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The determination of tensile properties from hardness measurements for Al-Zn-Mg alloys

S. C. CHANG*, M. T. JAHN†, C. M. WAN*, J. Y. M. LEE*, T. K. HSU‡
* *Department of Materials Science and Engineering, National Tsing Hua University, Taiwan, ROC*
† *Department of Physics, National Tsing Hua University, Taiwan, ROC*
‡ *Metal Industry Research Laboratory, Industrial Technology Research Institute, Taiwan, ROC*

The correlations between tensile properties (yield strength, ultimate tensile strength and uniform strain) and indentation hardness are studied for two types of Al–Zn–Mg alloys. The reasons why Tabor's equations do not well fit the experimental data when the strain-hardening coefficient is larger than 0.3 are discussed. New equations for the determination of tensile properties from hardness measurements are theoretically derived and found to be in excellent agreement with the experimental data for Al–Zn–Mg alloys. The equations are $T_u = (H_v/c_2)\,[4.6\,(m-2)]^{m-2}$ and $\sigma_y = (H_v/c_2)^{1/(3-m)}\,(12.5/E)^{(m-2)/(3-m)} + 25\,(m-2)$, where T_u and σ_y are ultimate tensile strength and yield strength, H_v is Vicker's hardness number, m is Meyer's hardness coefficient, E is Young's modulus, c_2 is a constant about 2.9 in magnitude. In these equations T_u, σ_y, H_v and E are all expressed in kg mm^{-2}.

1. Introduction

Non-destructive testing methods for estimating mechanical properties of metals are always attractive and in demand especially for those structural parts which are not suitable to conventional tension or compression tests. The engineering applications of the weldable, strong, easily machined and corrosion-resistant Al–Zn–Mg alloys are growing fast. Although intensive works [1–5] has been performed to relate hardness measurements to yield and tensile strength of certain metals and alloys, there appear to have been no attempts to obtain a good relationship specifically for Al–Zn–Mg alloys. Tabor [1–4] has undertaken much experimental work and has given a detail theoretical analysis of hardness in relation to the stress–strain curve. A number of investigators [2, 5, 6] hitherto adopted his calculations as a basis for comparison with their results. In comparing the experimental data for various alloys [5–7] with Tabor's calculations are inappropriate. The reasons why Tabor's equations do not fit the experimental data well when the strain-hardening coefficient is greater than 0.3 will be discussed. New equations for the determination of the ultimate tensile strength from hardness measurements will be derived theoretically and compared with the experimental data of Al–Zn–Mg alloys.

While many efforts have been made to investigate the relationship between hardness and the stress–strain curve, there seems to have no successful work in evaluating the 0.2% offset yield strength of metals from hardness measurements. Atkins and Tabor [4] derived a compressive stress–strain curve for steel and copper from hardness measurement. Nichols [8] calculated tensile stress–strain curve for some carbon and low alloy steels. However, their results cannot be extended to the region of less than 4% strain, and are not good enough for describing the stress–strain curves of Al–Zn–Mg alloys. We derive here a general expression which correlates the 0.2% offset yield strength and ultimate tensile strength with hardness test data. Our experimental data for two types of Al–Zn–Mg alloys under various heat-treatment conditions agree very well with the derived general expression.

2. Derivation of tensile strength

A relationship between the ultimate tensile strength of a metal and its hardness number as well as its Meyer's hardness coefficient was first deduced by Tabor [1]. Assuming the validity of Holloman's true stress/true strain curve [9] $\sigma = K\epsilon^n$, Tabor first derived the Meyer's Law $P = K'd^m$ theoretically and show that the work-hardening coefficient n of a metal is roughly equal to $m-2$, where m is the Meyer's hardness coefficient. Replacing true stress σ by $T(1+\epsilon)$, where T is the nominal stress, Tabor obtained

$$\epsilon_u = \frac{n}{1-n} \tag{1}$$

and

$$T_u = K(1-n)\left(\frac{n}{1-n}\right)^n \tag{2}$$

where ϵ_u and T_u are uniform strain and ultimate tensile strength respectively. Suppose the Brinell hardness test produces an indentation of chordal diameter $d = D/2$, where D is the diameter of the spherical indenter, the Brinell hardness number is given by

$$H_B = C_1 K(0.1)^n \tag{3}$$

where C_1 is a constant roughly equal to 2.6. Suppose the Vicker's pyramid produces an indentational strain of 8%, the Vicker's hardness number can be expressed by

$$H_v = C_2 K(0.08)^n \tag{4}$$

where C_2 is a constant roughly equal to 2.9. Substituting Equations 3 and 4 into Equation 2, Tabor obtained the relationships of ultimate tensile strength for a metal with its hardness number and work-hardening index, i.e.

