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On the prediction of tensile properties from hardness tests

M. O. LAI, K. B. LIM
Mechanical Engineering Department, National University of Singapore, Kent Ridge, Singapore

The possibility of correlating the hardness to the tensile properties of a material has been investigated using Assab 760 steel, mild steel and API Std 5LX grade X60 pipeline steel that have been heat-treated for different times at various tempering temperatures and 6063-T1 aluminium that has been solution heat-treated. It is found that the strain hardening coefficient and the strength coefficient of all materials tested were linearly related to the hardness, irrespective of the type of hardness measurement used. Using these relationships, equations were defined to estimate the yield and ultimate tensile stresses of the materials. Good agreement between experimental results and estimated values was obtained for all materials studied. The feasibility of using the present findings in non-destructive field testing is discussed.

1. Introduction

The idea of estimating the tensile properties of a material in terms of the yield stress and ultimate tensile stress using simple test methods such as the measurement of hardness, rather than the application of tension testing, is not new. Such methods are always attractive because they could help to decrease the large amount of testing that needs to be conducted in quality control of materials as well as in the non-destructive testing of structures. However, in structural repair, for example, when a new part is to be fabricated to replace a worn or fractured component, it is uncertain whether maintaining a constant hardness value between the new and old parts would give similar mechanical properties irrespective of different grades of materials. Although much research has been carried out and rules of thumb have been devised, simple yet accurate predictions are still being sought.

Tabor [1] has shown that, for steel and a variety of other metals, the ratio of the ultimate tensile strength to the Vickers hardness (H_v) is related to the strain-hardening coefficient of the materials. The latter quantity is obtainable from the slope of a log–log plot of true stress against true strain. Since then a number of investigators [2–5] have adopted Tabor's analysis as a basis for comparison with their results. However, Tabor's analysis has the limitation that the assumption involved in the derivation of the ultimate tensile strength was approximate. Moreover, his analysis did not fit the experimental data well when the strain-hardening coefficient was greater than 0.3. As the analysis involves the use of the strain-hardening coefficient, it is therefore limited in its application to field conditions. The main objective of the present investigation is hence to seek a more accurate correlation between hardness and tensile properties and also to extend, if possible, the usefulness of such relationship to field measurement.

2. Investigation procedures

2.1. Derivation of equations

The true stress, σ_t, against true strain, e, relationship of many metals can be expressed by the simple power curve relation

$$\sigma_t = Ke^n \tag{1}$$

where n is the strain-hardening coefficient and K is the strength coefficient of the material. From this, it can be shown that [6] at necking where the ultimate tensile strength is measured

$$e_u = n \tag{2}$$

and the ultimate tensile stress, is given as

$$\sigma_u = Kn^n/\exp(n) \tag{3}$$

Owing to the presence of flaws in the material, the ultimate tensile stress does not occur at a strain equal to n but somewhat less. Ono [7] modified Equation 3 to

$$\sigma_u = Kn^n/\exp(Fn) \tag{4}$$

where F is a constant less than unity, dependent upon the material.

The yield stress of a material can be obtained at the intersection of the plastic flow curve, Equation 1, and the elastic modulus line, $\sigma_t = Ee$, where E is Young's modulus. The stress at the intersection is given as

$$\sigma_0 = (K/E^n)^{[1/(1-n)]} \tag{5}$$

It is however, more applicable in engineering design to use the 0.2% offset yield strength rather than the true elastic limit. This can be evaluated from the intersection between Equation 1 and the equation $\sigma_t = E(e - 0.2)$. In the present investigation, the equations were solved using an iterative method. It was found that two iterations were sufficient to yield a result close enough to the actual solution. The 0.2% yield

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stress σ_y, is hence given by

$$\sigma_y = K[K(\sigma_0/E + 0.2)^n/E + 0.2]^n \quad (6)$$

2.2. Experimental procedures
2.2.1. Materials
The specimen materials used in the investigation were Assab 760 steel, API Std 5LX grade X60 pipeline steel, mild steel to JIS 3123 standard, and 6063-T1 aluminium. Assab 760 is a medium carbon steel that has wide applications in industries for its good machinability and mechanical strength. The typical composition was 0.50% C, 0.3% Si, 0.6% Mn and 0.04% S (nearest equivalent, AISI 1050 or En 43). The nominal composition for the pipeline steel was: 0.07% C, 0.23% Si, 1.44% Mn, 0.01% P, 0.002% S, 0.16% Ni, 0.02% Cr and 0.04% V. For the mild steel, the typical chemical composition was: 0.1% C, 0.2% Si, 0.65% Mn, 0.019% P and 0.021% S. The aluminium employed was 6063-T1 commercial grade with chemical composition of 0.4% Si, 0.35% Fe, 0.1% Cu, 0.05% Mg, 0.65% Mn, 0.1% each for Cr, Zn and Ti.

