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On the representative strain in Vickers hardness testing of 7010 aluminum alloy

M. Tiryakioğlu [a,*], J.S. Robinson [b]

[a] School of Engineering, University of North Florida, Jacksonville, FL 32224, USA
[b] Department of Mechanical, Aeronautical and Biomedical Engineering, University of Limerick, Limerick, Ireland

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ABSTRACT

A review of the concept of representative strain in Vickers hardness testing is provided and different values reported in the literature are summarized. A new criterion for the proper selection of the representative strain is introduced. By using this criterion, the stress–strain curves of 63 specimens excised from a 7010 aluminum alloy rectilinear forging, cooled differently from the solution treatment temperature have been analyzed. Regression analyses have been conducted between the Vickers hardness numbers and the true stress values corresponding to twenty eight true plastic strain levels. These results indicate that the representative strain associated with diamond indentation is between 0.0185 and 0.0301 with the most likely number of 0.0240. The value of the constraint factor changes with the assumed representative strain and is essentially equal to 3.00 when 0.0240 is chosen as the representative strain.

1. Introduction

In conventional hardness testing, an indenter is forced onto the surface of a specimen, leaving behind a permanent indentation. Hence the indenter generates stresses in excess of the material's yield strength (σ_Y) for plastic flow (or plastic strain) to occur during the formation of this indentation. There have been numerous attempts to correlate Vickers hardness number (H_V) with tensile properties in metals, including yield strength and tensile strength (S_T). Most of these studies developed empirical relationships between Vickers hardness and the mechanical property of interest. The motivation to develop empirical relationships between H_V and tensile properties has been driven by the relatively non-destructive nature of Vickers hardness testing, resulting in mechanical data that can be gathered quickly without the need for excising samples for testing destructively.

Vickers hardness tests use a square pyramidal indenter with the opposite faces making an angle of 136° with each other. The advantage of the Vickers hardness test is that (i) it produces geometrically similar indentations [1], unlike hardness tests that use spherical indenters, such as the Brinell test and most Rockwell tests, in which the geometry of indentation is dependent on its depth [2], and (ii) H_V is independent of the load applied by the indenter (L) on the specimen surface when L exceeds 50 N [3].

Although the strain distribution under a Vickers indenter is complicated [4–6], the concept of "representative strain" (ε_r), as defined by Atkins and Tabor [7] has received considerable attention. Atkins and Tabor stated that as long as indentations are geometrically similar, this representative strain should be independent of the size of the indentations for wedge, cone and pyramidal indentations. For Vickers hardness testing, Tabor [8] originally found the value of ε_r to be 0.08. Since then, there have been several studies [9,10] in which ε_r for Vickers hardness testing was analyzed through experiments and/or finite element modeling (FEM) and results as high as 0.36 [9] and as low as 0.0115 [10] have been reported. This wide range of representative strain values reported in the literature does not provide the clarity desired by materials engineers who wish to use H_V to estimate mechanical properties. The present study is motivated by the need to link the concept of "representative strain" to tensile deformation behavior. To accomplish this task, tensile stress–strain data from sixty three specimens with different quench paths from solution treatment temperature to room temperature were analyzed along with hardness data.

2. Background

In all hardness tests, the mean pressure under the indenter, P_m, alternatively referred to as the Meyer hardness [11], is found by dividing the load by the projected area of indentation, A_i;

* Corresponding author. Fax: +1 904 620 1391.

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$$P_m = \frac{L}{A_i} \quad (1)$$

The flow stress under the indenter, σ_f, is related to mean pressure;

$$\sigma_f = \frac{P_m}{C} \quad (2)$$

where C is referred to as the constraint factor. In calculating Vickers hardness, H_V,[1] load is divided by the contact area of indentation, not the projected area. Therefore, H_V and P_m are related by

$$H_V = 0.9272 P_m \quad (3)$$

Combining Eqs. (1)–(3), we obtain

$$\sigma_f = \frac{H_V}{0.9272C} \quad (4)$$

In fully work-hardened materials, stress increases elastically to yield strength, after which it remains constant despite increasing strain. In many early studies on the hardness of metals, the materials were specifically chosen to be fully work-hardened, ensuring that flow stress was equal to yield strength so that stress calculations always resulted in an estimate of the yield strength. In metals that are not yet fully work hardened, σ_f is larger than σ_Y and consequently, the effect of work hardening that occurs during indentation must be accounted for

$$\sigma_f = \sigma_Y + \Delta\sigma \quad (5)$$

where $\Delta\sigma$ is the increase in stress due to work hardening during deformation up to the representative strain. Combining Eqs. (4) and (5), we obtain [12]