$$\frac{T_u}{H_B} = \frac{(1-n)}{2.6}\left(\frac{10n}{1-n}\right)^n \tag{5}$$

and

$$\frac{T_u}{H_v} = \frac{(1-n)}{2.6}\left(\frac{12.5n}{1-n}\right)^n. \tag{6}$$

Tabor's equations fit experimental results quite well at $n \leqslant 0.3$. However, at $n \geqslant 0.3$ the deviation from experimental data is no longer tolerable. Since in his derivations, Tabor took nominal strain as true strain, we feel that a better approach to the correlation between hardness numbers and ultimate tensile strength can be made if we treat true strain properly.

From the constancy-of-volume relationship, it has been shown that the uniform strain ϵ_u is equal to n [10] provided that the Hollomon equation, $\sigma = K\epsilon^n$, is valid. Since the relationships between true stress/strain (σ/ϵ) and engineering stress/strain (T/e) are $\epsilon = \ln(1+e)$ and $\sigma = T(1+e)$, we have

$$T'_u = \frac{\sigma_u}{1+e_u} = \frac{K\epsilon_u^n}{\exp(\epsilon_u)} = \frac{Kn^n}{\exp(n)} \tag{7}$$

where T'_u denotes the ultimate tensile strength derived by our approach. σ_u and e_u are true stress and nominal strain, respectively, at $\epsilon = \epsilon_u$. Substituting Equations 3 and 4 into Equation 7, we now obtain

$$\frac{T'_u}{H_B} = \frac{(10n)^n}{C_1 \exp(n)} = \frac{1}{2.6}(3.68n)^n \tag{8}$$

and

$$\frac{T'_u}{H_v} = \frac{(12.5n)^n}{C_2 \exp(n)} = \frac{1}{2.9}(4.6n)^n. \tag{9}$$

In Fig. 1, we plot the theoretical curves given by Equations 5, 6, 8 and 9 and the experimental data given by O'Neill [7]. It is evident that our approach fits the experimental data much better than Tabor's results especially at $n \geqslant 0.3$. It will be shown later that Equations 8 and 9 agree very well with our experimental data on Al–Zn–Mg alloys.

3. Derivation of yield strength

Morrison [11] suggested that if the true strain in Hollomon equation was taken as the sum of plastic and elastic strains, a value of yield stress can be obtained at the intercept of the stress/strain curve $\sigma = K\epsilon^n$ and the elastic modulus line $\sigma = E\epsilon$. E is the Young's modulus. The intercept is at a stress

$$\sigma_0 = \left(\frac{K}{E^n}\right)^{1/(1-n)} \tag{10}$$

Since the exact value of elastic limit of a metal depends critically on the measuring device used to record extension, it is more applicable in engineering design to use the 0.2% offset yield strength than the true elastic limit. In order to calculate the 0.2% offset yield strength, we should find the common root σ_y of Hollamon equation $\sigma = K\epsilon^n$

