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Determination of strain-hardening exponent using double compression test

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ABSTRACT

In this investigation a new method for determination of strain-hardening exponent (n) is introduced. The presented method is named “Double Compression Test” in which two specimens with the same composition and geometrical dimensions but different processing background are compressed simultaneously. One of the two specimens is in annealed condition while the other has experienced a predetermined amount of pre-strain. This difference leads to different final length of the specimens which can be used in the theoretical relation presented to calculate the strain-hardening exponent. The major advantage of this method is its independency to the stress–strain data which is essential in the conventional method for determination of strain-hardening exponent. The test was performed experimentally and the results were compared with those obtained by the conventional method. Finally, the test was simulated using the commercial finite element code, ABAQUS/Explicit, to investigate it in more details. Experimental and simulation results showed that this test is capable of determining strain-hardening exponent with good accuracy.

1. Introduction

The value of the strain-hardening exponent (n) is of major importance in forming operations since it controls the amount of uniform plastic strain the material can undergo during a tensile test before strain localization, or necking, sets in leading to failure. It is easily shown that the maximum amount of uniform plastic deformation in tensile straining is given by the strain-hardening exponent (n) which is known as the Considère criterion. As a result, a high coefficient facilitates complex-forming operations without premature failure [1].

Therefore, strain-hardening exponent is an important parameter reflecting a material’s hardening property and its determination is of great importance. A standard method to perform this task is based on using stress–strain data obtained from uniaxial tensile test. Stress–strain curves are usually represented by the Hollomon equation. Therefore, by plotting stress–strain data on logarithmic coordinates, it can be shown that the slope of the line in the fully plastic region defines the strain-hardening exponent (n) [2,3].

Shinohara [4] investigated relationship between strain-hardening exponent and load dependence of Vickers hardness in copper and showed that the slope of the load dependence of the hardness was a good measure for correlating with strain-hardening exponent (n). By using the instrumented spherical-indentation technique, Nayebi et al. [5] presented a relationship between applied loads, indenter displacement, flow stress and strain-hardening exponent of steels. The model they presented yields to the steel mechanical parameters, σ_y and n from the indentation displacement–load curve. Kim et al. [6] evaluated plastic flow properties by characterizing indentation size effect using a sharp indenter and found a linear relationship between the strain-hardening exponent and the log of the indentation size effect characteristic length for Ni and structural steel samples with different plastic pre-strain values.

Antoine et al. [7] showed that there is a linear relationship between the value of the strain-hardening exponent and the yield strength, and presented a model giving the value of the strain-hardening exponent for Ti-IF steel. Nagarjuna et al. [8] investigated the relationship between strain-hardening exponent (n) and grain size of Cu–26Ni–17Zn alloy by analysis of constants in Hollomon equation as a function of grain size. They found that strain-hardening exponent (n) is independent of grain size in the range of 15–120 μm. Narayanasamya et al. [9] performed a study on the instantaneous strain-hardening behavior of an aluminum powder metallurgy composite with various percent of iron contents and for the various stress state conditions with two different aspect ratios. They calculated the instantaneous strain-hardening exponent (n_i) and the strength coefficient (k_i) using mathematical expressions. Zhang et al. [10] used two equations correlating the strain-hardening exponent and the strength coefficient with the yield stress–strain behavior, and also the fracture strength with the fracture ductility and presented a simple theoretical method of calculating the strain-hardening exponent and the strength coefficient of metallic materials.

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Nomenclature

k	strength coefficient
n	strain-hardening exponent
H_0	initial height of cylinder
H_p	height of pre-strained cylinder after deformation
H_a	height of annealed cylinder after deformation
ΔH	total reduction in height
D_0	initial diameter of cylinder
D_p	diameter of pre-strained cylinder after deformation
D_a	diameter of annealed cylinder after deformation
A_0	initial cross section area of cylinder
A_p	cross section area of pre-strained cylinder after deformation
A_a	cross section area of annealed cylinder after deformation
ε_0	amount of pre-strain

In the present study, a new approach is introduced which is capable of determining strain-hardening exponent without any need to know the stress–strain data. This method just deals with geometrical dimensions of the work piece before and after the test.

2. Theory

Double compression test is based on simultaneous compression of two specimens having the same composition and geometrical dimensions, one in the annealed condition, while the other undergone a predetermined amount of pre-strain. The scheme of the test is illustrated in Fig. 1.

