METHODS OF STUDYING THE STRUCTURE AND PROPERTIES
OF MATERIALS. PROCESS MODELING

Correlation between the Ultimate Tensile Strength and the Brinell Hardness of Ferrous and Nonferrous Structural Materials

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Abstract—The relations between ultimate tensile strength σ_u and Brinell hardness *HB* are known for some groups of steels. These relations represented in the form of formulas, tables, or plots make it possible to quickly estimate σ_u from *HB* without fabricating specimens. Therefore, they are necessary during input control of blanks, treatment of steels by various methods, diagnostics of steel state after long-term service, or reductive heat treatment, and in other cases. There are very limited data on such relations for nonferrous metals and alloys; however, there are tables, which give the values of σ_u and *HB* for some alloys based on aluminum, copper, and titanium. When establishing more general and correct σ_u–*HB* relations for various structural materials (ferrous and nonferrous alloys), it is appropriate to relate σ_u to the maximum Brinell hardness, which enables one to obtain a general relation for ferrous and nonferrous alloys. To determine the maximum Brinell hardness, it is proposed to use depth-sensing indentation with recording the load *F*–indenter displacement α indentation diagram with its subsequent conversion to the unrecovered Brinell hardness HB_t–relative indentation depth *t/R* diagram. The maximum hardness $(HB)^{max}$ can be easily determined from the maximum of the HB_t–*t/R* diagram. This report presents the results of tests, in which σ_u and $(HB_t)^{(max)}$ have been determined for many steels, aluminum, magnesium, and titanium alloys, and a directly proportional relation between these mechanical characteristics is found.

Keywords: steel, alloys based on nonferrous metals, ultimate tensile strength, Brinell hardness, instrumented indentation, indentation diagram

INTRODUCTION

The fact that there is a correlation between ultimate tensile strength σ_u and Brinell hardness for some groups of steels is known for a long time. Such correlations enable quick estimation of σ_u from the data on *HB* without fabricating specimens. Therefore, numerous research were performed to establish a more general correlation of σ_u with *HB* for steels of various classes and grades, and such investigations have been performed up to now. As a result of these studies, formulas, plots, and tables were proposed for determination of σ_u from *HB* for specific steel classes. The results are described, for example, in [1–4] and also in normative documents (e.g., GOST 22761, RTM3-1947–91, and Instruction I 1.2.102.019.1121–2016).

The σ_u–*HB* correlations are most often approximated by the following linear dependences:

$$\sigma_u = c \cdot HB \pm b, \qquad (1)$$

where *c* and *b* are constant coefficients characteristic of specific groups of materials.

If coefficient *b* is very small, it can be neglected in practice.

For nonferrous metals and alloys based on them, the data on the correlation between σ_u and *HB* are scarce as compared to steels. However, RTM3-1947–91 contains tables, which give the values of σ_u and *HB* for some nonferrous alloys based on aluminum, copper, and titanium.

However, it should be noted that, even for steels, the estimation of σ_u using the date on *HB* and known relationships is approximate and can be used for specific groups of steels with known compositions and strength and the hardness. Coefficients *c* and *b* in Eq. (1) can be substantially varied as functions of treatment conditions and the microstructure of steels.

Therefore, attempts to propose more justified and general σ_u–*HB* correlations taking into account the

strain-hardening parameters of materials were made in the mid-20th century. In [5, 6], such a parameter was the strain-hardening coefficient n entering in the Meyer formula

$$F = a \cdot d^n, \tag{2}$$

where F is the indentation load of a ball indenter, d is the indentation diameter, a is the coefficient characteristic of a material and depending on indenter diameter D, and n is the strain-hardening coefficient.