2.2.2. Specimen preparation and testing
Rectangular tensile samples were machined from the test material to give a gauge length of 50 mm, width of 12.5 mm and thickness of 3.2 mm. The steel specimens were austenitized at 900 °C for 1 hour, oil quenched and then tempered at temperatures ranging from 450 to 650 °C at 50 °C interval and times of 15 minutes to 5 hours, to obtain a wide range of hardness and strength values. Diamond pyramid hardness of all the specimens was determined on a Vickers hardness tester using a 5 kg load. Rockwell hardness (B scale) and portable hardness were also measured on the Assab 760 and pipeline steel respectively.

The 6063-T1 aluminium specimens were solution heat-treated at 520 °C for 2 hours and quenched in water at room temperature followed by single-step or two-step ageing at various temperatures and times as shown in Table I. Vickers hardness was measured using a load of 2.5 kg. For all specimens, at least ten impressions were measured for each specimen to obtain a representative average value.

The specimens were tested to failure on a 100 kN capacity Instron testing machine at a crosshead speed of 2 mm per minute for steel and 1 mm per minute for the aluminium. The 0.2% offset yield stress and ultimate tensile stress were recorded from the load extension plot. The strain hardening coefficient, n, and the strength coefficient, K, were evaluated from the tensile data in the usual manner by plotting ln σ_t against ln e, where n and K were the slope and intercept, respectively, of the plot.

TABLE I Heat treatment of aluminium specimens

Material	Specimen	Heat Treatment
Aluminium	1	unaged
	2	125 °C (2 hrs) + 160 °C (24 hrs)
	3	125 °C (6 hrs) + 160 °C (18 hrs)
	4	125 °C (24 hrs) + 160 °C (42 hrs)
	5	150 °C (1 hr) + 160 °C (48 hrs)
	6	150 °C (4 hrs)
	7	150 °C (24 hrs) + 160 °C (42 hrs)
	8	150 °C (24 hrs) + 160 °C (50 hrs)

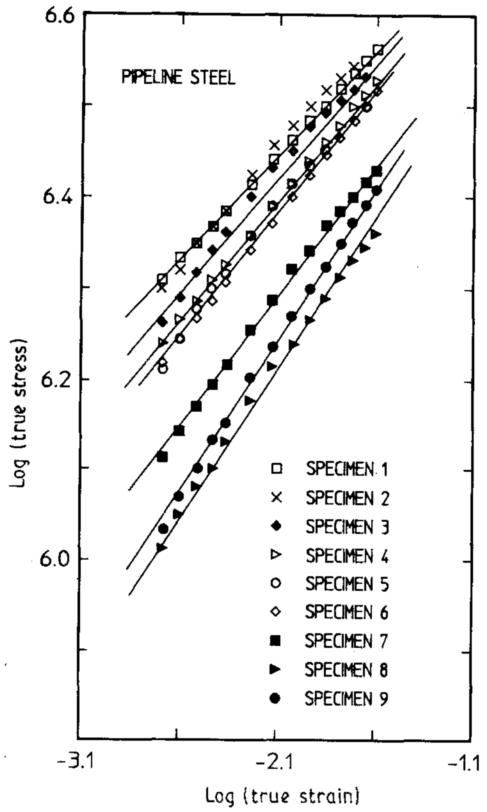


Figure 1 Typical log true stress against log true strain relationship.

3. Results and discussion
Fig. 1 shows the relationship between the logarithm of true stress and logarithm of true strain in the plastic region for pipeline steel. This relationship is also typical for the mild steel, Assab 760 steel and aluminium specimens. Except at higher strain levels, a linear plot can be observed over most of the range for all the materials tested, indicating that the behaviour is in accordance with the prediction of Equation 1. The values of n and K were found to range from 0.23 to 0.43 and 171.6 to 417.1, respectively, for the steel materials and from 0.31 to 0.38 and 40.0 to 55.4, respectively, for the aluminium. Values of n and K were observed to be different for different materials and heat treatment conditions, with Assab 760 steel having higher values than others.

