Hardness - Yield Strength Relation of Al-Mg-Si Alloys

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Abstract: Assessing the mechanical properties of materials through indentation hardness test is an attractive method, rather than obtaining the properties through destructive approach like tensile testing. The present work emphasizes on the relation between hardness and yield strength of Al-Mg-Si alloys considering Tabor type equations. Al-0.5Mg-0.4Si alloy has been artificially aged at various temperatures (100 to 250 °C) for different time durations (0.083 to 1000 h) and the ageing response has been assessed by measuring the Vickers hardness and yield strength. Correlations of the existing data from the open literature have also been reviewed. Lastly, it has been explained that the deviation in obtained relation from Tabor’s equation is owing to the dislocation accumulation during indentation.

1. Introduction
Over the years, indentation hardness measurements are being used to determine several mechanical properties like yield strength, Young’s modulus, fracture toughness etc. for different bulk materials, coatings and engineering surfaces. The hardness test is carried out in a conventional way by forcing the indenter onto the surface of the specimen. The additional stress generated by the indenter should be more than the yield strength of the material to assist the plastic flow for the permanent indentation. The strength of a material during service is often the primary concern to materials engineers. The yield strength is regularly considered essential for the design and selection of materials in various applications. Alloys for high-end structural applications need these properties as material specifications and have to frequently undergo quality assurance tests to monitor their strength [1]. However, the yield strength obtained from tensile tests is expensive, time consuming and requires a large volume of material with specified shape and dimension, and is also destructive in nature. Thus, the engineers have attempted an alternate route to estimate the mechanical properties by measuring the hardness, which is simple and semi-destructive in nature. Prior to this, an empirical relationship needs to be established between the hardness and tensile properties [1,2]. Hill et al. [3] have first correlated hardness test results with deformation properties obtained by tensile testing. Subsequently, Tabor has suggested an empirical relation between the Vickers hardness and the yield strength which has recently been theoretically explained by Tiryakioğlu et al. [4] considering the strain distribution under the indentation using the concept of representative strain. According to the knowledge of the present authors, the correlation between hardness and yield strength of age-hardenable Al-alloys, especially that of Al-Mg-Si (6xxx) system has not been systematically investigated. Considering their technological importance, it is essential to establish the hardness-yield strength relationship.

This study makes an attempt to establish the relation between the Vickers hardness (HV) and the yield strength (σy) of Al-Mg-Si alloys based on experimentally generated results. The suitability of the developed relation is evaluated by using similar data from the open literature.

2. Material and Methods
The commercial Al-Mg-Si alloy was procured in the form of extruded rods with 16.5 mm in diameter. The chemical composition of this alloy (0.50 Mg, 0.43 Si, 0.18 Fe, 0.08 Mn, minor amounts of Cu,
Cr, Zn, Ti, Al in balance; all in weight %) was obtained by atomic emission spectroscopic analysis. Solution treatment of hardness and tensile (25 mm gauge length and 6.25 mm diameter) specimens were done at 525 °C for 2h followed by ice-water quenching and then artificial aged for 0.083 to 1000 h at seven different temperatures from 100 to 250 °C at 25 °C intervals. The Vickers hardness measurements were made by using pyramidal diamond indent tester (VMHT: Leica, Germany) under an applied load of 2 kgf and for indentation duration of 15 s. An average of fifteen readings with the associated standard errors was used for subsequent analyses. Uniaxial tensile tests were carried out using a close-loop servo-hydraulic universal testing machine (Model: 8801, Instron, USA). These tests were performed at a nominal strain rate of 1 x 10⁻³ s⁻¹ at room temperature (298 K). Three specimens were tested at each state of ageing and the mean values of the tensile properties are reported.

3. Background
The mean pressure under the indenter (Pₘ) also known as Mayer’s hardness is measured by considering the applied load (L) and projected area of indentations (Aₗ) which is given as:

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

Tabor [5] has suggested that for ductile metals, the mean contact pressure (Pₘ) is related with the flow stress (σₖ) of the material in simple compression test as:

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

where, C is the constraint factor. According to Hill et al. [3], the Pₘ acting on the surface of the wedge i.e., the principal compression stress which is uniform and is given as:

