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Correlation between yield stress and hardness of nickel–silicon–boron-based alloys by nanoindentation

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Based on the relation proposed by Tabor in 1951, which connects the ultimate tensile strength and the yield stress of classical materials to the Brinell or Vickers hardness numbers by a simple factor of proportionality, we propose an extended analytical model for the determination of the yield stress of brittle materials using nanoindentation data. This model considers the nanoindentation hardness calculated from the projected actual contact area between the indenter and the material which is representative of the real mean pressure exerted by the indenter compared to classical hardness numbers. A coefficient is introduced in the model to integrate the extent of the elastic recovery of the indented material occurring after the withdrawal of the indenter. This is possible by using the criterion defined by the residual to maximum indenter displacements ratio, this criterion being already related to the deformation mode under indentation. Indeed, this criterion allows identifying the piling-up deformation observed for complete or fully plastic deformation materials or the sinking-in deformation for purely elastic materials. The proposed model thus allows a good estimation of the yield stress of brittle materials for which classical tensile tests are not applicable. The model is validated on a variety of amorphous nickel–silicon-based alloy ribbons, i.e., $Ni_{89}Si_9B_2$, $Ni_{78}Si_9B_{13}$ and $Ni_{68}Fe_3Cr_7Si_8B_{14}$ on which both nanoindentation tests and tensile experiments have been performed.

1. Introduction

Mechanical properties such as hardness, elastic modulus, tensile strength and toughness of thin ribbons composed of amorphous alloy are difficult to obtain by means of classical mechanical tests. During the past decades, many efforts have been made to relate the strength of materials to the hardness based on the relation of Tabor [1], which proposes a simple relationship between the ultimate tensile strength (UTS) and the microhardness using spherical or sharp indenters. A simple coefficient of proportionality of 2.8 is often used as a first approximation in majority of the situations. For full or complete plastic deformation materials and when the strain-hardening exponent differs by 0.217, Moteff et al. [2] suggest the introduction of a coefficient only related to the strain-hardening exponent. Following this approach, Cahoon et al. [3,4] presented simplified expressions relating the ultimate tensile strength (UTS) and the yield stress (YS) to the microhardness numbers (HN) and the strain-hardening exponent. To avoid any confusion, it is important to note that the microhardness which is considered in these relationships between HN and UTS or YS is the Meyer hardness which is defined by the ratio between the applied load and the projected area of the residual indent. This hardness calculation is more representative of a mean pressure compared to the Vickers hardness which considers the true contact area between the indenter and the material. As a conclusion, these relations are very helpful for characterizing complete or fully plastic deformation materials but inapplicable for ceramic materials [5]. Indeed, Swab et al. [5] present results obtained on a large variety of ceramics. They showed that the factor of proportionality varies between 1.4 and 3.5 depending on the nature of the material. Unfortunately, these authors do not present a simple calculation of such a coefficient. However, the work of Swab et al. [5] clearly shows that this coefficient does not have a constant value.

In this work, we propose this simple relation for the calculation of the proportionality factor using nanoindentation data. This methodology, compared to classical indentation tests, allows a better consideration of the mean pressure because the real deformation of the material under indentation, i.e., piling-up for work-hardening materials and sinking-in for brittle materials, can

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be taken into account. This is possible by applying the methodology of Oliver and Pharr [6] which allows determining the 'contact' area between the indenter and the material. Finally for estimating the yield stress, we suggest the use of the nanoindentation hardness (HIT) and a coefficient Δ already used to estimate the deformation mode around the indent. HIT allows considering the true projected contact area by means of the contact depth corresponding to the distance for which the indenter stays in contact with the material. Δ is defined by the ratio between the residual indentation depth and the maximum displacement of the indenter and its value gives information on the elastic recovery which occurs during the unloading of the indenter. The model is validated on three nickel–silicon-based ribbons, i.e., $Ni_{89}Si_9B_2$, $Ni_{78}Si_9B_{13}$ and $Ni_{68}Fe_3Cr_7Si_8B_{14}$.

2. Hardness and strength relationships

The basis for relating the ultimate tensile stress to the mean pressure using spherical indentation was introduced by Tabor in 1951 [1]. The ultimate tensile stress, UTS, is correlated to the mean pressure underneath the indenter, P_m, as follows:

$$\mathrm{UTS} = \frac{P_m}{\Psi} \tag{1}$$

where Ψ is the constraint factor whose value depends on the deformation regime.

Note that in this relation (1), the calculation of the mean pressure, P_m, depends on the indenter type used. Even if this approach was first developed for spherical indenter, an extension to the use of sharp indenters like Vickers or Knoop indenters is possible. Indeed, Swab et al. [5] have shown some results obtained with a Knoop indenter applied for characterizing the tensile properties of several ceramics. Nevertheless and independently of the indenter used, knowledge of the deformation regime is required for the calculation of the constraint factor. Different deformation regimes were identified by Johnson [7] by using an adimensional parameter connected to the elastic modulus (E), the yield stress (YS), the contact diameter (d_c) and the indenter diameter (D) as follows:

$$\Phi = \left(\frac{E}{\mathrm{YS}}\right)\left(\frac{d_c}{D}\right) \tag{2}$$

where the first bracket is only material-dependent and the second one related to the indentation parameters.