In [7, 8], such a parameter was taken to be the limiting uniform elongation of a specimen during tension δ_u. Markovets [7] was the first to formulate one of the main similarity conditions: the tensile stress of a specimen should be placed in correspondence with its Brinell hardness at the same plastic strain during tension and indentation. Markovets proposed to estimate the conventional plastic strain during indentation using the following relationship:

$$\Psi^{ind} = \frac{1}{2}\left[1 - \sqrt{1 - \left(\frac{d}{D}\right)^2}\right].$$

Based on this similarity condition, to estimate σ_u using the data on HB, it is necessary to provide, during a ball indentation, the plastic deformation in the indentation Ψ_u^{ind} that is equal to the residual ultimate uniform tensile strain of the specimen corresponding to σ_u. The correlation between σ_u and HB^{max} should be established with allowance for the existence of a maximum in the stress σ–relative elongation δ tensile diagram with coordinates σ_u and δ_u and also a maximum at the HB–Ψ^{ind} indentation diagram with HB^{max}–Ψ_u^{ind} coordinates.

HB^{max} can be most correctly determined from HB–Ψ^{ind} or HB–F indentation diagrams. However, the construction of such diagrams with determination of load F, indentation diameter d, and calculation of HB at each loading stage is a very difficult process. Therefore, formulas were proposed for calculations of HB^{max} from parameters a and n entering in Meyer formula (2). The most known formula is [9]

$$HB^{max} = \left(\frac{2}{\pi}\right)aD^{n-2}n^{n/2}(n-2)^{(n-2/2)}(n-1).$$

Parameters a and n can be determined by two indentations of an indenter at two different arbitrary loads F_1 and F_2, measuring indentation diameters d_1 and d_2 corresponding to these loads,

$$n = (\ln(F_2/F_1)/\ln(d_2/d_1)).$$

However, the accuracy of determining parameter n is significantly dependent on the chosen ratio of loads F_2/F_1, which can be different in the dependence on the mechanical properties of a material. Ratio F_2/F_1 can be justifiably determined only using an indentation diagram.

Therefore, in 1968, researchers of MPEI under direction of Prof. M.P. Markovets proposed to determine HB^{max} using depth-sensing (instrumented) indentation [1]. This method was developed and gained recognition due to more perfect instruments and information measurement engineering, and now it is possible to quickly and reliably determine the maximum hardness by instrumented indentation recording a ball indentation diagram in the load–indentation depth coordinates [10]. In this work, we perform comprehensive experimental studies, including the determination of the maximum Brinell hardness by instrumented indentation for materials of various classes and grades. The aim of this work is to establish a general correlation between the ultimate strength with the maximum Brinell hardness of ferrous and nonferrous metal and alloys.

EXPERIMENTAL

We prepared specimens for tensile tests and indentation tests from various steels and alloys based on nonferrous metals. The steels to be studied were carbon steels and also alloy steels of pearlitic, austenitic, ferritic–martensitic and martensitic classes with σ_u from 300 to 1700 N/mm^2 (in all, 18 types of steels). The group of nonferrous alloys consisted of alloys based on aluminum (18 alloys), magnesium (3 alloys), and titanium (9 alloys). The aluminum alloys had σ_u from 100 to 700 N/mm^2, magnesium alloys, from 240 to 280 N/mm^2, and titanium alloys, from 380 to 1216 N/mm^2.

To determine the ultimate strength by tensile tests according to GOST 1497–84 as a function of the range of sizes, either cylindrical tensile specimens (type III) or proportional planar specimens with heads (type I) were prepared from each material under study. Tensile tests were carried out on an Instron 5982 universal testing machine at a strain rate of 2 mm/min (3.3×10^{-4} m/s). Three specimens were tested per material, and the resulting ultimate strength σ_u was calculated as the value averaged over the results of three tests.

The hardness characteristics of a material were determined by several various methods.

At the first stage, the Brinell hardness was measured on each of the materials according to GOST 9012. Tests were carried out on a MEI-T7 device using an indenter of diameter $D = 2.5$ mm. The indentation load F^G was 1839 N (187.5 kg) for materials with hardness $HB > 100$ kg/mm^2 and 307 N (31.25 kg) for materials with a lower hardness. The resulting values of Brinell hardness HB were found as the average of three measurements.

Then, on each of the materials, tests were carried out by stepwise loading of an indenter with a step-by-step increase in indentation load F and the measure-

ment of indentation diameter d at each step of loading. These tests were also performed on the MEI-T7 device using an indenter of diameter $D = 2.5$ mm. The results of these tests were used to build stepwise $HB–F$ indentation diagrams with the determination of the hardness at each loading step. Such diagrams enabled us to determine maximum hardness HB^{max}, load F^{max}, and the degree of loading $K^{max} = F^{max}/D^2$ at which this hardness is attained.

