VARIATION OF STEEL PROPERTIES DURING HARDNESS TESTS BY BALL INDENTATION

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In testing the hardness of metals by Brinell or Rockwell methods (scale B) a steel ball is forced into the surface of the test piece under a definite load. In the process of plastic deformation the metal hardens and its resistance to indentation increases.

To study the process of hardening under ball pressure and the effect of this phenomenon on the results we have conducted tests of several grades of low- and medium-carbon steels (commercial iron, steel St-3, annealed, hardened, and aged steels 20 and 45). The tests were

PLASTIC DEPTH, IMPRESSION MODULUS, AND HARDNESS VARIATION AT DIFFERENT INTERVALS OF LOADING IN TESTS OF STEEL AND COMMERCIAL IRON

Grade of steel and method of heat treatment	HRB/H	Load P in kg	Plastic depth of the impression of μ		Impression modulus in kg/μ		Average hardness at a given load		Hardness, separately for each loading stage		Initial Hardness H_0
			$h_{пл}$	$\Delta h_{пл}$	$\frac{P}{h_{пл}}$	$\frac{\Delta P}{\Delta h}$	HB	в % от H_{50}	HB	в % от H_{50}	
Commercial iron	46/82	50 90 140	92,0 167,4 210,0	92,0 75,4 42,6	0,544 0,538 0,667	0,544 0,530 1,174	109,0 107,9 133,6	100 99,0 122,6	109,0 106,6 233,0	100 97,8 214,0	110
St. 3, annealed	61/99	50 90 140	80,3 138,4 190,1	80,3 58,1 51,7	0,623 0,650 0,736	0,623 0,688 0,967	124,8 130,5 147,7	100 104,5 118,4	124,8 138,0 194,0	100 110,5 155,3	125
St. 3, quenched from 710°	74/126	50 90 140	62,4 112,5 169,5	62,4 50,1 57,0	0,801 0,800 0,826	0,801 0,798 0,877	161,0 160,5 166,0	100 99,7 103,1	161,0 160,0 175,8	100 99,5 109,3	161,5
St. 3, quenched and aged for 5 days	82/149	50 90 140	52,2 96,4 150,4	52,2 44,2 54,0	0,958 0,934 0,931	0,958 0,905 0,926	192,4 187,4 186,8	100 97,4 97,1	192,4 181,3 185,6	100 94,2 96,4	198
St. 3, quenched and aged for 15 days	89/174	50 90 140	45,1 82,5 132,4	45,1 37,4 49,9	1,109 1,091 1,058	1,109 1,070 1,002	222,7 219,0 212,4	100 98,4 95,4	222,7 214,3 200,8	100 96,2 90,2	227
20, annealed	69/115	50 90 140	67,7 122,4 177,8	67,7 54,7 55,4	0,738 0,736 0,787	0,738 0,731 0,902	148,0 147,5 158,0	100 99,7 106,7	148,8 147,0 181,0	100 99,3 122,3	148,5
45, hot-rolled	102/240	50 90 140	29,8 56,9 90,4	29,8 27,1 33,5	1,678 1,582 1,548	1,678 1,476 1,493	337,0 318,0 311,0	100 94,3 92,3	337,0 295,0 299,0	100 87,6 88,8	358

Note: Commas are equivalent to decimal points.

carried out with a Rockwell-type indentor using a ball 1.588 mm in diameter under 50, 90, and 140-kg loads (not counting the preliminary load of 10 kg). The values corresponding to the depth of plastic indentation and the increase in depth resulting from additional load application were calculated on the basis of the instrument indications (see Table).

The depth of the impression does not vary in proportion to the load when the latter is increased, because the similarity conditions are upset by geometrical and structural factors. These factors act in opposite directions.

Unlike the pointed indenters (a cone, or a pyramid) which have constant angles of taper and impression, and which, therefore, produce geometrically similar indentations under different loads, a ball has a variable angle of impression. At the initial moment the ball's impression angle is close to zero, and its "taper" angle is at its maximum value (180°). As the ball penetrates deeper into the material, the angle of impression increases, while the taper angle diminishes. When the depth of the indentation attains 57.3 μ the taper angle of the ball in the Rockwell tester is equal to 136° (or, it corresponds to the taper angle of the pyramid in the Vickers instrument). When the ball is forced to a depth of 100 μ this angle diminishes to 120° and becomes equal to that of the Rockwell instrument cone. These depths of impression correspond to the instrument's readings of HRB 111 and 80.

