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Estimation of the Ultimate Tensile Strength of Steel from Its *HB* and *HV* Hardness Numbers and Coercive Force

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Abstract—A formula is derived to accurately describe the tabulated relation between the Brinell (*HB*) and Vickers (*HV*) hardnesses of steel over the entire range of their possible variation. This formula and the formulas describing the relation between the *HB* hardness of chromium–molybdenum and chromium–nickel steels and their ultimate tensile strength σ_u are used to analyze the change in σ_u of 38KhNM steel upon quenching and tempering. The data that reveal a relation between σ_u of 38KhNM steel and its coercive force are obtained.

Keywords: steel, hardness, relation between *HB* and *HV* hardness numbers, ultimate tensile strength, nondestructive testing

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INTRODUCTION

Hardness is the characteristic of a material that reflects a set of its mechanical properties [1–4]. Among the existing methods of estimating the mechanical properties of materials, the determination of hardness is most widely used due to its simplicity, availability, and the absence of necessity of preparing special-purpose specimens. In most cases, hardness measurements do not cause fracture of machine components and they can be performed during complete control, whereas the determination of the strength and plasticity requires sampling of components. The advantage of hardness tests is also the possibility of determining a quantitative relation between the hardness determined upon static standard indentation (Brinell hardness *HB*, Vickers hardness *HV*) and ultimate tensile strength σ_u.

The Brinell method is most widely used to determine the hardness of heat-treated steel with a nonpolished surface (hardness *HB* is determined from indentation diameter *d* of a hard steel ball (indenter) on a plane metal surface after unloading using special-purpose tables according to GOST 9012–59 (measurement 5) [5]). The revealed relation between hardness *HB* and σ_u of steels of various classes was tabulated [6]. It is not recommended using the Brinell method for materials with a hardness >450 *HB* (4500 MPa) to avoid deformation of a steel ball. Materials with a higher hardness can be analyzed by the Vickers method, in which a tetrahedral diamond pyramid with an angle of 136° between opposite faces is used (hardness *HV* is measured according to GOST 2999–75 (measurements 1, 2) [7] and GOST R ISO 6507-1–2007 [8] at a load of 9.8–980 N, i.e., 1–100 kgf).

The Vickers method is used to determine the hardness of thin components and their surface layers. This method resembles the Brinell method (hardness *HB*), and the indentation diagonal measured on a polished metal surface is used in the hardness *HV* calculation formula. When Vickers hardness is described, the subscript indicates the load applied to an indenter (information on the load is given in units of kgf the loading time if this time is longer than 10–15 s). For materials with a hardness of <450 *HB*, hardnesses *HB* and *HV* almost coincide. The Vickers method is usually applied for materials with a hardness of >360 *HB*, i.e., for heat-treated steels. The generalization of numerous experimental determinations of the hardness of a metal allowed researchers to express the relation between hardnesses *HB* [5] and *HV* [7, 8] in the form of tables (see, e.g., [6, 9]) or algebraic functions [10]. This relation is used only in a narrow *HV* range. For example, for the range $80 < HV < 250$ MPa and the steels applied in nuclear power plant equipment and pipelines, we have

$$HB = HV. \tag{1}$$

In the range $250 < HV \leq 500$ [10], we have

$$HB = HV - 0.0002HV(HV - 57). \tag{2}$$

At the boundary of these ranges, the values of *HB* calculated by Eqs. (1) and (2) do not coincide: at 250 *HV*, the difference in the *HB* calculations by Eqs. (1) and (2) is 3.86%.

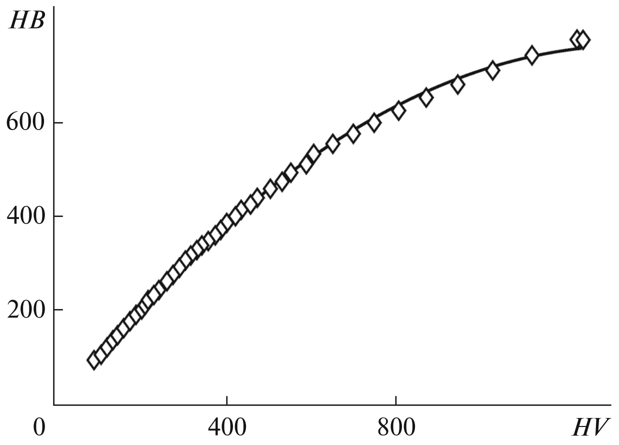

Fig. 1. Relation between *HB* and *HV* hardness numbers of steels according to [6, 9]. (solid line) Calculation by Eq. (3).