Instrumented indentation tests were carried out on the Instron 5982 testing machine, recording a load–indenter displacement indentation diagram. The indentation loads were chosen to assure the achievement of the maximum hardness for each of the materials taking into account the results obtained during the step-by-step loading of the indenter. Then, these diagrams were converted into unrecovered Brinell hardness HB_t–relative indentation depth t/R diagrams using the algorithms and programs developed in [10]. These $HB_t–t/R$ diagrams were used to determine the maximum hardness HB_t^{max}. Three indentation diagrams were recorded for each of the materials, and the resulting values of the Brinell hardness HB were found as the average of three measurements.

After the tensile and indentation tests, the obtained results were compared. The values of ultimate strength found by the tensile methods were put in correspondence with the Brinell hardness determined according to GOST 9012 (σ_u/HB), the maximum hardness determined by step-by-step loading (σ_u/HB^{max}), and the maximum hardness determined by instrumented indentation (σ_u/HB_t^{max}).

RESULTS AND DISCUSSION

To compare the ultimate tensile strength and the Brinell hardness HB determined according to GOST 9012, we built the dependences of σ_u on HB for steels (Fig. 1a), aluminum and magnesium alloys (Fig. 1b), and titanium alloys (Fig. 1c). When constructing the general $\sigma_u(HB)$ dependence for all abovementioned materials, we observed a substantial scatter of the experimental points and, hence, divided the materials into groups. After statistical processing of the curves presented in Fig. 1, the following formulas were obtained, where the values of σ_u and HB are given in N/mm^2 (correlation coefficient r is indicated in parentheses):

for steels, $\sigma_u = 0.369HB - 59.5$ ($r = 0.995$);

for aluminum and magnesium alloys, $\sigma_u = 0.378HB + 13.4$ ($r = 0.952$);

for titanium alloys, $\sigma_u = 0.337HB + 8.1$ ($r = 0.986$).

