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On the Tensile Strength and Hardness Relation for Metals

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A method for predicting the ultimate tensile strength (S_u) of a material from Brinell-type hardness tests is described for several metals including steel, aluminum, and copper alloys. The prediction of S_u is based on a consistent relationship between S_u and a material's hardness coefficient, K_d. A simple experimental procedure for determining K_d from indentation-hardness test data is presented. The relationship between S_u and K_d is found to be 1/3 for all cubic metals. Comparisons between predicted and experimentally determined values of S_u are made for each of the materials studied, and sources of error between the two S_u values are discussed.

Keywords Brinell hardness, mechanical properties, metals, ultimate tensile strength

Introduction

It has been known for some time that hardness testing can be used to estimate other material properties, particularly ultimate strength, S_u. Estimation of S_u can be a useful tool in design when S_u cannot be measured directly. In such cases, hardness tests may provide a viable substitute for the direct measurement of S_u, as they are fast and easy to do, relatively nondestructive, and can often be done on existing parts with minimal sample preparation.

Various investigators have attempted to develop relationships between hardness and S_u for certain materials. Brinell, who developed the commonly used hardness test, observed that the Brinell-hardness number (HB) for steel was about twice the S_u expressed in ksi.[1] This relationship, while quite useful, is limited in its application to noncold-worked steels and requires use of a 3000 kg load for the Brinell-hardness test. Depending upon the thickness of the piece to be tested, it may not be possible to use a 3000 kg load.

Subsequent investigators expanded upon Brinell's work in an attempt to better define the link between hardness and tensile properties. In the early 1900s, Meyer investigated the relationship between applied load, L (called W by Meyer), and measured indentation diameter, d, and developed the relationship

$$L = kd^n$$

where the Meyer index, n, is observed to vary between 2 and 2.7, and k is the load for unit diameter.[2,3] Meyer also observed that k and, to a much lesser extent, n could change depending upon the diameter of the indenter (D) used in the hardness test. Specifically, k varied inversely with D. From these observations, Meyer wrote the expression

$$A = k_1 D_1^{n-2} = k_2 D_2^{n-2} \ldots$$

where A is a constant. Thus, the most general relationship involving d and D was written as

$$L = \frac{Ad_1^n}{D_1^{n-2}} = \frac{Ad_2^n}{D_2^{n-2}} = \ldots^{[2]}$$

This equation can then be rewritten as

$$\frac{L}{d^2} = A\left(\frac{d}{D}\right)^{n-2} \text{ or } \frac{L}{D^2} = A\left(\frac{d}{D}\right)^{n} {}^{[2]}$$

For geometrically similar indentations, d/D is constant. Thus, L/d^2 and L/D^2 must also be constant. In this case, then, a geometrically similar indentation could be expected with a 10 mm ball and a 3000 kg load as with a 5 mm ball and a 750 kg load.

In 1951, Tabor further expanded these concepts to encompass materials with different n values and to relate the stress-strain curve and, thus, S_u, to d/D. Tabor began with the true stress-true strain curve expressed as

$$\sigma = b\varepsilon^x$$

where $x = n - 2$, and b is a constant. He then developed an expression for tensile strength, S_u (called T_m in Tabor's original work).

$$S_u = b(1 - x)\left(\frac{x}{1 - x}\right)^x$$

Last, for specific d/D ratios, he developed expressions for the HB in terms of b and x. For example, for the case of $d/D = 0.5$, Tabor found that HB could be written as

$$HB = 2.62b(0.1)^x$$

Combining the two preceding expressions for $d/D = 0.5$, he wrote

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$$\frac{S_u}{HB} = \frac{1 - x}{2.62}\left(\frac{10x}{1 - x}\right)^x$$

Equations of a similar form were developed for d/D ratios of 0.3 and 0.7.[2]

While the above equation expresses tensile strength in terms of HB, it has two limitations. First, it was developed for a particular d/D ratio, so it is dependent on test conditions. Second, it depends on the material constant, x. In order to use Tabor's approach to determine a material's tensile strength from its HB, a new equation must be developed for each d/D ratio and for each particular value of x.