The correlations between Vickers hardness and strength and strain hardening coefficients are typically shown in Figs 2 and 3, respectively, for the aluminium specimens. Similar correlations using Rockwell hardness on Assab 760 steel and portable hardness on pipeline steel are respectively shown in Figs 4 and 5. For all the materials studied, linear relationships were obtained with an average coefficient of correlation of 0.98 irrespective of the type of hardness measurement. It can be seen from the figures that n decreases with the increase in hardness, while K increases with increase in hardness. The figures also show that, for a

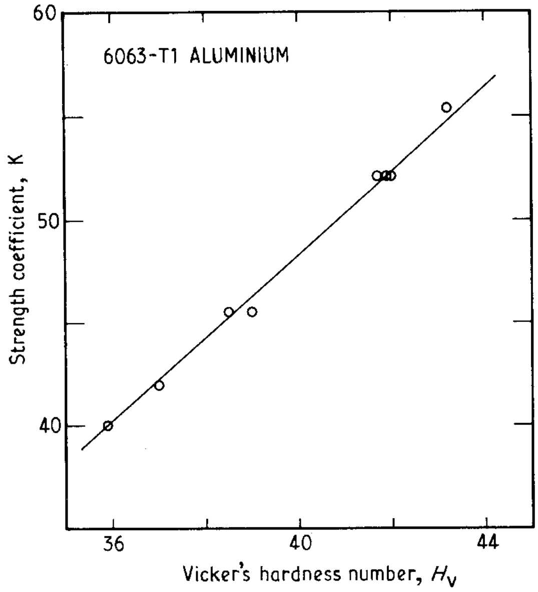


Figure 2 Typical strength coefficient against Vickers hardness relationship.

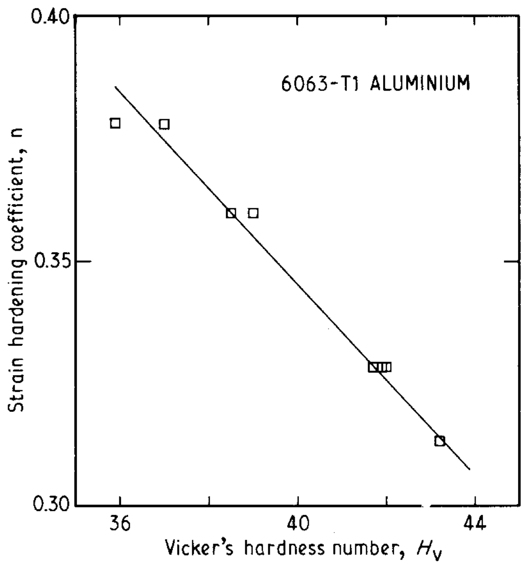


Figure 3 Typical strain hardening coefficient against Vickers hardness relationship.

given material, regardless of the heat treatment condition the material has undergone, one hardness against n or K relationship applies. The values of n and K can therefore be defined as

$$\left.\begin{aligned} K &= AH + B \\ n &= CH + D \end{aligned}\right\} \tag{7}$$

where H is the hardness value and $A, B, C,$ and D are constants for a given material.

From Equation 7, the ultimate tensile strength, σ_u, and yield strength, σ_y, may be redefined from Equations 4 and 6 as follows

$$\sigma_u = K\ [100.Fn]^n/\exp(n) \tag{8}$$

$$\sigma_y = K[K(\sigma_0/E + 0.2)^n/E + 0.2]^n \tag{9}$$

where $K = AH + B$, and $n = CH + D$. The values A, B, C, D and F are shown in Table II for the materials investigated.

Equations 8 and 9 were used to predict the ultimate tensile and yield stresses of the Assab 760, mild and pipeline steels and aluminium used in the study. The results are shown in Table III. It can be discerned that the prediction is accurate for all the materials tested. The average deviation of the calculated values from the observed values for ultimate tensile stresses is 0.85%, 1.42%, 1.65% and 2.31% for aluminium, pipeline steel, mild steel and Assab 760 steel, respectively. The deviations are larger in the prediction of the 0.2% yield stresses: 2.34%, 4.84%, 2.65% and 8.80%, respectively. The larger discrepancy may be due to the slight inaccuracy in determining graphically the proof stress point on the load extension chart.