The penetration of the indenter into the material becomes easier as the taper angle decreases. This is characteristic for the pointed indenters, which attain a greator depth of penetration under equal loads. Consequently, if the properties of the material manifest little or no change at all as a result of loading, the penetration of the ball into the material should also be facilitated as the impression becomes deeper.

In order to evaluate the combined effect of these factors we have calculated the magnitude of the load capable of causing a 1 μ advance in the depth of the indentation (which we have termed the modulus of indentation) over different test intervals (0-50, 50-90, and 90-140 kg). From the Table it becomes apparent that the steels tested may be classified into three groups in terms of the indentation modulus variation. For the harder steels (45, and St. 3) the $\frac{P}{h}$ modulus shows a persistent drop after ageing. In the third loading range their resistence to indentation diminished to 92.3, 97.1 and 95.4% as compared to the values registered for the 0-50-kg interval.

For steel 20 and the hardened St. 3 grade the indentation modulus values were the same over the first and the second loading ranges, with a slight increase in the third interval. The annealed St. 3 steel and commercial iron (HRB 46-61) manifested an 18.4 and 22.6% increase of the indentation modulus in the third interval as against the first. This means that the depth of indentation produced by the indenter in these steels became relatively lower in the third interval when the load was 140 kg, in spite of the above-mentioned effect of the geometric factor.

These results evidence that a considerable hardening of the soft steels occurs in the process of ball penetration and that their properties experience a substantial change. There is no doubt that this phenomenon also takes place in harder steels. It is known that in annealed carbon steels, which showed HB values of 115, 137, and 160 in the initial state, the hardness increased by 36, 30, 17% after drawing with a 10-% reduction, by 52, 44, and 27% after 20-% reduction, and by 60, 52, and 35% after 30-% reduction, and so on. Even the absolute increase in hardness for harder steels is less considerable in magnitude than for soft steels and, particularly, for commercial iron.

Under the influence of plastic deformation occurring in the process of hardness testing the properties of all steels manifest a change, but quantitatively this change is unequal. It may be small for harder steels and attain a considerable value in soft steels and alloys. This is the reason why the effect of the geometric factor was predominant in the hard steels, for which a certain drop was observed in the indentation modulus values, whereas in soft steels the greatest influence was produced by the structural factor.

In accordance with this fact the numerical hardness values vary continuously as the material is tested. The established Brinell hardness values (see Table) represent averaged values depending on the depth of the impression and the tendency of the material to harden.

The hardness of materials not responsive to cold working (steel 45 and St. 3 after quenching and age hardening) will continue to drop with increasing load as a result of the geometric factor, especially when the depth of the impression is small. The hardness of low-carbon steels and alloys will increase considerably as a result of cold working, since its influence is greater than that of the geometric factor (Fig. 1-b).

These hardness values (in Brinell units) for 50, 90, and 140-kg loads were calculated from formula:

$$HB = \frac{P}{\pi D h} = \frac{M}{\pi D}$$

and characterized the average hardness of the material from 0 to the selected load value. At the same time the average hardness values were determined for 50-90 and 90-140 kg (see Table) which were defined on the basis of the increments in load and the depth of the impression for each testing stage: $HB = \frac{P}{D\ h}$.

Test hardness variation curves were plotted on the basis of these values calculated for the different loading ranges (Fig. 1-a). Since these are averaged values, they were plotted in the middle of each interval. The trend of the curves is additionally controlled here by the mean hardness values for the first two (HB 90) and for the three ranges (HB 140) shown in the Table.

As it may be seen from Fig. 1-a, a decline in hardness is to be observed at the beginning of the test in steels 45 and St. 3 (after ageing), with steel 45 exhibiting a particularly sharp drop. A slight increase in hardness begins to appear at 140-kg load. This bears witness to the fact that the geometric factor exerts a predominant influence at the beginning of the test.