These two limitations led to Datsko's work over a period of years from the 1960s to the 1980s, which is reported here, where sets of hardness tests were performed on various metals. In these tests, both the test load, L, and indenter diameter, D, were varied for each metal. The resulting data were fit to the equation described by Meyer, written here as

$$\frac{L}{D^2} = K_d\left(\frac{d}{D}\right)^s$$

When plotted on log-log coordinates, an extremely good straight-line fit was obtained for all the materials tested. For each material, S_u was determined experimentally, and K_d was extrapolated from the log-log plot. Graphically, K_d is the value of L/D^2 corresponding to $d/D = 1$. The ratio of S_u/K_d was then calculated. This ratio was consistently found to be approximately 1:3.

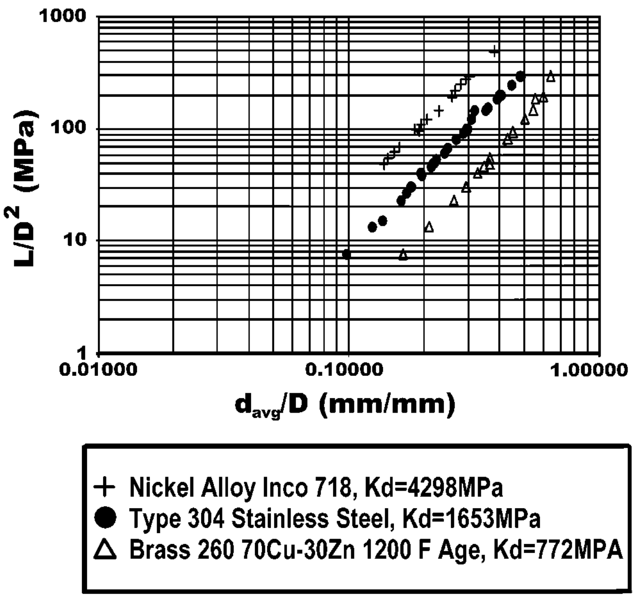

Fig. 1 Plot of indentation-hardness data for three metals

Materials

A total of 31 material samples were tested during this experimentation including eight carbon and alloy steels, seven stainless steels, nine copper alloys, five aluminum alloys, one cobalt-base alloy, and one nickel-base alloy. Most metals were tested in an annealed condition, with the exception of three of the aluminum alloys and the beryllium copper alloys. Those metal specimens were heat treated. Table 2 shows the specific heat-treatment condition of those metals.

Procedure

The results discussed in this paper were based upon the data collected from two types of testing: tensile testing and indentation-hardness testing. These tests were performed on multiple samples under standard test setup and procedures.

Tensile Testing

This data collection followed the standard tensile test procedure outlined by the American Society of Testing and Materials (Philadelphia, PA). The process consisted of preparing test specimens to conform to tensile test machine requirements and, then, applying uniaxial tensile load until failure occurred. In this experiment, cylindrical specimens with threaded ends and test diameters of 12.83 and 9.07 mm were used. The gauge lengths were four times the diameter.

An extensometer was used to determine the yield strength of the metal. The extensometer was then removed, and the minimum diameter was measured simultaneously with the applied load until the specimen failed. The load application was conducted at room temperature at a strain rate of approximately 10^{-3}/s. The experimental value of tensile strength was determined by dividing the maximum load by the original cross-sectional area.

Indentation Hardness Testing

The procedure for this test is very simple and does not require extensive preparation. The surface to be tested is machined or ground to produce a smooth, flat surface. The load is then placed on a ball to create a spherical indentation, which is measured and recorded.