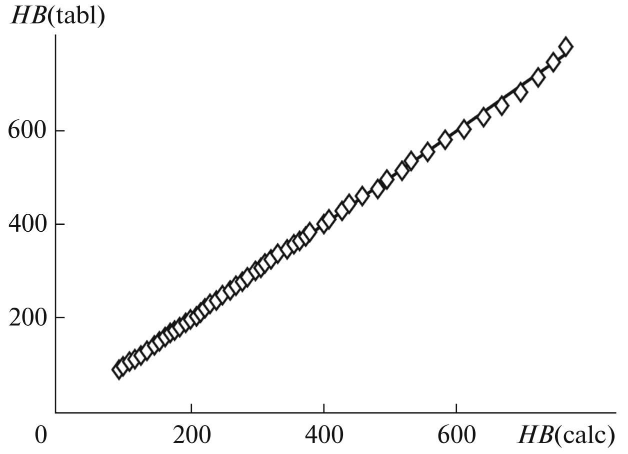

Fig. 2. Relation between the *HB*(calc) hardness numbers of steels calculated by Eq. (3) and the *HB*(tabl) hardness numbers of steels with the *HV* hardness taken from [6, 9]. (solid line) Calculation by Eq. (4).

It is also important that the tabulated data are inconvenient for analysis and are inaccurate. The data presented in different handbooks and monographs are often different and inaccuracies and misprints are repeated without critical analysis. For example, numerous discrepancies exist between indentation diameter *d* and the *HB* number according to GOST 9012 [5] in [9, Table 11.8] (in particular, at $d = 2.20$–2.40, 2.50, 2.65, 2.70, 3.20, 5.60, and 5.90–6.00 mm). The *HB* numbers in repeatedly published handbook [6] do not correspond to GOST 9012 [5] at $d = 2.4$, 3.2, and 5.65–5.75 (see [6, Table 15.11]).

In this work, we suggest a formula to describe the relation between the Brinell and Vickers hardnesses statistically accurately over the entire range of its possible variation. This formula can be used to obtain information on the changes in ultimate tensile strength σ_u of steels induced by heat treatment and to estimate the possibilities of nondestructive testing of σ_u by a magnetic method.

ANALYTICAL RELATION BETWEEN THE *HB* AND *HV* NUMBERS OF STEELS

We used the data from [6, Tables 15.11; 9, Table 11.8], according to which the range $95 \le HV \le 1234$ at a given *HB* number covers all possible changes in the *HV* number that are known from other numerous sources. The indicated discrepancies between the values of *HB* hardness and indentation diameter *d* in these tables were corrected according to the recommendations in [5, Appendix 3, Table 1]. In addition, the misprints in the *HV* numbers at 363 *HB* are corrected (376 *HV* is correct rather than 386 [6, Table 15.11] or 380 [9, Table 11.8]).

Figure 1 illustrates the correspondence between *HB* and *HV* hardness numbers according to [6, 9]. The data were statistically processed by a standard program (XL electronic tables). This correspondence is described by the expression

$$HB \approx 1.1465HV - 0.000421HV^2 - 11 \qquad (3)$$

at a coefficient of correlation $R^2 \approx 0.9993$ for the approximation of the tabulated data by the *HB* hardness calculation by Eq. (3).

The curve in Fig. 2 demonstrates the correspondence between the results of *HB* calculation by Eq. (3) and the *HB* tabulated data for steel with known *HV* hardness. The linear trend obeys the equality

$$HB(\text{tabl}) = HB(\text{calc}). \qquad (4)$$

The average modulus of deviation $|\overline{\Delta}|$ and modulus $\overline{\delta}$ of the relative deviation of hardness *HB*(calc) from *HB*(tabl) for the data in [6, 9] are as follows:

$$|\overline{\Delta}| = \frac{1}{n}\sum_{i=1}^{n}|HB(\text{calc})_i - HB(\text{tabl})_i|, \qquad (5)$$

$$\overline{\delta} = \frac{100}{n}\sum_{i=1}^{n}\frac{|HB(\text{calc})_i - HB(\text{tabl})_i|}{HB(\text{tabl})_i}, \qquad (6)$$

where $n = 149$ is the number of the *HB* and *HV* hardness numbers of steel used in [6, Table 15.11; 9, Table 11.8].