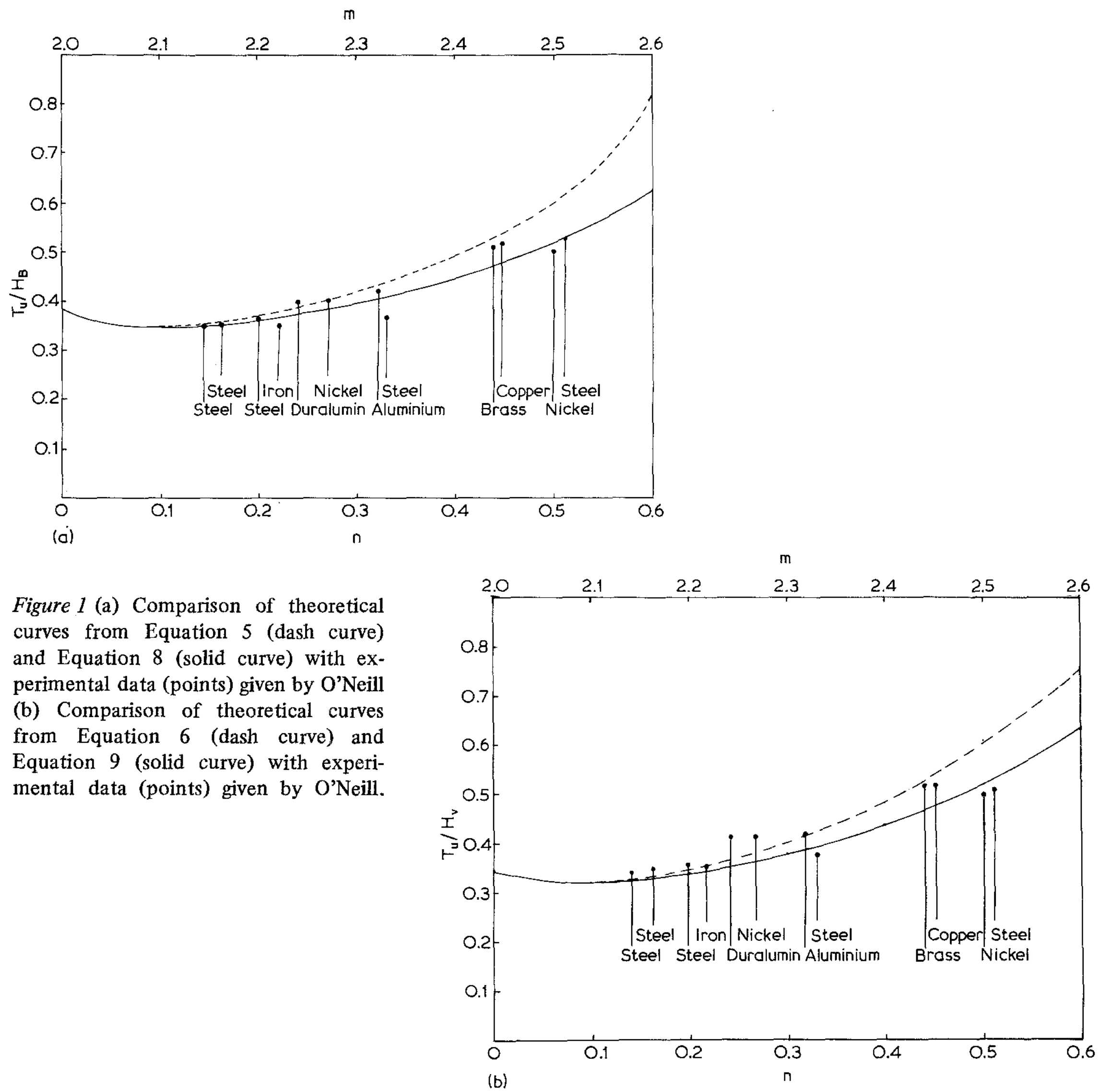

Figure 1 (a) Comparison of theoretical curves from Equation 5 (dash curve) and Equation 8 (solid curve) with experimental data (points) given by O'Neill (b) Comparison of theoretical curves from Equation 6 (dash curve) and Equation 9 (solid curve) with experimental data (points) given by O'Neill.

and equation $\sigma = E(\epsilon - 0.002)$. It means one should solve the equation

$$K\epsilon^n - E\epsilon + 0.002E = 0. \qquad (11)$$

In general, as the value of n ranges from 0 to 0.5, it is not easy to solve Equation 11. However, a schematic method can be used to find the first order approximation of the common root σ_y. Keeping E constant, and plotting a straight line $\sigma = E(\epsilon - 0.002)$, and then plotting the curves $\sigma = K\epsilon^n$ for varying values of n on the same co-ordinates with σ as ordinate and ϵ as abscissa, we find that the intercepts of the straight line and curves are approximately a linear function of n, i.e.

$$\sigma_y \simeq \sigma_0 + cn = \left(\frac{K}{E^n}\right)^{1/(1-n)} + cn, \qquad (12)$$

where c is a constant depending on the value of Young's modulus E. The stress/strain curves in our experiments indicate that E is very close to 7000 kg mm^{-2} for all of our specimens. This is a typical value of Young's modulus for aluminium alloys. Once E is fixed, the constant c is then determined as $c \simeq 25\,\text{kg mm}^{-2}$. It will be shown later that Equation 12 explains our experimental data on 0.2% offset yield strength very well for Al–Zn–Mg alloys.