The lowest correlation coefficient r was obtained for aluminum and magnesium alloys. The difference of the values of σ_u calculated by the obtained formulas and the values of σ_u obtained by the tensile tests of the
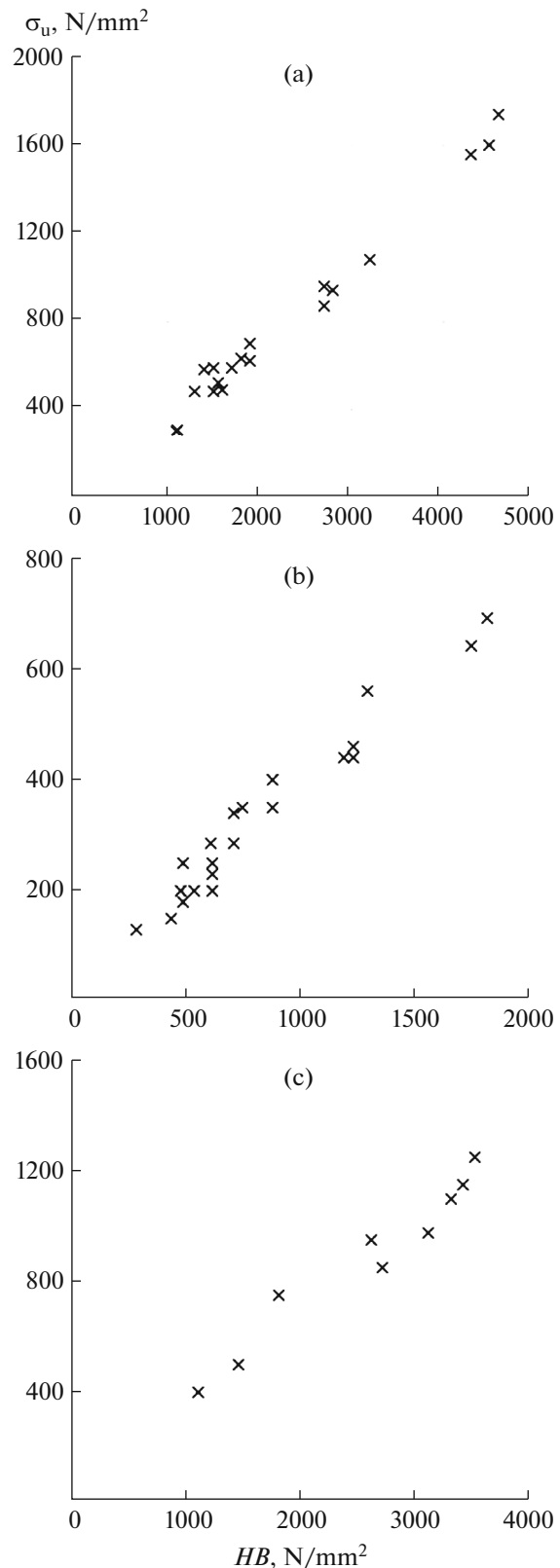
Fig. 1. Ultimate tensile strength σ_u vs. Brinell hardness HB for (a) steels, (b) aluminum and magnesium alloys, and (c) titanium alloys.
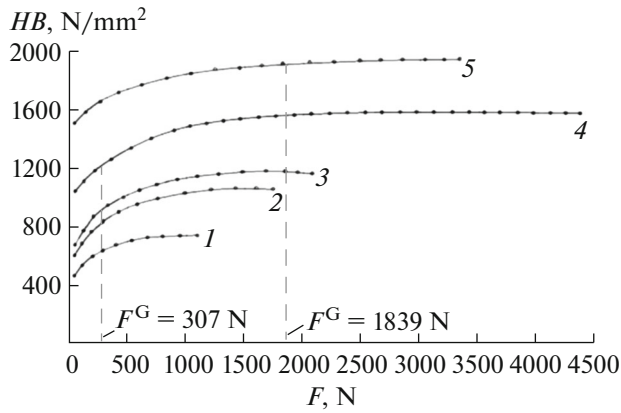
Fig. 2. Step-by-step HB–F indentation diagram for structural materials (D = 2.5 mm): (*1*) MA20, (*2*) AMg6, (*3*) VT1-0, (*4*) EP184, and (*5*) V95T1.

specimens is ±25% for aluminum and magnesium alloys, ±12.5% for titanium alloys, and ±11% for steels.

When comparing σ_u with hardness HB determined under the loads recommended by GOST 9012, it is impossible to obtain a quite correct general correlation for various ferrous and nonferrous metals and alloys. The cause is that the indentation load F^{max} at which the maximum hardness is reached can be substantially different from load F^G recommended by GOST 9012 for the determination of the Brinell hardness for some materials. In this case, the tensile maximum stress σ_u

is actually compared not to the maximum hardness; correspondingly, the relation between these stresses can vary within over limits as a function of a material. This fact supports the assumption that it is necessary to relate σ_u to the maximum Brinell hardness HB^{max} to obtain justified general relations between σ_u and the hardness.

Figure 2 shows the obtained stepwise indentation diagrams for some steels, aluminum, magnesium, and titanium alloys. It is seen from the diagrams that load F^{max} at which maximum hardness HB^{max} is achieved is most often higher than load F^G regulated by GOST 9012. For some materials, F^{max} is equal or very close to F^G. However, for an AMts aluminum alloy, which has a small uniform deformation during tension of a specimen, load F^{max} was significantly lower than F^G. Expressing the indentation load as the degree of loading $K = F/D^2$, we can see that, in most cases, the degree of loading $K^{max} = F^{max}/D^2$ at which the maximum hardness is achieved is significantly higher than the degree of loading $K^G = F^G/D^2$ regulated by GOST 9012. The highest value $K^{max} = 675$ N/mm^2 was obtained for EP184 austenitic steel, and the lowest value $K^{max} = 31.4$ N/mm^2, for an AMts aluminum alloy.