In Fig. 3, we compare the *HB* and *HV* hardness numbers calculated by Eqs. (1)–(3). An analysis of the calculated results demonstrates that the correlation of Eqs. (1) and (3) is acceptable in the range $80 < HV < 250$ ($\overline{\delta} < 1\%$ at $R^2 > 0.9996$), and the *HB* calculation by Eq. (3) in the range $250 < HV < 500$ is thrice as accurate ($\overline{\delta} \approx 1.18\%$ at $R^2 \approx 0.9993$) as the calculation by Eq. (2), where $\overline{\delta} \approx 3.63\%$ at $R^2 \approx 0.9988$. Only Eq. (3) ensures an acceptable *HB* calculation accuracy over the entire hardness range ($95 < HV < 1234$): the aver-

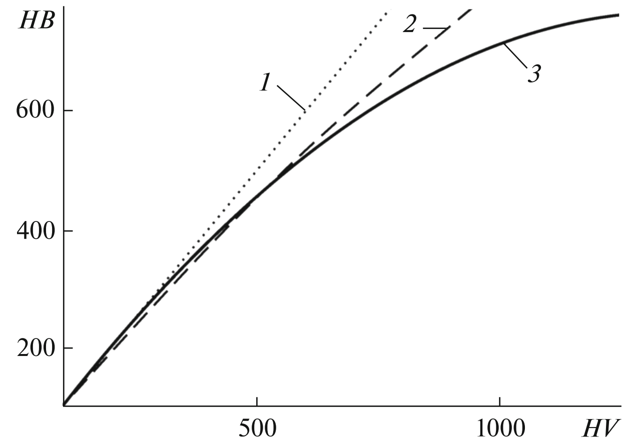

Fig. 3. (*1–3*) Results of calculation of the relation between the *HB* and *HV* hardness numbers of steels by Eqs. (1)–(3), respectively.

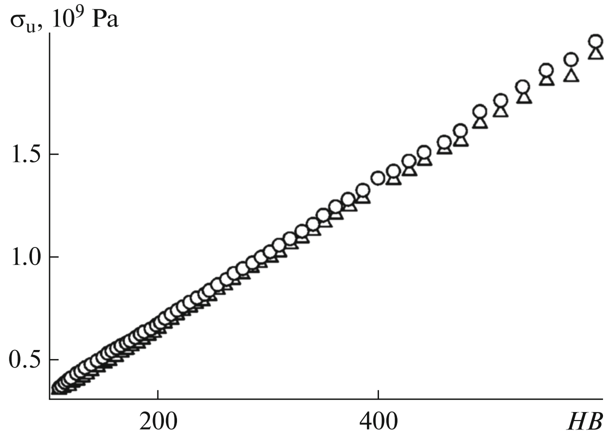

Fig. 4. Relation between the ultimate tensile strength σ_u of (○) chromium–nickel and (△) chromium–molybdenum steels and their *HB* hardnesses taken from [6].

age deviation is $|\overline{\Delta}| = 3.03$ *HB* units and $\overline{\delta} < 1\%$, which is four times smaller than the error of measuring *HB* hardness by a hardness tester [11].

This result, allows us to recommend Eq. (3) for estimating *HB* hardness of steels from *HV* hardness and analyzing the relation between these hardness numbers over the entire range of their variation (instead of inconvenient tables and less accurate Eqs. (1) and (2)).

RELATION BETWEEN *HV* HARDNESS NUMBER OF STEEL AND ITS ULTIMATE TENSILE STRENGTH

We used the data from [6, Table 15.8] to find a relation between ultimate tensile strength σ_u and *HB* hardness for a chromium–nickel–molybdenum 38KhNM steel.[1] As follows from [6], the values of σ_u of chromium–nickel and chromium–molybdenum steels are related to their *HB* hardnesses; this relation can be approximated by linear equations of the form

$$\sigma_u \approx k\xi HB, \tag{7}$$

where $\xi = 1$ mm^2/kgf is the dimension factor and k is the material-dependent coefficient of proportionality (Fig. 4).

