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Hardness–strength relationships in the aluminum alloy 7010

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ABSTRACT

The relationship between Vickers hardness, yield stress and tensile strength was analyzed by combining data from two independent studies involving 7010 alloy plate and a rectilinear forging. The hardness–yield stress data from the two studies overlapped, suggesting a possible fundamental relationship. Constraint factors calculated by using contact mechanics models were evaluated and the one found by Shaw and DeSalvo was found to agree with the slope for the hardness–yield stress data. The y-intercept of the hardness–yield stress relationship was explained by the work hardening taking place during Vickers testing. The equation found to fit the hardness–yield stress data for 7010 plate and forgings also provided a very respectable fit to a third independent study. Moreover, an empirical equation was developed to express the hardness–tensile strength relationship.

1. Introduction

Wrought Al–Zn–Mg–Cu alloys are used extensively in aerospace applications due to their high strength-to-density ratio (specific strength). Heat treatment of these alloys involves a solution treatment, subsequent quenching, and finally artificial aging that may involve several stages depending on the desired temper. Aluminum alloy 7010 was developed for applications requiring high strength, high fracture toughness, exfoliation resistance and stress corrosion cracking resistance in thick sections [1].

Quality assurance practices in the aerospace industry usually require tensile tests to be conducted on specimens excised from the aluminum parts [2]. Although this practice yields reliable results, excising the tensile coupons not only is time consuming, but also in some applications, leads to the destruction of the part. Therefore, nondestructive methods to estimate the tensile properties, especially yield stress (σ_Y) and tensile strength (S_T), have been of interest to process engineers. One of the most common techniques to estimate yield stress and tensile strength has been hardness testing because of its nondestructive (or semi-destructive) nature, leaving behind only an indentation. Moreover, mechanical data can be gathered quickly without the need for excising samples for testing.

Brinell and Rockwell are among the hardness tests most commonly used in industry. Brinell and most scales in Rockwell use spherical indenters, which yield geometrically dissimilar indentations [3]. Vickers hardness tests use pyramidal indenters, which result in geometrically similar indentations [3]. There have been numerous studies on the geometrical aspects of spherical [3–7] and Vickers [8–10] indentations. In addition, there has been a strong interest in estimating tensile properties from hardness tests. These efforts can be categorized in three groups:

1. Estimating σ_Y and S_T directly from the correlation with hardness [11–14],
2. taking multiple hardness measurements at different loads, calculating mean pressure values and coefficients in given equations which can then be used to estimate σ_Y and S_T [11,15,16],
3. collecting load–indentation depth data throughout the loading and unloading stages of hardness testing, calculating coefficients in a set of equations and using an algorithm to estimate σ_Y and modulus of elasticity, E [8,17].

The present study follows the first method, building on the contact mechanics principles established in the literature. Data from two independent studies, one conducted on a 7010 forging [18] with different quench paths but the same aging treatment, the other [13,19] on 7010 plate with the same quench path but different aging treatments, are combined in the analysis.

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2. Background

The mean pressure under the indenter, P_m, alternatively referred to as the Meyer hardness [20], is found by dividing the load, L, by the projected area of indentation, A_i;

$$P_m = \frac{L}{A_i} \tag{1}$$

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

$$\sigma_f = \frac{P_m}{C} \tag{2}$$

where C is the constraint factor. Hill et al. [21] developed a solution for the stress distribution under a wedge indenter and showed that the pressure normal to the surface of the indenter tip can be found as,

$$P_m = 2\tau_c(1+\theta) \tag{3}$$

where τ_c is the critical maximum shear stress and θ is an angle in the geometric model developed by Hill et al. that is a function of the half angle of the nose of the wedge. For a flat punch, $\theta = \pi/2$. For Vickers indentation, Tabor [3] assumed that the model for a flat punch would be a good approximation. Tabor also used the Huber–Mises criterion, such that,

$$2\tau_c = 1.15\sigma_Y \tag{4}$$

Combining Eqs. (3) and (4) and taking $\theta = \pi/2$, we obtain

$$P_m = 1.15\sigma_Y\left(1+\frac{\pi}{2}\right) \tag{5}$$

Therefore,

$$P_m = 2.956\sigma_Y \tag{5.a}$$

Hence, C is approximately 3 from Eqs. (5.a) and (2) [3], since flow stress is assumed to be equal to yield stress in these loading conditions. Tabor [22] conducted experiments on three fully work-hardened metals, namely tellurium lead, copper and mild steel, and found C to be 2.9, 2.8 and 2.8, respectively. Since Tabor's statement was that $C \approx 3$, many researchers assumed the mean pressure under an indenter to be three times the tensile yield strength of the metal.