The objective of this study was to obtain as large a range of the ratio of the indentation diameter, d, to the ball diameter, D, as possible because the accuracy of the data increases in direct proportion to the size of the range. To accomplish this goal, loads of 500, 1000, 1500, 2000, and 3000 kg were applied to a 10 mm ball on a Brinell-hardness testing machine. Since the metals selected for this study included soft ones, such as aluminum and copper, as well as hard ones, such as steel and a cobalt alloy, additional tests were conducted on a Baldwin tension-compression machine using balls of 12.7, 19.05, and 25.4 mm, with loads varying from as low as 45 kg for the soft metal to 4100 kg for the hard ones. The indentation diameters were measured with a Brinell microscope and with a toolmaker's microscope.

An example of load and indentor combinations is shown in Table 1, which contains the data collected for brass alloy #260 (70Cu-30Zn). Tables 2 and 3 record the specific number of d/D combinations applied to each specimen and also the test results.

Table 1 Indentation hardness data for 70Cu-30Zn brass

Indentor diameter (mm)	Load (N)	d_1 (mm)	d_2 (mm)	d_{avg}/D	L/D^2 (MPa)	log L/D^2	log d/D
25.4	4893	4.22	4.24	0.1665	7.585	.880	−0.778
25.4	14,678	6.71	6.71	0.2640	22.754	1.357	−0.578
25.4	19,571	7.47	7.44	0.2935	30.338	1.482	−0.532
25.4	29,357	8.79	8.81	0.3465	45.507	1.658	−0.460
19.05	4893	4.01	4.01	0.2107	13.484	1.130	−0.676
19.05	14,678	6.27	6.25	0.3287	40.451	1.607	−0.483
19.05	19,571	6.96	6.96	0.3653	53.934	1.732	−0.437
19.05	29,357	8.23	8.23	0.4320	80.901	1.908	−0.365
12.7	4893	3.76	3.76	0.2960	30.338	1.482	−0.529
12.7	14,678	5.74	5.72	0.4510	91.014	1.959	−0.346
12.7	19,571	6.40	6.45	0.5060	121.352	2.084	−0.296
12.7	29,357	7.06	7.01	0.5540	182.028	2.260	−0.256
10	4893	3.66	3.66	0.3655	48.858	1.689	−0.437
10	14,678	5.49	5.49	0.5482	146.574	2.166	−0.261
10	19,571	5.97	6.02	0.5989	195.431	2.291	−0.223
10	29,357	6.43	6.38	0.6396	293.147	2.467	−0.194

Table 2 Summary of experimental results of tensile and indentation-hardness tests

Material	S_u (MPa)	K_d (MPa)	S_u/K_d	Number of d/D combinations
Cobalt alloy HS25	834.30	2295.92	0.363	5
Nickel alloy Inco 718	1316.95	4298.12	0.306	14
AISI 1118 steel	431.63	1290.75	0.334	5
AISI 1144 steel	615.72	2148.99	0.287	5
AISI 1212 steel, sample 1	386.12	1266.93	0.305	5
AISI 1212 steel, sample 2	431.63	1099.26	0.393	17
AISI C1045 steel	577.11	1730.22	0.334	5
AISI B1060 steel	717.08	2373.17	0.302	14
AISI 4340 steel	1005.98	3011.38	0.334	5
AISI 52100 steel	646.75	2055.12	0.315	5
Type 303 annealed stainless steel	506.09	1537.31	0.329	24
Type 302 annealed stainless steel	638.48	1802.70	0.354	30
Type 304 annealed stainless steel	598.49	1653.03	0.362	24
Type 321 annealed stainless steel	519.19	1558.68	0.333	30
Type 316 annealed stainless steel	574.35	1574.60	0.365	30
Type 416 annealed stainless steel	503.34	1351.06	0.373	5
Type 416 annealed stainless steel	503.34	1471.46	0.342	24
ETP Cu 649 C anneal	202.74	526.75	0.385	19
ETP Cu 538 C anneal	188.93	513.64	0.368	8
BeCu 25 C age	723.67	2103.37	0.344	12
BeCu 425 C age	794.86	2388.30	0.333	18
BeCu 470 C age	776.89	2164.06	0.359	6
Brass 260 70Cu-30Zn 649 C age	302.74	771.95	0.392	16
Brass 60-40 538 C anneal	328.31	853.26	0.385	10
Brass 60-40 593 C anneal	318.63	881.43	0.361	24
Brass 60-40 593 C anneal	306.88	845.58	0.363	15
Al 1100-O	88.47	256.34	0.345	4
Al 2024 T351	443.74	1381.94	0.321	24
Al 2024 T351	434.75	1359.79	0.320	15
Al 2024 T351	430.61	1356.37	0.317	15
Al 6061-T T651	314.14	837.68	0.375	5