TABLE I Chemical composition of testing alloys

Material	Zn (%)	Mg (%)	Mn (%)	Fe (%)	Si (%)	Cu (%)	Ti (%)	Zr (%)
Type A	4.15	1.50	0.35	0.30	0.14	0.10	0.05	0.00
Type B	4.20	1.55	0.30	0.28	0.14	0.07	0.04	0.13

4. Experimental details

Two types of Al–Zn–Mg alloys were used in this investigation. The compositions of both alloys are shown in Table I. The specimens were solution heat-treated at 465° C for 2 h and quenched in water at room temperature followed by a single-step or two-step ageing at various temperatures and times such that different values of hardness and strength resulted. Hardness tests were carried out with a Wolpert-hardness tester. A load of 30 or 50 kg was used in the determination of Vicker's hardness, H_V. All specimens were tested on the same tester with a 2.5 mm diameter ball indentor for the determination of Meyer's hardness coefficient, m. The tensile tests were carried out on an Instron Universal Testing Machine. A strain gauge extensometer was employed to insure an accurate load–elongation curve.

For each specimen, the 0.2% offset yield strength, ultimate tensile strength and uniform strain were measured from load–elongation curve. The experimental data used for the calculation of parameters K and n in the true stress–strain equation ($\sigma = K\epsilon^n$) were obtained from the strain ranging from 0.02 to 0.09. It was observed that the stress–strain curves showed stepped phenomenon for a few specimens. In these cases, measurements were taken from the envelope of the stepped curves. Meyer's law, $P = K'd^m$, was employed in calculating Meyer's hardness coefficient, m, from the observed load, P, and chordal diameter, d. In this investigation, all the parameters (K, n, m) were calculated using an IBM 1130 computer with least-square fit.

5. Experimental results and analysis

The details of the ageing process for each specimen, its resultant Vicker's hardness H_V, the proportional constant K of the Hollomon equation, the work-hardening index n, Meyer's hardness coefficient m, and the uniform strain for A and B type Al–Zn–Mg alloys, are listed in Tables II and III respectively. It is easily seen that the experimental data of n and m agree very well with the equation

TABLE II The details of ageing processes for each specimen and its resultant Vicker's hardness, H_V, strength coefficient, K, work-hardening index, n, Meyer's hardness coefficient m, and uniform strain, ϵ_u, for type A Al–Zn–Mg alloys

Specimen	Ageing process	H_V (kg mm^{-2})	K (kg mm^{-2})	n	$m-2$	$\frac{n}{1-n}$	ϵ_u
Al	125° C (2 h)	79.98	55.69	0.275	0.267	0.38	0.19
A2	125° C (4 h)	90.96	54.77	0.226	0.181	0.293	0.17
A3	125° C (4 h)	87.12	53.97	0.223	0.214	0.288	0.21
A4	125° C (8 h)	83.82	53.92	0.215	0.221	0.274	0.15
A5	125° C (8 h)	83.94	53.86	0.204	0.213	0.276	0.14
A6	125° C (16 h)	114.50	53.60	0.150	0.152	0.176	0.14
A7	125° C (24 h)	128.60	53.70	0.108	0.109	0.109	0.11
A8	125° C (48 h)	134.30	54.62	0.087	0.095	0.095	0.09
A9	125° C (48 h)	136.00	53.94	0.087	0.080	0.095	0.09
A10	125° C (96 h)	142.00	55.38	0.080	0.086	0.87	0.08
A11	125° C (96 h)	140.80	55.05	0.076	0.075	0.0825	0.08
A12	80° C (24 h) + 120° C (96 h)	134.60	56.96	0.078	0.063	0.0846	0.10
A13	80° C (24 h) + 150° C (12 h)	124.30	55.08	0.088	0.103	0.0965	0.09
A14	150° C (6 h)	80.30	50.36	0.196	0.193	0.244	0.13
A15	150° C (12 h)	92.40	50.60	0.153	0.146	0.181	0.09
A16	150° C (24 h)	104.80	51.68	0.139	0.151	0.161	0.09
A17	25° C (70 days)	107.70	67.91	0.237	0.224	0.311	0.19
A18	25° C (70 dats)	104.50	68.52	0.243	0.259	0.321	0.20
A19	25° C (180 days)	101.90	64.58	0.220	0.230	0.282	0.18