To further verify that Equations 8 and 9 give good predictions of the ultimate tensile and yield stresses of a material, the experimental data of Chang *et al.* [5],

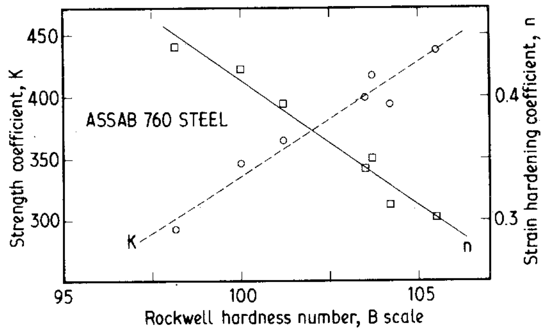


Figure 4 Correlation between Rockwell hardness and strength and strain hardening coefficients for Assab 760 steel.

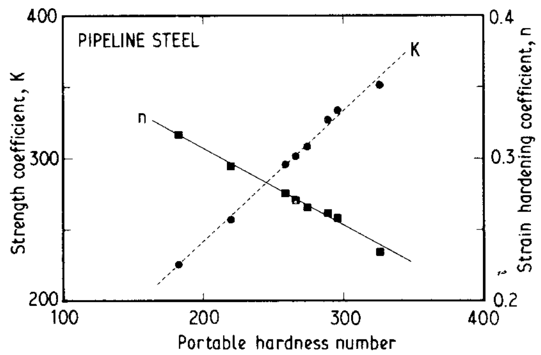


Figure 5 Correlation between portable hardness and strength and strain hardening coefficients for pipeline steel.

TABLE II Values of A, B, C, D and F for materials used

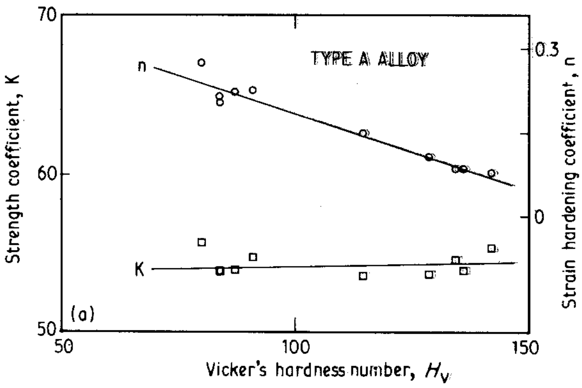
Material	A	B	C	D	F
Aluminium	2.093	− 35.40	− 0.0094	0.721	0.725
Pipe steel	2.576	− 92.11	− 0.0017	0.526	0.914
Mild steel	2.603	− 92.92	− 0.0014	0.503	0.933
Assab 760	4.038	− 657.19	− 0.0040	1.40	0.757

TABLE III Prediction of yield and ultimate tensile stresses

Material	No.	Observed yield stress (MPa)	Calculated yield stress (MPa)	Error %	Observed tensile stress (MPa)	Calculated tensile stress (MPa)	Error %
Assab 760 steel	1	543	599	10.4	921	912	− 1.0
	2	596	660	10.7	914	912	− 1.3
	3	663	691	4.2	931	892	− 4.3
	4	679	736	8.4	888	866	− 2.5
	5	669	739	10.4	879	864	− 1.7
	6	679	746	9.9	869	857	− 1.4
	7	699	751	7.5	871	839	− 3.8
Mild steel	1	493	499	1.3	620	622	0.4
	2	371	363	− 2.4	544	543	− 0.2
	3	354	374	− 5.6	554	550	− 0.8
	4	405	402	− 0.9	553	567	2.5
	5	365	358	− 2.0	541	539	− 0.4
	6	323	340	5.3	528	527	− 0.4
	7	298	305	2.5	496	502	1.3
	8	286	282	− 1.4	456	484	6.0
	9	221	216	− 2.4	415	427	3.0
Pipe steel	1	474	500	5.6	568	584	2.8
	2	450	462	2.7	581	568	− 2.4
	3	434	453	4.3	568	564	− 0.7
	4	435	433	− 0.6	555	555	0.1
	5	427	422	− 1.3	549	550	0.1
	6	443	412	− 7.7	545	545	0.0
	7	378	353	− 7.3	503	514	2.1
	8	317	291	9.2	489	475	− 3.1
Aluminium	1	40	39	− 2.3	95	97	2.5
	2	47	47	− 0.2	102	102	− 0.1
	3	48	49	0.6	102	103	0.7
	4	55	57	2.5	107	106	− 0.7
	5	56	57	2.8	107	106	− 0.6
	6	42	42	0.7	100	99	− 0.7
	7	56	57	3.7	107	107	− 0.4
	8	58	61	5.7	109	108	1.2