Discussion

For each material, a data table was constructed, which contained the test load, L, indentor diameter, D, and impression diameters, d_1 and d_2, measured at 90 deg to each other. The two impression diameters were averaged to arrive at a representative value (d). From these data, the quantities L/D^2 and d/D were computed, and the logarithm of these two computed quantities was taken. The resulting values log L/D^2 and log d/D were plotted against one another with d/D as the independent variable, and a linear regression fit of each data set was done. Table 1 shows an example of the test data recorded for 70Cu-30Zn brass, and a plot of L/D^2 versus d/D for several of the metals tested is shown in Fig. 1.

Table 3 Comparison of experimental to predicted tensile strengths

Material	Experimental S_u (MPa)	S_u/K_d	Predicted Su ($S_u = K_d/3$) (MPa)	% Error	Number of d/D combinations
Cobalt alloy HS 25	834	0.363	765	8	5
Nickel alloy Inco 718	1317	0.306	1432	−9	14
AISI 1118 steel	432	0.334	430	0	5
AISI 1144 steel	616	0.287	716	−16	5
AISI 1212 steel, sample 1	386	0.305	422	−9	5
AISI 1212 steel, sample 2	432	0.393	366	15	17
AISI C1045 steel	577	0.334	576	0	5
AISI B1060 steel	717	0.302	791	−10	14
AISI 4340 steel	1006	0.334	1004	0	5
AISI 52100 steel	647	0.315	685	−6	5
Type 303 annealed stainless steel	506	0.329	512	−1	24
Type 302 annealed stainless steel	638	0.354	601	6	30
Type 304 annealed stainless steel	598	0.362	551	8	24
Type 321 annealed stainless steel	519	0.333	520	0	30
Type 316 annealed stainless steel	574	0.365	525	9	30
Type 416 annealed stainless steel	503	0.373	450	11	5
Type 416 annealed stainless steel	503	0.342	490	3	24
ETP Cu 649 C anneal	203	0.385	175	13	19
ETP Cu 538 C anneal	189	0.368	171	9	8
BeCu 25 C age	724	0.344	701	3	12
BeCu 425 C age	795	0.333	796	0	18
BeCu 470 C age	777	0.359	721	7	6
Brass 260 70Cu-30Zn 649 C age	303	0.392	257	15	16
Brass 60-40 538 C anneal	328	0.385	284	13	10
Brass 60-40 593 C anneal	319	0.361	294	8	24
Brass 60-40 593 C anneal	307	0.363	281	8	15
Al 1100-O	88	0.345	85	3	4
Al 2024 T351	444	0.321	460	−4	24
Al 2024 T351	435	0.320	453	−5	15
Al 2024 T351	431	0.317	452	11	15
Al 6061-T T651	314	0.375	279	7	5

The line fit to each data set is described by the equation

$$\left(\frac{L}{D^2}\right) = K_d \left(\frac{d}{D}\right)^s$$

which Tabor and O'Neill derived but did not find useful.