$$\sigma_Y = \frac{H_V}{0.9272C} - \Delta\sigma \quad (6)$$

Eq. (6) is consistent with the results in the literature [12–21] because the linear relationship between σ_Y and Vickers hardness consistently yielded a negative intercept in specimens that work harden during tensile deformation. In other words, the strain at the yield strength is consistently lower than the representative strain. The H_V–S_T relationships in the literature, however, have mostly a positive intercept [12,13,20], and occasionally an intercept of zero [22] or a negative intercept [15]. The connection between the representative strain and the value of the y-intercept is presented schematically in Fig. 1. A positive y-intercept of a H_V–σ regression line means that the true strain corresponding to the stress data used in the regression analysis is higher than the representative strain. Conversely, a negative y-intercept shows that the value of ε used to find the true stress values is lower than ε_r. Only when $\varepsilon = \varepsilon_r$, the y-intercept is zero and the corresponding true stress is σ_f. Therefore, an important issue in determining the correct value of the representative strain, is that the H_V–σ_f relationship should have an intercept of zero. To the authors' knowledge, this aspect of representative strain has not been fully addressed before.

The value of ε_r was first investigated by Tabor [8] who conducted experiments on mild steel and annealed copper. Tabor deformed the two materials plastically and tested them in tension. Then he determined the stress at $\varepsilon = 0.08$ ($\sigma_{0.08}$) and reported a strong correlation with H_V. It is noteworthy that Tabor used values of 3.2 and 3.5 for the constraint factor, C, for mild steel and annealed copper, respectively. Later Tabor [1] showed that for a conical indenter, the strain can be found by

[1] In this study, Vickers hardness is reported in MPa, which is found by multiplying the traditional Vickers number by the gravitational acceleration.

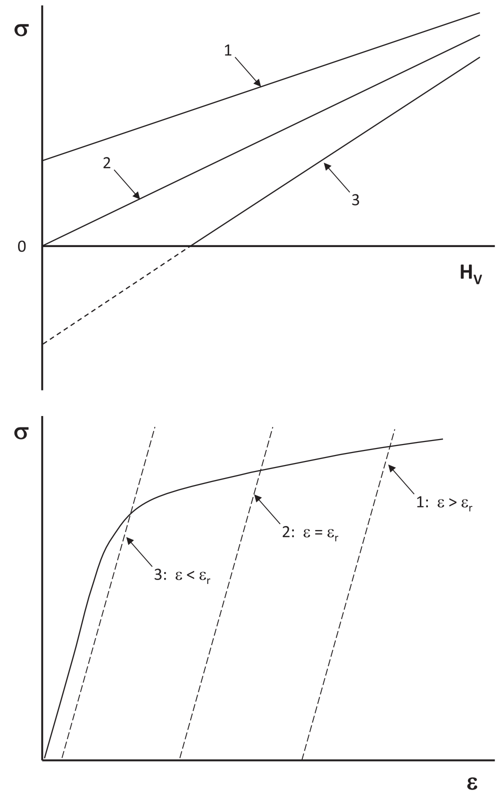

Fig. 1. Schematic illustration of the relationship between the representative strain and the slope and y-intercept of the regression line for H_V–σ data. The y-intercept is zero only when the true stress corresponding to the representative strain is plotted versus H_V.

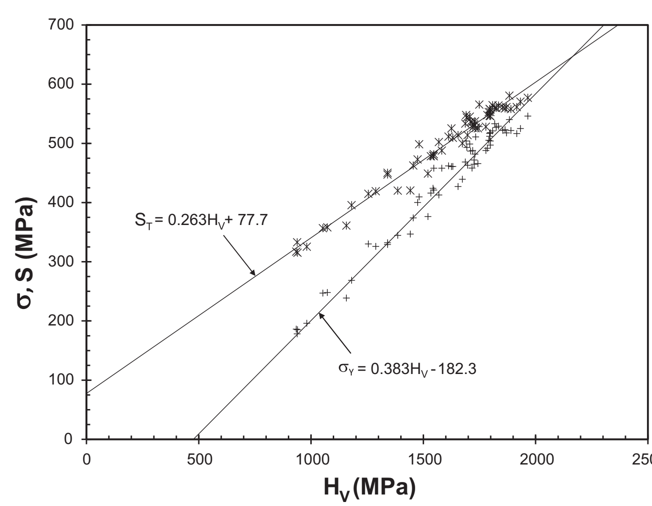

Fig. 2. Vickers hardness versus yield strength and tensile strength for 7010 forging investigated in this study.

$$\varepsilon_r = 0.2\cot(\gamma) \quad (7)$$

where γ is half angle of the tip of the indenter. Because $\gamma = 68°$ for the pyramidal diamond of a Vickers indenter, Eq. (7) yields $\varepsilon_r \approx 0.08$ which is consistent with the initial experimental results of Tabor. However, a conical indenter that would displace the same amount of metal would have $\gamma = 70.3°$ [4]. Using this value for γ, Johnson [4] stated that ε_r should be 0.07, which corresponds to the maximum strain value found by Samuels and Mulhearn [23] under a Vickers indenter in their experiments on 70–30 brass. It was