In the softer steels (20 and St. 3 hardened) the hardness values remain practically unchanged over the first period, i.e. the effects of the geometric and the structural factors are equivalent in them. But under the load of 140 kg, hardness already shows a noticeable increase. For the most ductile steels (annealed St. 3 and commercial iron) the final-stage hardening considerably exceeds the effect of the geometric factor, and in the final count one observes a considerable increase in hardness.

On the basis of these data it is possible to determine the tendency of the steels to increase in hardness (work-harden)

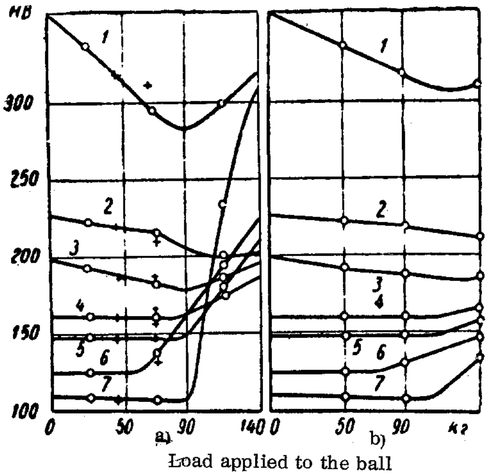

Fig. 1. Variation of the steel hardness numbers in the process of testing with ball indenter:
a - values determined for the intervals 0-50, 50-90, and 90-140 kg; b - values determined for the 50, 90, and 140-kg loads; 1 - steel 45; 2 - steel St. 3, 15 days' ageing; 3 - steel St. 3, 5 days' ageing; 4 - steel St. 3, hardened; 5 - steel 20; 6 - steel St. 3, annealed; 7 - commercial iron.

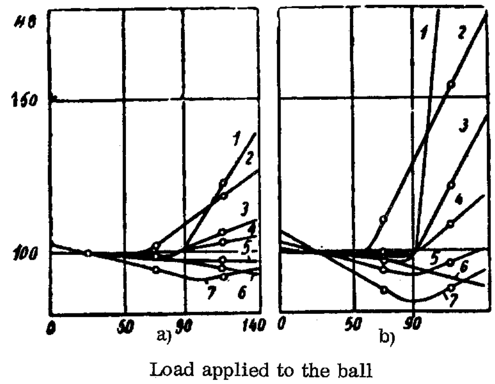

Fig. 2. The tendency of steel to increase in hardness in the process of testing (% in relation to the hardness in 0-50 kg interval):
a - for 50, 90, and 140-kg loads; b - for loads ranging from 0-50, 50-90, and 90-140 kg;
1 - commercial iron; 2 - steel St. 3, annealed; 3 - steel 20; 4 - steel St. 3, hardened; 5 - steel St. 3, aged 5 days; 6 - steel St.3, aged 15 days; 7 - steel 45.

in the process of testing, if one takes their hardness values at 0-05 kg for 100% (see Table). The hardness variation for the tested steels is shown in Fig. 2 in percentage ratio to the initial range. In terms of their susceptibility to work hardening the steels may be arranged in an order inversely proportional to their hardness values: the lower the hardness, the greater the response to cold working and the more intensive is the increase of this tendency with increasing load.

In extrapolating the hardness variation curves, it is easy to determine the "initial" value H_0 (corresponding to zero load) on the Y-axis. This value does not depend on the effects of the geometric and structural factors and characterizes the metal's resistance to indentation before it has been subjected to cold working in the process of testing. (see Table).

CONCLUSIONS

1. A departure from geometric similarity, associated with the variation of the ball's angle of impression with increasing load, leads to a drop in the numerical hardness value, while a departure from structural similarity (work hardening of metal) causes the hardness to increase.

2. In metals not responsive to cold working the hardness value at the initial moment may remain unchanged, or it may even decline, but ultimately the effect of cold work is greater than that of the geometric factor, and the numerical hardness value increases as greater loads are applied to the ball.

3. With increasing load on the ball, the hardness of the ductile metals increases more rapidly and becomes higher than the hardness value of a number of harder metals. The difference in the hardness of steels diminishes as the load applied to the ball continues to increase.

4. The tendency of the soft steels to work harden in the process of testing is higher, and in order of their susceptibility to cold working the investigated metals range in a succession inversely propertional to their hardness value.