TABLE III The details of ageing processes for type B specimens and their resultant Vicker's hardness, H_v, strength coefficient, K, work-hardening index, n, Meyer's hardness coefficient, m, and uniform strain, ϵ_u.

Specimen	Ageing process	H_v (kg mm^{-2})	K (kg mm^{-2})	n	$m-2$	$\frac{n}{1-n}$	ϵ_u
B1	125 (1 h)	67.50	67.06	0.298	0.345	0.425	0.13
B2	125 (1 h)	68.62	68.43	0.310	0.275	0.449	0.13
B3	125 (2 h)	74.16	69.56	0.309	0.291	0.447	0.11
B4	125 (2 h)	75.90	67.43	0.286	0.299	0.401	0.12
B5	125 (4 h)	100.20	68.89	0.208	0.210	0.263	0.14
B6	125 (4 h)	103.20	68.91	0.206	0.204	0.260	0.15
B7	125 (8 h)	96.00	65.98	0.209	0.229	0.263	0.14
B8	125 (8 h)	100.80	65.79	0.202	0.185	0.254	0.12
B9	125 (16 h)	127.50	64.50	0.132	0.141	0.152	0.12
B10	125 (16 h)	124.20	64.82	0.124	0.112	0.142	0.12
B11	125 (24 h)	134.30	65.80	0.101	0.097	0.112	0.10
B12	125 (24 h)	134.70	64.84	0.104	0.101	0.116	0.10
B13	125 (48 h)	142.40	66.57	0.095	0.087	0.105	0.09
B14	125 (48 h)	141.30	66.72	0.096	0.088	0.106	0.09
B15	125 (96 h)	135.20	62.84	0.089	0.062	0.098	0.09
B16	80 (48 h)	112.20	80.50	0.198	0.189	0.247	0.15
B17	80 (96 h)	121.50	77.82	0.169	0.180	0.204	0.15
B18	80 (144 h)	125.40	78.38	0.157	0.161	0.186	0.15
B19	25 (70 days)	112.60	84.25	0.229	0.206	0.296	0.15
B20	25 (70 days)	112.50	84.91	0.222	0.206	0.286	0.13
B21	25 (180 days)	112.50	81.73	0.199	0.188	0.248	0.13

$n = m-2$ derived by Tabor. However, our experimental data of uniform strain ϵ_u show large deviation from Tabor's expression of uniform strain ($\epsilon_u = n/(1-n)$). Instead, the experimental data fit the equation $\epsilon_u = n$ quite well, if n is small. For large n the observed uniform strains are smaller than that predicted by $\epsilon_u = n$. This phenomenon has been previously reported by Ono [12]. He stated that "It is expected, however, that the stress concentration at macroscopic and microscopic flaws produces premature necking". Therefore, if the flaws can be removed, the observed uniform strain would be closer to the value predicated by $\epsilon_u = n$. Although the deviation of observed uniform strain from the value of n is not small at larger n, the effect of this deviation on the calculated value of tensile strength is negligible. This can be seen by comparing $T'_u = K\epsilon_u^n/(\exp \epsilon_u)$ and $T'_u = Kn^n/(\exp n)$. The ratio of these two equations is $R = (\epsilon_u/n)^n \exp(n-\epsilon_u)$. Since both n and ϵ_u are small values with same order of magnitude, R always has a value of about 1. For instance, at $n = 0.22$ and $\epsilon_u = 0.15$, $R = 0.986$. This means that the deviation of the calculated T'_u is only 1.4% if ϵ_u is substituted by n, even though the difference between n and ϵ_u is quite large. Thus we can rearrange Equations 9 and 12 and $\epsilon_u = n$ and obtain

