THE MEANING AND THE MEASUREMENT OF HARDNESS

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Hardness, as the term is ordinarily used, implies resistance to penetration, scratching, or wear. From a somewhat more general view one would define hardness as resistance to permanent deformation under any kind of stress, with the single qualification that this stress is applied through steady loading, thus excluding impact.

It would appear, therefore, that the measurement of the hardness of any given material would be a comparatively simple matter, involving merely the use of a mechanically suitable testing machine, with load, penetrator, and method for calculating and reporting, standardized. In metallurgy it is a well recognized principle that hardness, as determined by almost any standard method, is, in at least an approximate measure, proportional to mechanical strength. This would naturally follow from the above general definition which, in turn, rests upon the equally well recognized principle that, no matter how static deforming stresses are applied, yield to these stresses involves the same fundamental effect—translational slip within the crystalline grains of the metal. The case is not so simple, because metals and their alloys present the interesting and unique anomaly of becoming harder—and therefore stronger—as a result of strain. In other words, when a metal is subjected to plastic deformation it becomes harder and stronger than before, as measured by its resistance to further deformation under stress. The strength of all metals is increased by strain, although to different degrees.

It would not be profitable here to go into a detailed discussion of accepted explanations for this phenomenon, but the fact is well known and frequently utilized for improving strength characteristics of metals and alloys. From this arises the question: Is hardness to be understood as a measure of resistance to *any* permanent deformation, however small, or of the ability of the metal finally to *stop* deformation. If the latter (and this is the only significance of the term, as applied to any existing methods for measurement) then it should be noted that we are actually determining the "hardness" of strain-hardened material and not that of the original unstrained metal, as it is when it goes into service. If the former, then at present we have no standard method for determining hardness, since it is obviously necessary to penetrate, scratch, or otherwise deform in order to note the effect of the application of the stress which causes this deformation.

In this connection it seems not necessary to go into a detailed discussion of the various hardness testing methods or of standard testing machines, although it may be useful to classify some of the better known as to type, limiting this to static loading methods, since impact "hardness" tests bring into play various other qualities, such as ultimate strength, ductility and resiliency. Testing methods involving penetration under steady loading include the Brinell, Vickers, Rockwell, Monotron, Firth Hardometer, and numerous other less used testers. The only scratch tester that has been refined to the point of quantitative usefulness is the Microcharacter, as perfected by Bierbaum. Wear hardness

tests are so varied in nature and so uncertain in results that they cannot be regarded as better than empirical tests, sometimes useful but not susceptible to very scientific interpretation.

Absolute Hardness.—This term is used to designate the maximum unit stress which a metal will support, as applied through a loaded penetrator, without suffering any permanent deformation. Considering this along with conventional hardness numbers, there is shown a sort of analogy with limit of elasticity and ultimate strength in compression. It is generally recognized by engineers that in compression, tension, torsion, or bending, the limit of elasticity is a more useful figure than is the ultimate strength, for two reasons: (1) correct design must preclude the possibility of any permanent deformation whatever, in service; (2) ultimate strength is, like conventional hardness numbers, a measure of the strength of strain-hardened material.

There is on record a report of only one attempt to determine absolute hardness by "strainless indentation." Harris[1] proceeded by first applying the conventional Brinell test, then annealing in a non-oxidizing atmosphere to remove the effects of strain-hardening. Upon reapplying the load to the Brinell ball in the impression already made, the ball, of course, increased the depth of penetration. The annealing and application of the load were repeated until it was found that no further penetration occurred. The final maximum diameter of the impression and the load employed were used in the calculation of the absolute hardness of unstrained material.

The Harris "absolute hardness" cannot be an ideal representation of the hardness of the original unstrained material, for two reasons: 1. It is obvious that each application of the load after annealing would cause a certain additional straining—therefore hardening—of the metal. This effect would diminish with each successive test but it could never reach a value of zero but only approach zero as a limit, and this after an indefinitely large number of tests. 2. It is well known that annealing after strain produces grain refinement and that grain refinement increases hardness.

Method Used in the Present Investigation.—We have attempted to avoid these complications by producing a "Brinell" impression by mechanical removal of metal, rather than by inducing plastic flow, as is the case with the Brinell and all other existing hardness tests. For the softer metals and alloys a special drill was used. This is a two-fluted drill, ground to spherical curvature and with a radius of five millimeters, thus giving a depression of the same form as that of the Brinell ball, but with no strain-hardening effects except those produced by the drilling operation, limited to an extremely shallow layer at the surface of the depression. A special precision measuring microscope was used for measuring the diameter of the impressions. This microscope is provided with cross hairs, thus eliminating the errors of parallax, and measurements may be made with a precision of ± 0.002 millimeter.

The procedure is, of course, rather tedious. A conventional Brinell test is first made, to serve as an approximate indication as to the depth

[1]J. Inst. of Metals, 2:327. 1922.

of drilling that will be required. A series of depressions is then made by means of the special drill, testing after each is finished, until a depth is found such that the Brinell ball, under the selected load, just fails to widen the impression. The measured diameter of this is used in calculating the absolute hardness of the metal.

A few of the many results obtained in this test are given as illustrations of the general relations that are found to exist between absolute and Brinell hardness. There is no exception to the general rule that absolute hardness is very much lower than conventional hardness numbers. Tests upon five classes of materials are shown in Table I.

TABLE I

COMPARISON OF BRINELL AND ABSOLUTE HARDNESS

Material	Brinell Number	Absolute Hardness
Nickel steel	163	113
Tool steel, S. A. E. 1095	170	110
Tool steel, S. A. E. 1125	174	114
Swedish iron	83	47
Bronze	56	31

Discussion.—All of these hardness numbers are calculated as unit stress, in kilograms per square millimeter. It was recognized by Brinell that his formula, involving as it does the spherical surface of the impression, is mathematically incorrect since the true supporting surface is the circular projection of the impression, rather than its spherical surface. This gives a somewhat lower hardness number but is the method which is practically universally used. In calculating the present absolute hardness numbers the circular, rather than the spherical, area has been used.

From the few determinations reported above it is seen that, although there is a marked difference between the hardness numbers of the two types, absolute hardness always being much lower than conventional hardness, no constant relation exists between the two. This is the expected result, considering the fact that the various metals and alloys differ to a large degree in their capacity for work-hardening. As a result of the accumulation of many more data it is hoped that some formula may be derived for calculating the work-hardening capacity in terms of the two hardness numbers. Such a formula must necessarily be somewhat empirical, but it should be a useful addition to our repertoire of testing methods.

Experimental investigations are now being pursued in the field of age-hardening alloys, as typified by Duralumin and copper-beryllium. Some results have already been obtained which are somewhat startling in nature. A report upon these has not yet been made and they are here mentioned merely to indicate the general field covered by the investigation.