Table 1 gives the values of F^G, F^{max}, K^G, K^{max}, HB, and HB^{max} for several grades of steels, aluminum and magnesium alloys, and titanium alloys. The ratios σ_u/HB^{max} determined for all materials presented in Table 1 are close to 1/3. Here, it should be noted that

Table 1. Results of determining the mechanical properties of steels and alloys based on nonferrous metals

Material	σ_u, N/mm^2	F^G, N	F^{max}, N	K^G, N/mm^2	K^{max}, N/mm^2	HB, N/mm^2	HB^{max}, N/mm^2	HB_t^{max}, N/mm^2	σ_u/HB	σ_u/HB^{max}	σ_u/HB_t^{max}
15Kh1M1F (pearlitic steel)	525	1839	3237	294	518	1530	1561	1670	0.343	0.336	0.314
EP184 (austenitic steel)	521	1839	4218	294	675	1511	1593	1670	0.345	0.327	0.312
AMts (aluminum alloy)	184	307	196	49.1	31.4	540	550	568	0.341	0.334	0.324
AMg6 (aluminum alloy)	361	307	1373	49.1	220	710	1078	1087	0.508	0.335	0.332
V95T1 (aluminum alloy)	636	1839	2943	294	471	1766	1881	1893	0.360	0.338	0.336
MA2-1 (magnesium alloy)	270	307	1177	49.1	188	638	796	805	0.423	0.339	0.335
MA20 (magnesium alloy)	244	307	981	49.1	157	601	731	735	0.406	0.334	0.332
VT1-0 (titanium alloy)	380	1839	1839	294	294	1158	1158	1192	0.328	0.328	0.319
VT16 (titanium alloy)	907	1839	1839	294	294	2698	2698	2794	0.336	0.336	0.325

the ratio σ_u/HB, in which hardness HB is determined by GOST 9012, has values from 0.336 to 0.508. For titanium alloys, the values of σ_u/HB and σ_u/HB_{max} differ insignificantly, since the indentation load is $F^G \approx F^{max}$.

When instrumented indentation is used upon recording a load F–indenter displacement α indentation diagram and subsequent conversion of this diagram into an HB_t–t/R diagram, the process of testing and determination of $(HB_t)^{max}$ is accelerated and takes no longer than 3 min. The regularities and properties of such diagrams are considered in [11]. Figure 3 shows F–α and HB_t–t/R indentation diagrams for several materials tested in this work.

Table 1 also gives the values of HB_t^{max} and ratios $\sigma_u/(HB_t)^{max}$. From Table 1, it is seen that the values of $\sigma_u/(HB_t)^{max}$ are close to 1/3 for all materials under study.

The statistical processing of σ_u–$(HB)^{max}$ and σ_u–$(HB_t)^{max}$ for all the materials subjected to the tests resulted in the following formulas (correlation coefficient r is indicated in parentheses), in which the values of σ_u and HB are given in N/mm^2:

$$\sigma_u = 0.336 HB^{max} - 2.7 \quad (r = 0.999), \quad (3)$$

$$\sigma_u = 0.322(HB_t)^{max} - 3.0 \quad (r = 0.998). \quad (4)$$

An experimental verification showed that the maximum difference in the values of σ_u determined by indentation and calculated using Eqs. (3), (4) and the values of σ_u found in tensile tests is at most ±5%.

Formulas (3) and (4) are valid when a indenter with $D = 2.5$ mm is used. It is interesting to note that the relation of σ_u to HB was found earlier without considering the influence of the scale factor. We used the values of the hardness determined by indentation of various indenters of diameters $D = 10$–1 mm. However, the smaller D, the higher hardness HB. By analogy, in the case of tensile tests, σ_u increases when the initial cross-sectional area decreases [12].