$$T'_u = \frac{H_v}{C_2}\,[4.6(m-2)]^{m-2} \qquad (13)$$

$$\sigma_y = \left(\frac{H_v}{C_2}\right)^{1/(3-m)} \left(\frac{12.5}{E}\right)^{(m-2)/(3-m)} + 25\,(m-2) \qquad (14)$$

and

$$\epsilon_u = m-2 \qquad (15)$$

since

$$K = \left(\frac{H_v}{C_2}\right)\frac{1}{(0.08)^n}$$

as shown in Equation 4.

Equations 13 to 15 give the relationships between tensile properties (ultimate tensile strength, yield strength, and uniform strain) and the numbers of hardness measurements (Vicker's hardness and Meyer's index). Thus, non-destructive tests can describe the tensile properties of a metal quite well. From Tables II and III it is clear that the strength coefficient, K, of the Hollomon equation is a function of ageing temperature. However, K is independent of ageing time in the present work. for example, for type A specimens aged at 125° C, in spite of the fact that the ageing time ranges from 4 to 96 h, K is always approximately equal to 54.4 kg mm^{-2}. The general trend is that K decreases as ageing temperature is increased. It

TABLE IV Comparison of yield and ultimate tensile strengths calculated from Equations 13 and 14 with experimental observed data for type A Al–Zn–Mg alloys

Specimen	Observed yield strength σ_{y0} (kg mm^{-2})	Calculated yield strength σ_y (kg mm^{-2})	$\frac{\sigma_y - \sigma_{y0}}{\sigma_{y0}}$ (%)	Observed tensile strength T_u (kg mm^{-2})	Calculated tensile strength T'_u (kg mm^{-2})	$\frac{T'_u - T_u}{T_u}$ (%)
A1	15.01	15.85	5.6	28.98	29.17	0.6
A2	18.56	21.06	13.5	31.07	30.36	−2.2
A3	19.10	18.85	− 1.2	31.52	29.97	−4.9
A4	19.98	17.95	−10.1	30.69	29.03	−5.3
A5	20.87	18.27	−12.4	30.98	28.84	−6.8
A6	26.51	28.27	6.6	34.76	37.41	7.6
A7	32.38	35.16	8.5	38.46	41.14	6.9
A8	36.37	37.94	4.3	40.88	42.81	4.7
A9	36.24	39.71	9.5	40.16	43.29	7.7
A10	38.43	40.99	6.6	42.12	45.21	7.3
A11	38.85	41.60	7.0	42.09	44.82	6.4
A12	40.30	40.74	1.1	43.48	42.91	−1.2
A13	37.05	34.40	− 7.1	40.88	39.69	−2.8
A14	20.17	18.27	− 9.3	29.06	27.08	−6.7
A15	25.14	23.11	− 8.0	32.33	30.08	−6.9
A16	27.17	25.91	− 4.6	33.51	34.22	2.1
A17	23.17	22.51	− 2.8	38.77	37.42	−3.4
A18	22.55	20.24	−10.2	38.77	37.75	−2.6
A19	23.50	21.07	−10.3	38.29	35.63	−6.9

has been suggested by Morrison [11] that for steels K is a linear function of carbon content and of the square root of grain size. In present work, however, the chemical compositions are fixed and the grain sizes are almost the same for all specimens of the same type. Therefore, it is suggested that K might also be a function of the volume fraction of G.P. zones. This suggestion is now under investigation.

The calculated values of yield strength and ultimate tensile strength from Equations 13 and 14 are now compared with the observed experimental data as shown in Tables IV and V. It can be seen from the tables that the agreement between

