulated materials