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

$$H_V = 0.927P_m \tag{6}$$

Eqs. (5.a) and (6) can be combined to obtain

$$\sigma_Y = \frac{H_V}{0.927C} \tag{7}$$

Taking $C = 2.956$, H_V (MPa) versus σ_Y (MPa) plots can be expected to have a slope of 0.365 (3.580 when H_V is given in kg/mm^2) and the best fit lines should go through the origin. However, research on steels [14,23–26], magnesium [27], and aluminum [13,28] showed that the relationship between Vickers hardness and tensile yield stress is better expressed in the form

$$\sigma_Y = \beta_1 H_V + \beta_0 \tag{8}$$

In steels, the slope in Eq. (8), β_1, was found [24] to change between 0.268 and 0.390. In all studies, the y-intercept, β_0, was found to be negative. To the authors' knowledge, the consistent presence of a y-intercept that is different from zero has not been fully addressed in the literature. That is why some researchers [24,26] have chosen to report their findings in terms of $\Delta\sigma_Y/\Delta H_V$ (β_1).

Estimating tensile strength from hardness data has been mostly empirical in nature because the phenomenon of tensile instability after which engineering stress decreases with increased engineering strain does not occur during indentation. Based on data published in the literature, Zhang et al. [12] made the observation that for most carbon and alloy steels with different thermal treatments, S_T is approximately $H_V/3$, which if plotted against one another respectively would produce a slope of 0.333. This slope is similar to the one found (0.312) by Arptin and Murphy [29] for metals with $E \approx 70$ GPa, such as aluminum.

Although estimating σ_Y and S_T directly from the correlation with hardness has been viewed as a practical method [26], most research efforts have focused on the two other methods. Moreover, the discrepancy between the theoretical values based on contact mechanics and the best-fit equations to experimental data has not been addressed in detail. This study is intended to fill this gap in the literature.

3. Experimental details

A rectilinear open die forging of 7010 alloy was manufactured by HDA Forgings Ltd. (now Mettis Aerospace, Ltd.), Redditch, UK on a 20 MN draw down hydraulic press. The forging temperature was in the range 390–400 °C. This forging was similar to a production item that receives extensive machining and ultimately forms part of the wing spar assembly in the Airbus A330/A340. The rectilinear forging had dimensions of 3045 mm (L, longitudinal) × 158 mm (LT, long transverse) × 125 mm (ST, short transverse). The chemical composition of the forging is given in Table 1. Tensile specimens with 6 mm diameter and 30 mm gage length were excised from the forging. The long axis of the specimens corresponded to the L direction of the forging. Specimens were solution treated in an air-recirculating furnace at 475 °C for 50 min. Solution treatment was followed by 32 different quench paths, both interrupted and delayed quench [30] to obtain a wide interval of yield strength and hardness values. Quenches were interrupted at seven temperatures for various durations by inserting specimens into a salt bath filled with a eutectic mixture of KNO_3 and $NaNO_2$. In delayed quench experiments, specimens were initially cooled in still air until the target temperatures (400, 350, 300, 250, and 200 °C) were reached, and subsequently quenched in cold water. For each interrupted and delayed quench path, two tensile specimens were used. In addition, two specimens were quenched directly in cold water from the solution treatment temperature. Specimens were then naturally aged at room temperature for 5 days. Subsequently they were artificially aged at two stages, 120 °C for 10 h followed by 173 °C for 8 h, to attain the overaged condition.

Tensile and Vickers hardness tests were conducted on each specimen. A Zwick tensile tester was used at an engineering strain rate of 0.001/s and σ_Y and S_T values were recorded. A total of sixty five tensile tests were conducted. Three Vickers hardness tests at 20 kg load were conducted on an Instron Wolpert 930 Tester machine. At least three indentations were made on each specimen and their average was taken as the representative hardness value.

The composition of the 7010 plate used in this investigation is also given in Table 1. The material was supplied as a rolled plate (3403 × 1320 × 157 mm), which was manufactured from cast slab. A number of cross sectional slices (5.0 mm thick) were cut from one end of the plate perpendicular to the rolling direction. Each slice was further cut into five strips of equal width, each representing a different depth through the plate thickness. Flat tensile test specimens were manufactured from the strips to the dimensional requirements of British Standard BS 4A-4. They had a gauge length of 50 mm, a minimum parallel length of 63 mm, a minimum transition radius of 25 mm, a width of 12.5 mm and a thickness of 3 mm. The tensile test specimens were solution tre-

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