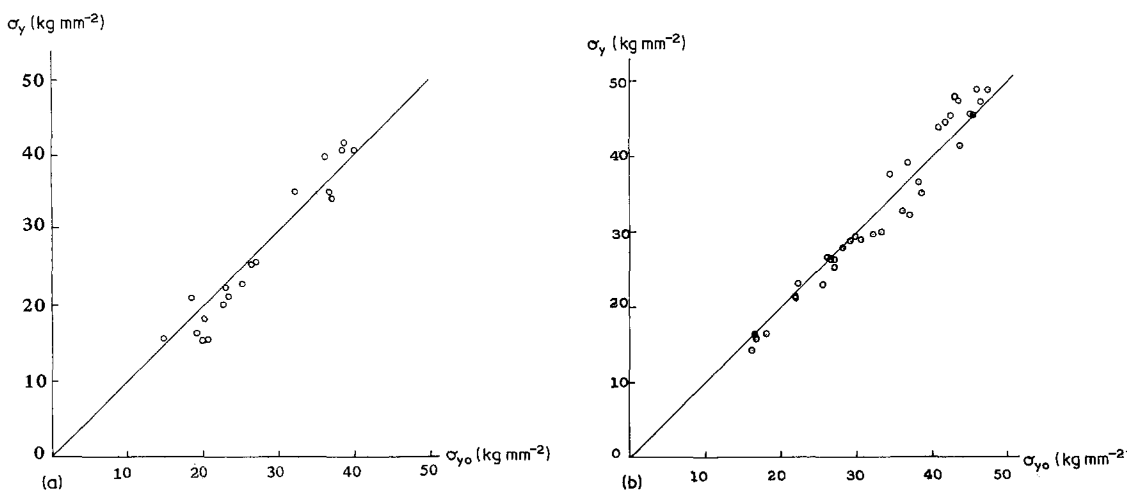

Figure 2 Comparison of experimentally observed values of yield strength (σ_{y0}) with theoretical values (σ_y) calculated from Equation 14 for type A (a) and type B (b) Al–Zn–Mg alloys.

TABLE V Comparison of yield and ultimate tensile strength: calculated from Equations 13 and 14 with experimental observed data for type B Al–Zn–Mg alloys

Specimen	Observed yield strength σ_{y_0} ($kg\,mm^{-2}$)	Calculated yield strength σ_y ($kg\,mm^{-2}$)	$\frac{\sigma_y - \sigma_{y_0}}{\sigma_{y_0}}$ (%)	Observed tensile strength T_u ($kg\,mm^{-2}$)	Calculated tensile T'_u ($kg\,mm^{-2}$)	$\frac{T'_u - T_u}{T_u}$ (%)
B1	16.24	14.07	−13.3	31.22	31.71	1.5
B2	16.61	15.59	− 6.1	31.22	29.31	− 6.0
B3	16.70	16.13	− 3.4	31.14	32.33	3.8
B4	18.06	16.20	−10.2	32.12	33.43	4.1
B5	27.02	25.07	− 7.2	39.46	39.82	0.9
B6	26.60	26.25	− 1.2	39.44	40.74	3.3
B7	25.64	22.99	−10.3	37.07	38.90	4.9
B8	26.35	26.75	1.5	37.52	39.16	4.3
B9	34.95	37.85	8.3	43.16	48.00	11.2
B10	37.07	39.31	6.0	44.67	46.13	3.2
B11	42.21	44.09	4.4	47.23	49.68	5.1
B12	40.69	43.84	7.7	46.52	49.87	7.2
B13	43.42	47.88	10.2	48.53	52.60	7.6
B15	42.11	47.78	13.4	46.28	50.02	8.0
B16	32.24	29.57	− 8.2	48.49	43.74	− 9.7
B17	36.19	32.84	− 9.2	49.84	47.01	− 5.6
B18	36.68	35.51	− 8.1	51.09	47.82	− 6.3
B19	29.30	28.50	− 2.7	48.30	44.58	− 7.6
B20	30.77	28.47	− 7.4	48.10	44.54	− 7.3
B21	33.21	29.73	−10.4	48.89	43.82	−10.3

calculated and observed values is excellent. Generally, the deviations are less than 10%. Since the data on mechanical properties obtained from tensile and hardness tests frequently exhibit considerable fluctuation, it seems that a more precise approach is of no significance. In order to obtain a clearer picture, we plot the observed values versus calculated values of yield and tensile strength in Figs. 2 and 3. The datum points fall close to the 45° centre line. Averaging the deviations of all datum points, we found that the average deviations are less than 1% for type Al–Zn–Mg alloys, and less than 4% for type B Al–Zn–Mg alloys.