Coefficient of proportionality k was calculated by Eq. (7), and the reliability R^2 of application of the results of σ_u calculation by Eq. (7) was determined using the data on σ_u from [6, Table 15.8]. The average modulus of deviation $|\overline{\Delta}|$ and modulus $\overline{\delta}$ (%) of the relative deviation of the calculation of $\sigma_u(\text{calc})_i$ by Eq. (7) from the tabulated data on $\sigma_u(\text{tabl})_i$ given in [6, Table 15.8] are determined by the formulas

$$|\overline{\Delta}| = \frac{1}{n}\sum_{i=1}^{n}|\sigma_u(\text{calc})_i - \sigma_u(\text{tabl})_i|, \tag{8}$$

$$\overline{\delta} = \frac{100}{n}\sum_{i=1}^{n}\frac{|\sigma_u(\text{calc})_i - \sigma_u(\text{tabl})_i|}{\sigma_u(\text{tabl})_i}, \tag{9}$$

where $n = 62$ is the number of the values of ultimate tensile strength σ_u and *HB* hardness of steels in [6, Table 15.8].

Table 1 gives the results of statistical processing of the data shown in Fig. 4 using a standard program (XL electronic tables).

The values of R^2, $|\overline{\Delta}|$, and $\overline{\delta}$ demonstrate that the moduli of relative deviation $\overline{\delta}$ of σ_u calculated by Eq. (7) and measured for chromium–molybdenum and chromium–nickel steels are smaller than the discreteness of σ_u (2–4%) caused by the discreteness of changing the *HB* hardness number when indentation diameter d is changed at a step of 0.05 mm by a factor 5–10 [5]. Therefore, we can use the reported data on the *HB* hardnesses of chromium–molybdenum and chromium–nickel steels to estimate their ultimate tensile strength σ_u by Eq. (7) at the values of coefficient k given in Table 1.

For chromium–nickel–molybdenum 38KhNM steel, we chose the average value of coefficient k in Eq. (7) with respect to its values given in Table 1 for chromium–molybdenum and chromium–nickel steels ($k \approx 0.3343$). Then, from Eqs. (3) and (7) for 38KhNM steel, we obtain

$$\sigma_u \approx \xi(0.383HV - 0.000141HV^2 - 3.7). \tag{10}$$

Figure 5 shows σ_u of 38KhNM steel as a function of the quenching temperature and the tempering tem-

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[1] Equation (3) was used to analyze the influence of the quenching and tempering conditions on the ultimate tensile strength σ_u of chromium–nickel–molybdenum 38KhNM steel (German analog is steel 1.2311, USA analog is P20 steel). Data on only the *HV* hardness of this steel are available [12; Tables 20.1, 20.3].

Table 1. Results of statistical processing of the data calculated by Eq. (7) and the ultimate tensile strengths of steels of various classes according to [6]

Alloy	Symbol in Fig. 4	k	R^2	$\|\overline{\Delta}\|$, N/mm^2	$\overline{\delta}$, %
Chromium–nickel	○	0.3399	0.9999	3.45	0.377
Chromium–molybdenum	△	0.3296	0.9998	3.98	0.436

perature. σ_u was calculated by Eq. (10) using the data on the HV hardness of this steel from [12; Tables 20.1, 20.3]. An analysis of these dependences demonstrates that, upon quenching from a heating temperature of ≥800°C, the ultimate tensile strength σ_u of 38KhNM steel doubles as compared to the unquenched state. As the tempering temperature of the steel increases from 300 to 700°C, the ultimate tensile strength decreases linearly to the σ_u level in the unquenched state. Our formulas can be applied to obtain similar results for any steels from their HV hardnesses, which can be measured or taken from the scientific literature.