Completing the consideration of the σ_u–HB relations, we should note that the relations of σ_u to the Vickers hardness HV are also known for specific groups of materials. For example, the relations between σ_u and HV for several grades of steels presented in [13] are also described by a linear dependence, which is similar to Eq. (1). However, a general σ_u–HV relation for ferrous and nonferrous metals cannot be established for the following reason. It is known that the indentation of a Vickers pyramid with a apex angle of 136° leads to a conventional contact deformation of approximately 0.073 [10]. This deformation remains constant on the macroscale of indentation at various indentation loads and pyramid indentation depths. When a ball is indented, the same deformation is achieved at a relative indentation diameter
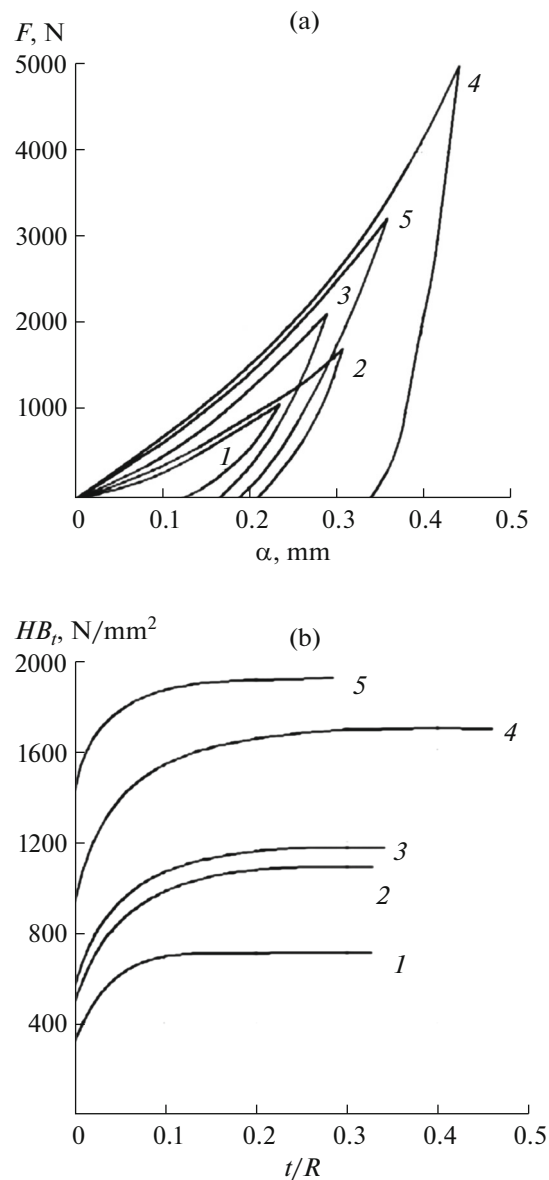

Fig. 3. (a) F–α and HB_t–t/R indentation diagrams for structural materials ($D = 2.5$ mm) obtained by instrumented indentation: (*1*) MA20, (*2*) AMg6, (*3*) VT1-0, (*4*) EP184, and (*5*) V95T1.

$d/D = 0.376$, which corresponds to the indentation angle of 136°. Under this condition for materials with a limiting uniform tensile deformation close to 0.073, general directly proportional relations σ_u–HB and σ_u–HV take place with a coefficient of proportionality close to 1/3. When the limiting uniform deformation of the material is higher or lower than 0.073, the σ_u–HB and σ_u–HV relations are described by Eq. (1) with various coefficients. Therefore, instrumented pyramid indentation with recording a load–indenter displacement indentation diagram cannot be used to find a general relation between σ_u and HV for ferrous and nonferrous metals.

CONCLUSIONS

The experiments on ball indentation performed in this work to determine $(HB)^{max}$ and $(HB_t)^{max}$ using indentation diagrams and to determine σ_u from tensile diagrams of various steels, aluminum, magnesium, and titanium alloys showed that there is general direct proportional relation between these mechanical characteristics. The maximum deviation of the values of σ_u found by the revealed relation from the values of σ_u found from tensile tests of specimens is at most $\pm5\%$ for all materials.

When σ_u was compared to HB under the loads recommended by GOST 9012, it is impossible to obtain a fairly correct general relation for various ferrous and nonferrous metals and alloys. The main cause of this fact is that indentation the load (F^{max}) at which the maximum hardness is achieved can significantly differ from the load (F^G) recommended by GOST 9012 to determine the Brinell hardness for some materials. It was found that a justified general correlation between σ_u and the hardness can only be obtained when σ_u is compared to the maximum Brinell hardness HB^{max} determined from an indentation diagram. In addition, in the search for a correlation between σ_u and the hardness, the conditions of the physical, mechanical, and geometric similarities should be met and tensile and indentation tests should be carried out on the same scale.

FUNDING

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