For each material, the value of the hardness coefficient, K_d, was determined from the log-log plot. Then, the relationship between S_u and K_d was found by calculating S_u/K_d for each of the materials tested. The S_u, K_d, and S_u/K_d experimental values for each material are given in Table 2.

It is readily apparent by examining the data in Table 2 that the relationship between S_u and K_d is a consistent one. It is the consistency of this relationship that provides the most interesting and useful finding of this study. In nearly all cases, S_u was found to be approximately 1/3 of K_d, and the average of all the S_u/K_d values was found to be 0.35.

The most useful outcome of the relationship between S_u and K_d is that as few as two simple Brinell-hardness tests performed at any test load can now be used to determine K_d for any metal and then to estimate the ultimate strength of that material. However, it is recommended that five d/D ratios be used, if possible, to improve the reliability of the result and that low d/D values be avoided. In addition, if a small or thin test specimen is used, care should be taken to ensure that the properties of the test piece are representative of the bulk material as a whole. All that is required is a small specimen of the material of interest and the ability to conduct an indentation hardness test. Until now, the relationship between hardness and tensile strength was only documented for noncold-worked steels and only for hardness tests conducted using a 3000 kg load. By using these latest findings, engineers may now obtain a reasonably accurate estimate of a material's tensile strength from a small piece of the material without the time and expense of preparing a tensile test specimen and conducting a tensile test. The suggested procedure is as follows.

1. Conduct five ball indentation tests on the available material, each at a different d/D ratio. More tests can be conducted at different loads for greater accuracy if desired.
2. For each test, record the test load, L, and indentor diameter, D, measure the impression diameter, d, and calculate the quantities L/D^2 and d/D.
3. Plot L/D^2 versus d/D on log coordinates and fit a line through the data.
4. To find K_d, extrapolate the resulting line so that the value of log L/D^2 can be determined for log $d/D = 1$. This value is K_d.
5. Estimate S_u as $K_d/3$.

To determine how accurate an estimate of S_u the preceding relationship gives, the estimated value of S_u found using this relationship was compared to the measured value of S_u for the materials in this study. The results of this comparison are shown in Table 3. Table 3 indicates that the percent error obtained when estimating S_u as $K_d/3$ is usually small. In 24 of the 31 materials tested, the observed error in predicted S_u was within 10% of the experimentally measured S_u value. Furthermore, the average of the observed errors in predicted S_u was a mere -1.6%. In analyzing the data, it was also observed that better agreement was obtained between experimentally determined values of S_u and predicted values of S_u from the $S_u = K_d/3$ relationship when multiple indenter diameters were used in the tests. Finally, the accuracy of this method can also be improved, in some cases, by manually fitting a line through the L/D^2 versus d/D data. This would be appropriate in cases where there is an obvious outlyer in the data that should be disregarded.

Another contributing factor to the error between experimental and predicted values of S_u observed in these results should be noted. Namely, there is a natural distribution of experimentally measured tensile-test values for any material. For example, it is not uncommon to see a difference of 15% or more between the lowest and highest measured S_u values in one lot of steel. This is particularly true in free-machining steels containing manganese-sulfide inclusions, which contribute to variations in tensile strength in different regions of the tensile-test specimen depending upon location and orientation of the inclusion. In this study, two of the materials that exhibited the largest error between the predicted and experimental values of S_u were 1144 and 1212 steel. Both of these are free-machining steels containing a large amount of manganese-sulfide inclusions. Thus, it is reasonable to expect that a major contributor to the error between measured and predicted S_u values from this study is the inherent error in measuring S_u experimentally.

Conclusions

In summary, the results presented here offer a reasonably easy experimental method for estimating a material's ultimate tensile strength using indentation-hardness testing for metals having a cubic-lattice structure. The engineer need only to determine K_d from as few as two hardness tests (although more are recommended) and, then, estimate S_u as roughly 1/3 of K_d. The advantages of this method are its applicability to a wide range of materials, its speed, limited investment in test equipment, and the small quantity of material actually required for testing.

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