TABLE IV Comparison between present method to work by Chang *et al.* [5]

		By present method			Work by Chang *et al.* [5].		
Material	No.	Observed tensile stress (MPa)	Calculated tensile stress (MPa)	Error %	Observed tensile stress (MPa)	Calculated tensile stress (MPa)	Error %
Type A alloy	1	80.0	83.4	4.3	80.0	80.5	0.6
	2	91.0	92.5	1.7	91.0	89.0	− 2.2
	3	87.1	85.9	− 1.3	87.1	82.9	− 5.2
	4	83.8	83.8	0.0	83.8	79.4	− 5.6
	5	31.0	30.7	− 0.9	31.0	28.9	− 7.3
	6	34.8	35.3	1.6	34.8	37.4	7.6
	7	38.5	38.3	− 0.5	38.5	41.1	6.9
	8	40.9	40.0	− 2.3	40.9	42.8	4.7
	9	40.2	40.1	− 0.2	40.2	43.3	7.7
	10	42.1	41.8	− 0.8	42.1	45.2	7.3
Type B alloy	1	31.2	32.4	3.8	31.2	31.7	1.6
	2	31.2	32.5	4.1	31.2	29.3	− 6.5
	3	31.1	32.3	3.7	31.1	32.3	3.8
	4	32.1	33.6	4.6	32.1	33.4	4.1
	5	39.5	38.0	− 3.8	39.5	39.8	0.9
	6	39.4	38.7	− 1.9	39.4	40.7	3.3
	7	37.1	37.1	0.1	37.1	38.9	4.9
	8	37.5	38.1	1.5	37.5	39.2	4.4
	9	43.2	44.2	2.4	43.2	48.0	11.2
	10	44.7	44.2	1.1	44.7	46.1	3.3



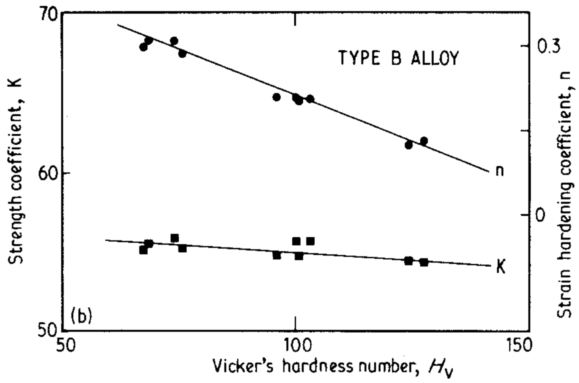


Figure 6 Correlation between hardness and strength and strain hardening coefficients of reference [5].

using Al–Zn–Mg type A and B alloys are recalculated and shown in Table IV. The correlations between hardness and strength and strain hardening coefficients for Chang's alloys are also found to be linear as shown respectively in Fig. 6a and b, similar to those obtained in the present study. However, because of the lack of exact Young's modulus values, the yield stresses of the alloys cannot be estimated. It can be seen from Table IV that Equation 8 gives a more accurate estimation of the ultimate tensile stress with deviations of only 1.36% and 2.72% for type A and B alloys, respectively, rather than the original estimation of 5.5% and 4.4%. In addition, it is believed that the present method of estimating the tensile and yield strengths is easier to use in practice, in that Equations 8 and 9 involve only constants *A*, *B*, *C*, *D* and *F* which are dependent only upon material and not the condition of the individual test specimen. Such a method, especially when portable hardness is employed, may be well suited to field measurements where non-destructive tests are conducted. Equations that require the evaluation of the strain hardening coefficient of a particular test specimen may be suitable to the laboratory environment but may inevitably be too cumbersome for applications in the field.