6. Conclusions

The correlations between hardness and tensile

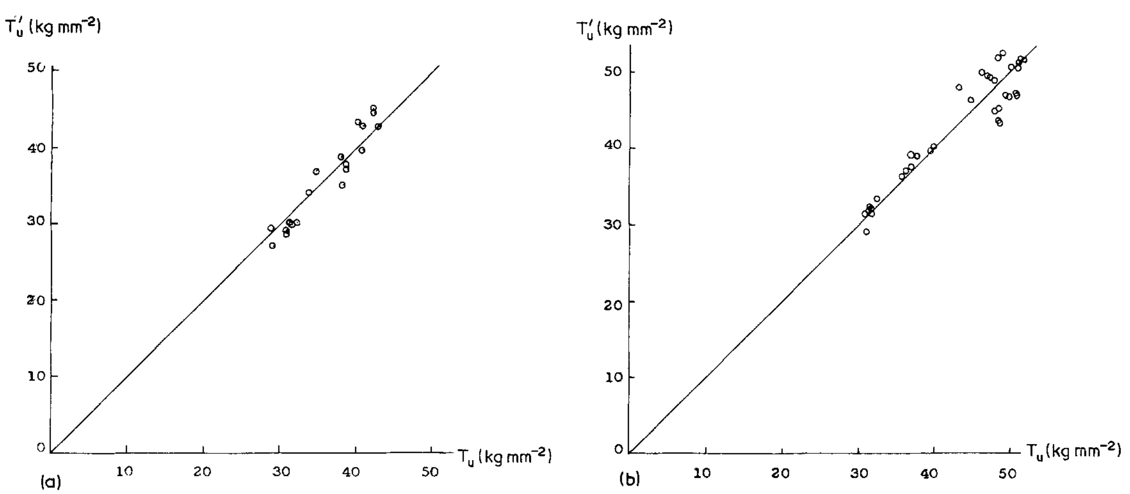

Figure 3 Comparison of experimentally observed values of tensile strength (T_u) with theoretical values (T'_u) calculated from Equation 13 for type A (a) and Type B (b) Al–Zn–Mg alloys.

properties have been studied for two types of Al–Zn–Mg alloys. The following conclusions were drawn from this study.

(1) The reason why Tabor's equation do not fit the experimental data well when the strain-hardening coefficient is larger than 0.3 is attributed to the improper use of true strain.

(2) The tensile strength of a material can be calculated from hardness measurements by the following equation, if the true stress–true strain curve is given by Holloman equation.

$$T'_u = \frac{H_v}{C_2}\frac{(12.5n)^n}{\exp n} = \frac{H_v}{C^2}[4.6 \times (m-2)]^{m-2}$$

where C_2 is a material constant about 2.9 in magnitude.

(3) Under the condition that the true strain in the Hollomon equation was taken as the sum of the plastic and elastic strains, the 0,2% offset yield strength can be obtained from the intercept of the Hollomon equation and the offset line $\sigma = E(\epsilon - 0.002)$. To a first order approximation, it might be written as

$$\sigma_y = \left(\frac{K}{E^n}\right)^{1/(1-n)} + Cn,$$

where C is a constant of about 25 in magnitude. Therefore, the 0.2% offset yield strength can be obtained from hardness measurements by the following equation:

$$\sigma_y = \left(\frac{H_v}{C_2}\right)^{1/(3-m)} \left(\frac{12.5}{E}\right)^{(m-2)/(3-m)} + 25(m-2).$$

(4) A small amount addition of Zr can influence the mechanical properties significantly for the Al–Zn–Mg alloys employed in present work.

(5) The observed uniform strain ϵ_u is in agreement with the value predicted by the equation $\epsilon_u = n = m - 2$, when n is small. For large n, however, the stress concentration at macroscopic and microscopic flaws produces premature necking, and the observed ϵ_u are generally less than the predicted values.

(6) It is found that the strength coefficient K of the Hollomon equation, in spite of different ageing times, are almost the same for all specimens aged at the same temperature. Moreover, the value of K decreases as ageing temperature is increased. It is suggested that K might be a function of the volume fraction of G.P. zone or precipitates which appear in the alloys.

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