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

where, τ_c is the critical maximum shear stress and \(\theta\) is half angle of the tip of indenter. Tabor has relied on the Von-Mises yield criterion (2τ_c = 1.15σₖ) and suggested that for the Vickers indentation the flat punch, \(\theta = \pi/2\) would be a fair approximation. By substituting these in Eq. (3) one gets:

$$P_m = 2.956 \times \sigma_k \tag{4}$$

From Eqs. (2) and (4), the constraint factor C is found to be 2.956 for fully work hardened materials (σ_k = σ_y). Tabor [2] has quantified that the C value can be approximately 3 since it is found to be 2.9, 2.8 and 2.9 for Te-Pb, annealed Cu and mild steel, respectively. Therefore, the relation between HV and P_m can be expressed as:

$$HV = 0.927 P_m \tag{5}$$

Combining Eqs. (4) and (5) one gets:

$$\sigma_y = HV / 0.927C \tag{6}$$

The relation between HV and σ_y is likely to have a slope of 0.365 and should pass through the origin when one considers C = 2.956. Fully work-hardened materials validate this relation satisfactorily [2]. However, the HV and σ_y relation for strain-hardening materials like steels, Mg, Al and Cu alloys is better expressed as [1]:

$$\sigma_y = \beta_0 + \beta_1HV \tag{7}$$

In most of the cases, \(\beta_0\) is negative which is due to the characteristic strain during the Vickers indentation as suggested by earlier researchers [4]. It means that the true strain corresponding to the yield strength values is greater than the characteristic strain. This investigation uses Eq. 7 as suggested by earlier studies for age-hardenable alloys [1, 4].

4. Results and Discussion
4.1 Ageing response of the selected Al-0.5Mg-0.4Si alloy
Age hardening response has been studied by measuring Vickers hardness (HV) and yield strength (σ_y) at different temperatures (Tₐ) from 100 to 250 °C for time durations (tₐ) ranging from 0.083 to 1000 h as shown in Fig. 1. The variations in HV (Fig. 1(a)) and σ_y (Fig. 1(b)) indicate the typical ageing characteristics of Al-alloys. With increasing Tₐ, the peak HV and peak σ_y values decrease, and the time to achieve the peak values are also reduced. At lower Tₐ and for lesser tₐ, the rate of increase in
HV and σ_y is found to be very low. This state of ageing is identified as highly under-aged. On further ageing, there seems to be a sharp rise in the HV and σ_y due to the formation and dissolution of the GP Zones and β'' precipitates up to the peak ageing condition. Thereafter, the HV and σ_y values decrease due to the coarsening of precipitates allowing the dislocations to bow off during the deformation. It is observed that at T_A=250 °C for t_A > 8 h, the HV and σ_y values are less than the as-quenched values. This state of ageing indicates the highly over-aged condition. The obtained results are in good agreement with the reports for the similar alloy by Jiang et al. [6] and Munitz et al. [7]. However, these results deviate from the data reported by Siddiqui et al. [8] presumably due to the selection of different solutionizing condition.

4.2 Development of correlation between hardness and yield strength

The empirical relationships developed on a theoretical basis might assist as a valuable guide. However, the correlations which are developed based on experimental results are essential for the practical application of hardness indentation as a potential alternative to the yield strength values [9]. Experimental data sets of the selected Al-0.5Mg-0.4Si alloy in addition to the data collected from twelve different studies consisting of four different Al-alloys have been studied separately for the correlations of their hardness and yield strength. Linear regression analyses have been carried out on

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Figure 1. Variations of measured (a) hardness and (b) yield strength with ageing time for artificially aged Al-Mg-Si alloy specimens at different temperatures. Property of as-quenched (AQ) state is shown as horizontal line.

Figure 2. Correlation between the hardness and yield strength of Al-Mg-Si alloy from the present experimental data following (a) Eq. 7 and (b) the same with a constant slope of 0.383.
experimental data (Fig. 2(a)) and the best fit line is achieved with correlation coefficient \( R^2 \) of 0.937. The estimated coefficient values of \( \beta_0 \) and \( \beta_1 \) (as in Eq. 7) and the 95% confidence interval of these values are presented in Table 1. Shaw and DeSalvo [10] have suggested that constraint factor \( C \) is 2.82 for a blunt axisymmetric indenter. Shield [11] has also proposed almost similar \( C \) value of 2.84 for a circular flat-ended punch indenter against a plane surface. However, for the Vickers indentation, Larsson [12] has reported that the \( C \) value to be 2.8 by numerical analysis using finite element method. Now, substituting the value of \( C \approx 2.82 \), the slope \( \beta_1 \) is found to be 0.383 and the one suggested by Tabor is 0.365. Both the values of \( \beta_1 \) are found to be within the 95% confidence interval; however, the intercept \( \beta_0 = 0 \) suggested by Tabor is not within the 95% confidence interval which contradicts to the general assumption of \( P_m = 3\sigma_y \) for the selected Al-alloy. As the line of slope, 0.383, is almost similar to the regression line in Fig. 2(a), it is suggested that the regression is carried out once again with a constant slope of 0.383 as shown in Fig. 2(b) which can be expressed as:

\[
\sigma_y = 0.383HV - 101.5
\]  

(8)