A straight line relationship between hardness and strength is normally assumed as a rule of thumb in the estimation of the strength of steel materials from hardness measurements. The advantage of using such direct correlation is that it is simple and convenient. However, in the repair of a flawed structure or worn component, for example, since the exact chemical composition and mechanical properties of the material of the defective part may not be readily available, one may very often be tempted to select a substitute material such that the hardnesses of the defective and the replacing part are the same. Such a method may be dubious as can be seen from the results obtained from the present study. Figs 7 and 8 show the relationship between yield strength and ultimate tensile strength with hardness, respectively, for all the steels used in the study. In Fig. 7, while a straight line may be fitted through the pipeline and mild steels data, a separate line is, however, needed for the Assab 760 steel indicating that Assab 760 steel is different from the other steels. This difference may be in the chemical compositions of the materials. Pipeline steel and mild steel have very similar carbon contents, 0.07% and 0.1%,

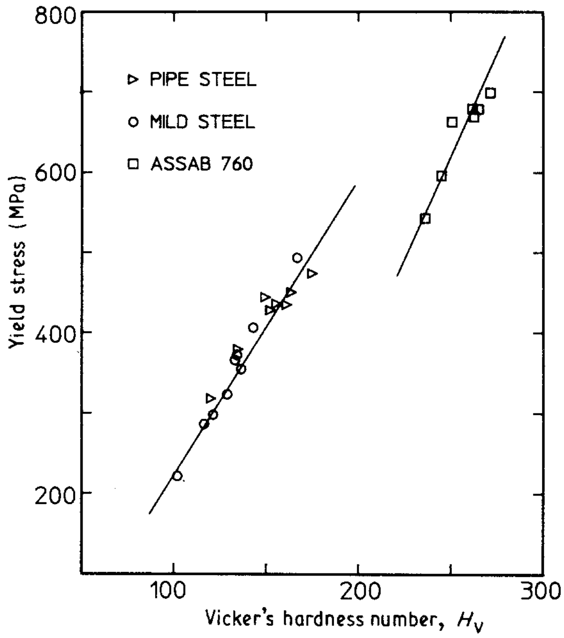


Figure 7 Relationship between yield stress and hardness of steels studied.

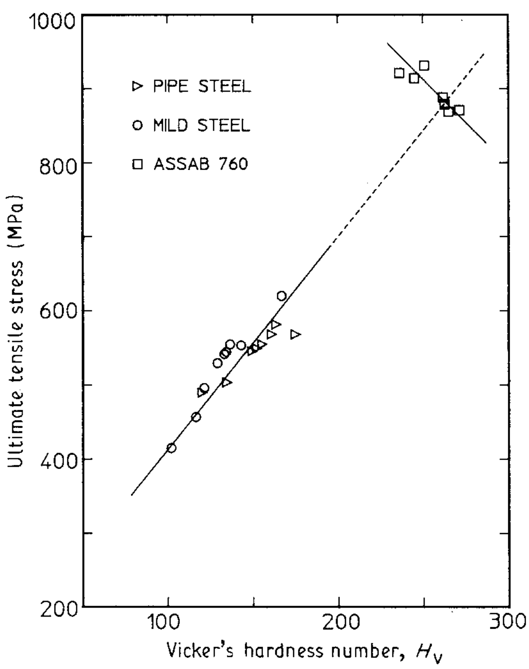


Figure 8 Relationship between ultimate tensile stress and hardness of steels studied.

respectively, and hence may behave in roughly the same manner. This is also reflected by their similarity in the values of A, B, C, and D as shown in Table II. On the other hand, Assab 760 steel has a rather different carbon content of 0.50% which may have caused it to behave differently from the pipeline and mild steels. Therefore, for the simple rule of thumb to duplicate the tensile property of a material by keeping similar hardness values to work well, it is necessary to ensure that their carbon contents are similar. As for the estimation of the tensile strength, although the present results are inconclusive, the rather large spread of data points may well portray a similar trend as that for yield strength, as can be discerned from Fig. 8.

4. Conclusion

The correlation between hardness and tensile properties for Assab 760 steel, mild steel, pipeline steel and 6063-T1 aluminium have been studied. The following results were obtained.

1. For all materials tested, the strength coefficient, K, and the strain hardening coefficient, n, vary linearly with hardness irrespective of the type of hardness measurement used. This relationship was employed to estimate the ultimate tensile and the 0.2% yield strengths of the materials.

2. The tensile strength and yield strength of a material can be predicted from the hardness measurement using Equations 8 and 9, respectively. The equations were observed to involve the use of constants A, B, C, D and F which were dependent only upon the material and not upon a particular specimen. The present method may therefore be better suited to application in field conditions.

3. Good accuracy in estimating the ultimate tensile and yield stresses have been obtained with Equations 8 and 9 for the materials investigated. Compared to the estimation of Chang *et al.* [5], the present method gives improved accuracy.

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