In the absence of internal effects, the same axial force (F) is transmitted through both cylindrical work pieces. Considering a frictionless condition and using the Hollomon equation, this can be expressed by the following equation:

$$k(\varepsilon_0 + \bar{\varepsilon}_p)^n \cdot A_p = k(\bar{\varepsilon}_a)^n \cdot A_a \tag{1}$$

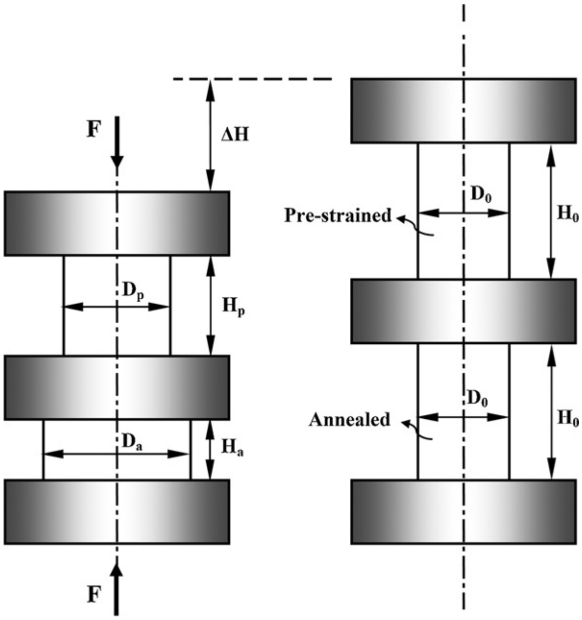

Fig. 1. A scheme of double compression test.

Table 1
The initial dimensions of the aluminum specimens.

Specimen	H_0 (mm)	D_0 (mm)	Aspect ratio
I	45	30	1.5
II	15	10	1.5

where, subscripts “a” and “p” apply to annealed and pre-strained conditions respectively. Thus:

$$\left(\frac{\varepsilon_0 + \bar{\varepsilon}_p}{\bar{\varepsilon}_a}\right)^n = \frac{A_a}{A_p} \tag{2}$$

where A_0, A_p and A_a are related to one another according to the following equations:

$$A_a = A_0 \cdot \exp(\bar{\varepsilon}_a) \tag{3}$$

$$A_p = A_0 \cdot \exp(\bar{\varepsilon}_p) \tag{4}$$

The strain-hardening exponent (n) is calculated using equation:

$$n = \frac{\bar{\varepsilon}_a - \bar{\varepsilon}_p}{\ln\left(\frac{\varepsilon_0 + \bar{\varepsilon}_p}{\bar{\varepsilon}_a}\right)} \tag{5}$$

By this method, strain-hardening exponent can be simply calculated by just using geometrical measurements, without needing to know the load values.

3. Experimental procedure

Two sets of cylindrical specimens with aspect ratio 1.5 and dimensions mentioned in Table 1 were machined from an aluminum alloy rod with unknown mechanical properties. These specimens were then annealed at 430 °C for 2 h. The specimens in set (I) were compressed to strain values of 0.2, 0.4, 0.6 and 0.8 as illustrated in Fig. 2. Compression tests were carried out using a screw press with the compression rate of 0.1 mm/s at room temperature.

Then, new specimens were machined out of these compressed cylinders. The final dimensions of these specimens were exactly the same as those in set (II). A pair of specimens including an annealed and a strained specimen with pre-strain value $\varepsilon_0 = 0.2$, were compressed simultaneously to the amount of $\Delta H = 10$ mm. The test set-up is illustrated in Fig. 3. The same procedure was repeated for specimens with pre-strain values $\varepsilon_0 = 0.4$, $\varepsilon_0 = 0.6$ and $\varepsilon_0 = 0.8$. The specimens' new heights were measured and are listed in Table 2. Using these dimensions and Eq. (5), it is possible to obtain the value of strain-hardening exponent without considering any load parameter.

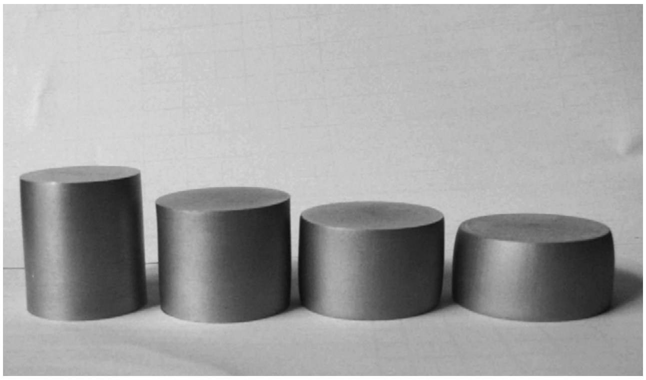

Fig. 2. Aluminum specimens compressed to strain values of 0.2, 0.4, 0.6 and 0.8 from left to right.