When ϕ is less than 1, the deformation is purely elastic and the constraint factor is equal to 1.11. For elastic–plastic deformation, i.e., when ϕ ranges between 1 and 27.3, ψ varies linearly as a function of $\ln(\phi)$: $1.11 + 0.534 \times \ln(\phi)$. For greater values of ϕ higher than 27.3 corresponding to a fully plastic deformation stage, the constraint factor is assumed to be constant and equal to $\psi_{max} = = 2.8$, which is an average value [1,8–10]. However, the limits between the different stages of deformation can differ according to the authors. For example, Haggag et al. [11,12] give values which depend on the strain-hardening exponent deduced from the relation of Hollomon and the strain rate. The maximum constraint factor dependency with the strain-hardening exponent according to Hollomon's relation has been demonstrated by Mathews [13] and Tirupataiah [14]. The corresponding equation valuable for work-hardening materials expresses the mean pressure and the true stress ratio as follows:

$$\Psi_{max} = \frac{P_m}{\mathrm{UTS}} = \frac{6}{2+n}\left(\frac{40}{9\Pi}\right)^n \tag{3}$$

In condition of a fully plastic deformation stage, ϕ is higher than 27.3. However, finite element simulations performed by Taljat et al. [15] show that the constraint factor is not constant even if the parameter ϕ is higher than 27.3, independently of the strain-hardening exponent. For example, ψ_{max} varies between 3 for $n=0$ to 2.5 for $n=0.5$. In this condition of deformation and using a simple approach, Yetna et al. [16] suggest relating the maximum constraint factor to the strain-hardening exponent by a simple relation as follows:

$$\Psi_{max} = (3 - n) \tag{4}$$

which can be applied after verifying that the adimensional parameter ϕ fulfills the limit condition.

Following the approach described above, Cahoon et al. [3,4] propose extending the determination of UTS to the determination of the yield stress following a similar relationship with a different factor as a function of the strain-hardening exponent. Thus, UTS and YS can be directly estimated from a hardness test. Although whatever the determination of UTS or YS, it is shown that for complete or fully plastic deformation materials, the constraint factor greatly depends on the strain-hardening exponent. In addition, Norbury and Samuel [17] have shown that pile-up or sinking-in occur during the indentation depending on the mechanical properties of the indented material. A numerical invariant called c^2 has been proposed for identifying the deformation mode around the indent. This invariant corresponds to the ratio between the contact diameter (taking into account the deformation) and the indent diameter. When c^2 is higher than 1, piling-up occurs whereas sinking-in occurs for values of c^2 less than 1. The expression of c^2 as a function of the strain-hardening exponent has been studied by Mathews [13] and Hill et al. [18].

Unfortunately for ceramic materials for which no plastic deformation occurs during a tensile test, the above-mentioned relationships introducing the strain-hardening exponent between the ultimate tensile stress or the yield stress and the hardness cannot be applied as it is. As an example, Swab et al. [5] have shown that the maximum constraint factor related to the yield stress, ψ_{max}, ranges between 3 and 1.5 depending on the tested ceramics. Unfortunately, no relationship between the values of this coefficient and the mechanical behavior of the ceramic has been proposed by the authors. We have seen that the relationships between UTS and YS must consider the deformation mode for better accuracy. As originally suggested by Tabor [1], the contact diameter is defined as the diameter measured in the plan where the spherical indenter is always in contact with the indented material. As a consequence, this methodology allows us to take into account the deformation of the indent, i.e., the pile-up along the edges of the indent or the sinking-in which corresponds to the deflection of the faces of the residual indent. Classical hardness measurement with sharp indenters does not allow such a consideration since the diagonal of the indent is not affected by the deformation around the indent [19,20]. On the contrary, the methodology proposed by Oliver and Pharr [6] for determining the hardness from a load–displacement curve allows us to consider the deformation mode. Indeed, that is possible by means of the contact area calculation which integrates the contact zone between the material and the indenter. Consequently, the contact hardness (HIT) corresponding to the ratio between the applied load and the real projected contact area seems to be more representative of the mean pressure than classical hardness.

Additionally, the work of Swab et al. [5] has clearly shown that the constraint factor does not have a unique value due to the extent of the sinking-in representative of the deformation mode of the ceramic. From a general point of view, for soft materials having low values of both hardness-to-elastic modulus ratio (H/E) and strain-hardening exponent, n, to elastic modulus ratio (n/E), the piling-up mode predominates [21]. Similarly Cheng and Cheng [22] and Xu and Rowcliffe [23] found that, for a given indenter, piling-up or sinking-in behavior is associated with the ratio of the