Abdulwahab et al. [13] have reported that the hardness and yield strength values of Al-0.3Mg-7Si (A356) alloy whose relation is found to be sharply linear as demonstrated in Fig. 3(a) by a simple linear regression. Earlier, Rometsch and Schaffer [14] has attempted the direct correlations between Brinell hardness and yield strength of both A356 and A357 cast alloys and found that there is a significant amount of scatter. However, these data exhibit good linear relationships when yield strength values are correlated with Vickers hardness as shown in Figs. 3(a) and (b). The data collected

Figure 3. Correlations between the hardness and yield strength data collected from existing literature for (a) A356 (b) A357 (c) AA6061 and (d) AA6063 Al-alloys.
from several sources [15-24] of Al-0.9Mg-0.8Si-0.3Cu and Al-0.47Mg-0.45Si alloys also depict a linear relation (Figs. 3(c) and (d)). The slope ($\beta_1$), intercept ($\beta_0$) with correlation coefficient ($R^2$) and their corresponding confidence interval values are summarized in Table 1.

Table 1. Summary of regression analyses results between hardness and yield strength as per Eq. 7 for different Al-Mg-Si alloys.

| Material                  | $\beta_1$ | 95%LCL | 95%UCL | $\beta_0$ | 95%LCL | 95%UCL | $R^2$ |
|---------------------------|-----------|--------|--------|-----------|--------|--------|-------|
| Al-0.5Mg-4Si [Present study] | 0.383     | -      | -101.5 | -105.12   | -97.9  | 0.927  |
| Al-0.3Mg-7Si [13]         | 0.309     | 0.292  | 0.313  | -79.7     | -91.28 | -68.01 | 0.991 |
| Al-0.4Mg-7Si [14]         | 0.266     | 0.244  | 0.288  | -34.6     | -57.43 | -11.72 | 0.902 |
| Al-0.6Mg-7Si [14]         | 0.269     | 0.254  | 0.285  | -26.9     | -40.57 | -13.31 | 0.930 |
| Al-0.9Mg-0.8Si-0.3Cu [15-18] | 0.277    | 0.216  | 0.337  | -13.3     | -73.01 | -46.42 | 0.884 |
| Al-0.47Mg-0.45Si [19-24]  | 0.321     | 0.273  | 0.367  | -66       | -97.08 | -35.16 | 0.767 |

4.3 Assessment of the model

Finally, to validate the modified Tabor’s equation established in this investigation (i.e., Eq. 8), the yield strength values (MPa) of the experimental data and the ones obtained from the open literature have been estimated by using the hardness values in MPa. Fig. 4 displays the plot of measured and the predicted yield strength values where most of the data are lying well within the 15% and 30% error bands. A few data points which are outside of the deviation bands are the alloys that are tested in differently solutionized and quenched conditions or highly over-aged state or involve data of differently homogenized samples. The deviations in the data are perhaps due to the higher rate of strain hardening occurring during the tests.

Tabor’s equation (Eq. 6) can be replaced as shown below for fully work hardened materials ($\sigma_f = \sigma_{ys}$):

$$\sigma_f = \frac{HV}{0.927C}$$

(9)

Whereas, for materials which are strain hardened, the Vickers hardness indenter has some representative strain [4] under it for which the $\sigma_f$ is greater than the $\sigma_{ys}$ and can be expressed as:

$$\sigma_f = \sigma_{ys} + \Delta \sigma$$

(10)

$\Delta \sigma$ is the increase in strain during the Vickers indentation and reaches a maximum of 8% representative strain.

Figure 4. Yield strength values (Eq. 8) of different Al-Mg-Si alloys from the present study as well as from the literature; these are combined to compare their corresponding yield strength values.
Now, substituting Eq. 9 in Eq. 10 one gets:

\[ \sigma_{ys} = \frac{HV}{0.927C} - \Delta \sigma \]  \hspace{1cm} (11)

The above equation is the modified version of Tabor’s equation (Eq. 6) with addition of the negative intercept. Tiryakioğlu et al. [4] have carried out this analysis and suggested that Eq. 11 would explain the reason behind the intercept being negative for all the strain hardened materials. The present study on correlation between hardness and yield strength demonstrates a slope of 0.383 and the negative intercept of 101.5; these values indicate the strain on the flow stress during indentation is less than the representative strain.

5. Conclusions

The correlation between hardness and yield strength of the selected Al-0.5Mg-0.4Si alloy has been established using the experimentally generated values considering the Tabor’s equations. The artificial ageing response of the alloy has been studied for seven different temperatures from 100 to 250 °C for the durations of 0.083 to 1440 h. Simple linear regression analysis has been carried out between hardness and yield strength data of various age hardenable alloys collected from the existing literature and the corresponding slope and intercept values have been noted. Finally, the adequacy of the developed relationship has been validated considering the experimental hardness and yield strength values as well as using data from the literature. The deviations from the obtained correlation for some reported data have been ascribed to increase in strain hardening due to accumulation of dislocations during indentation.

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