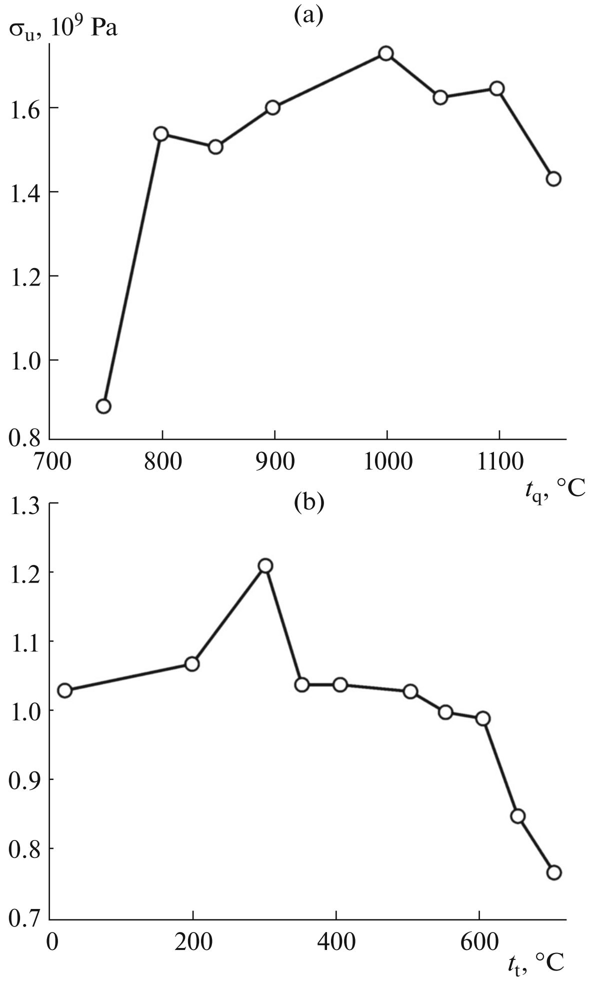

Fig. 5. Ultimate tensile strength σ_u of 38KhNM steel vs. (a) quenching temperature t_q and (b) tempering temperature t_t. σ_u was calculated by Eq. (10) using the data on the HV hardness of this steel from [12].

Figure 6 shows the relation between σ_u of 38KhNM steel and its coercive force H_c, which was obtained using the data on HV hardness and coercive force H_c of this steel [12; Tables 20.1, 20.3]. It is generally accepted that physical quantities are closely related at $|R^2| > 0.7$ [13]. The high reliability ($R^2 \approx 0.96$) of the correspondence between the results of calculating σ_u of 38KhNM steel by Eq. (10) and coercive force H_c of this steel, which can be determined by nondestructive testing methods, is a prerequisite for the possibility of estimating the ultimate tensile strength of a 38KhNM steel product without its fracture using only its measured coercive force.

Thus, the methodological novelty of this work consists in an analytical representation of the relation between the HB and HV hardness numbers of steels over the entire range of their possible variation, finding reliable coefficients of proportionality in the linear relation between HB hardness and ultimate tensile strength σ_u of chromium–molybdenum and chromium–nickel steels, and substantiation of a close relation between σ_u and H_c of 38KhNM steel. The devel-

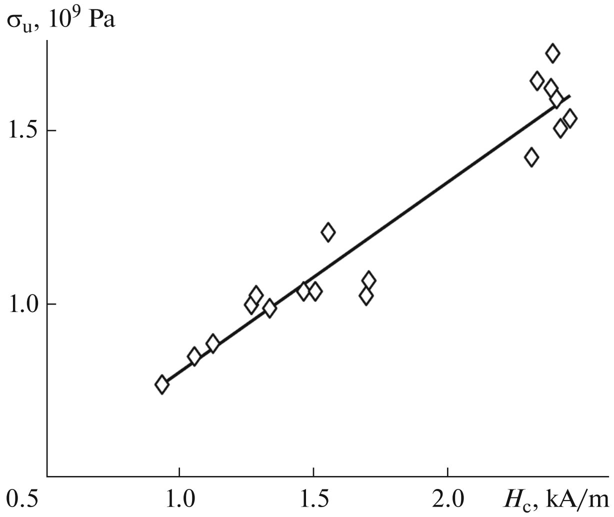

Fig. 6. Ultimate tensile strength σ_u of 38KhNM steel vs. its coercive force H_c and approximation of this relation. σ_u was calculated by Eq. (10) using the data on the HV hardness and the coercive force H_c of this steel from [12].

oped functions describe the analyzed relations over the entire parameter range mathematically simply with the minimum deviation from tabulated data.

CONCLUSIONS

(1) A formula was derived to describe the relation between the Brinell (*HB*) and Vickers (*HV*) hardnesses of steel. This relation is accurately described in the parameter range that is possible for structural steels.

(2) We determined statistically reliable coefficients of proportionality in the formula that describes the relation between the *HB* hardness and the ultimate tensile strength σ_u of chromium–molybdenum and chromium–nickel steels.

(3) The effect of the quenching temperature and the tempering temperature on the ultimate tensile strength σ_u of 38KhNM steel was quantitatively estimated from the results of measuring its *HV* hardness. It was shown that this ultimate tensile strength can be determined from the coercive force of this steel, which is measured using a nondestructive method.

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