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Coercive Force and Strength of Carbon Steel

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Abstract—By statistical analysis, a formula describing the tabular relationship between the Brinell (*HB*) and Rockwell hardness (*HRC*) of carbon steel is derived. Likewise, a formula relating *HRC* to the alloy strength σ_u is found. The dependence of the coercive force H_c of carbon steel on σ_u is established on the basis of measurements of *HRC* and H_c and σ_u values calculated from the proposed formula. Results of assessing σ_u on the basis of H_c are presented for 30, 35, 45, U8, U10, and U12 steel.

Keywords: carbon steel, strength, hardness, nondestructive monitoring, coercive force

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Carbon steel is used to manufacture components of low strength (steel 30 and 35), high strength (steel 45), and high wear resistance (steel 50 and 60) and tools operating without heating of the cutting edge (U7, U8, U10, and U12 steel) [1, 2]. The structural state of the steel, determined by its carbon content and the heat treatment, ensures that specific mechanical properties are assigned to the product. In particular, the steel structure determines its strength σ_u, which is the maximum load applied to the sample without failure [2, 3]. However, measurement of σ_u irreversibly destroys the part. Information regarding σ_u for a useful product may only be obtained by nondestructive methods [4, 5]. Magnetic methods are most effective. The magnetic parameter most sensitive to structural changes is the coercive force H_c, which is the magnetic field strength required to change the magnetization from the residual value to zero [6]. With increase in σ_u, the coercive force H_c of carbon steel also increases [4, 7]. However, no reliable analytical relation between σ_u and H_c has been established for carbon steel. That reduces the potential for nondestructive monitoring of carbon steel components.

In the present work, we develop a formula relating H_c and σ_u for carbon steel and assess the reliability of nondestructive monitoring of carbon steel components on the basis of H_c.

To that end, we analyze the experimental relation between σ_u and the hardness for carbon steel; this relation has been expressed in tabular form. (By the hardness of the steel, we mean its ability to resist plastic deformation in surface contact.) The hardness of heat-treated steel with a nonground surface is most often expressed in terms of the Brinell or Rockwell hardness [8, 9]. To determine the Brinell hardness *HB* of steel, a solid steel ball (diameter $D = 10$ mm) is forced into a plane metal surface under constant load $P = 29.42$ kN. After the load is removed, an indentation (diameter *d*) remains in the metal. The hardness *HB* is determined from the formula

$$HB = \frac{2P}{\pi D\left(D - \sqrt{D^2 - d^2}\right)}. \tag{1}$$

The Rockwell hardness (scale C) is determined from the depth *h* of the impression left in the metal by a diamond cone (vertex angle 120°). The cone is first inserted to a depth h_0 by a preliminary load of 98.07 B and then to a depth *h* under a total load of 1.471 kN. The Rockwell hardness *HRC* is determined from the formula

$$HRC = 100 - \frac{h - h_0}{0.002}. \tag{2}$$

Because of the different treatment conditions, well-founded analytical relations between the *HB* and *HRC* hardness values cannot be derived. Likewise, they cannot be satisfactorily related to σ_u. The Brinell hardness cannot be precisely converted to other measures of the hardness or the tensile stress, as noted in [8]. However, practical experience permits the formulation of relations between the experimental values of σ_u and the hardness (*HB*, HRC, and other measures) in tabular form; for example, see [10–14]. However, these tabular relations do not provide any physical understanding of the relationships and are inexpedient for practical use. To make matters worse, there are significant inconsistencies between the tabular data in different sources [10–14]. For example, the relations between *d* and *HB* are not the same in [8, 13]. There are even discrepancies between the values given in the

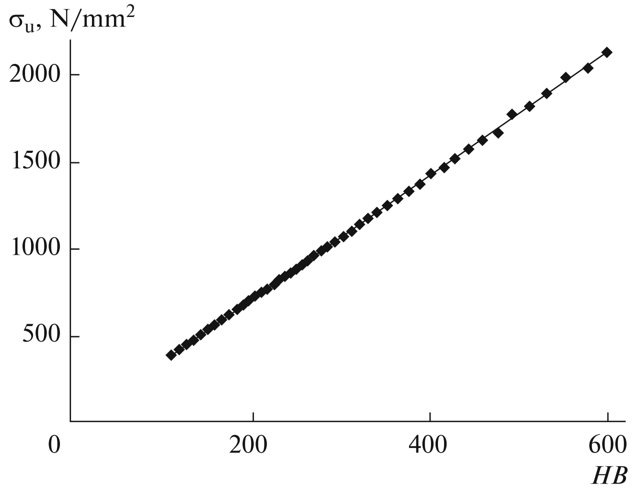

Fig. 1. Correlation between σ_u and the hardness *HB* for carbon steel according to [10]; the straight line corresponds to Eq. (3).

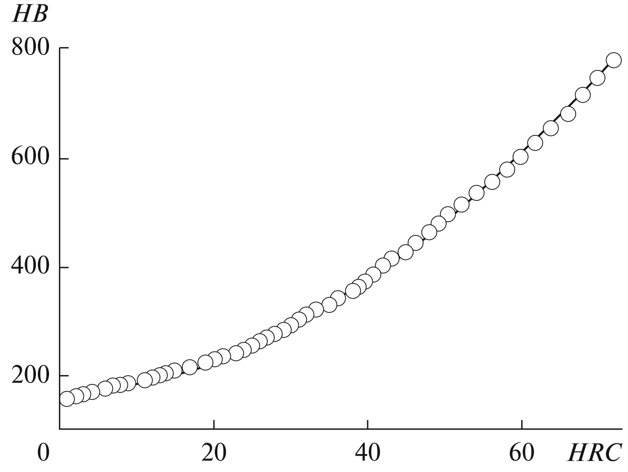

Fig. 2. Relation between the *HB* and *HRC* hardness values for steel. The points correspond to [10]; the curve corresponds to Eq. (5).

frequently updated handbook [10]: the *HB* values when $d = 2.8$ and 4.5 mm (Table 15.8) and when $d = 2.4$ mm (Table 15.11) do not agree, as pointed out in [8]. The precision of the tabular function *HB*(*HRC*) is also reduced by the discreteness of the *HRC* values. That leads to different *HB* values for the same *HRC* value [13, 14]; this is physically impossible.

To establish an analytical relation of σ_u and *HB* for carbon steel, we use the data in [10]. The discrepancies noted between the *HB* and *d* values in [10] are handled in accordance with [8, Appendix 3, Table 1]. In Fig. 1, we show the correlation between σ_u and *HRC* for carbon steel according to [10, Table 15.8]. The results show that the relationship between σ_u and *HB* for carbon steel may be approximated by a straight line

$$\sigma_u \approx 3.5307\tau HB, \tag{3}$$

where τ is a dimensional factor: $\tau = 10$ N/mm^2.

The mean discrepancy $\bar{\delta}$ between the values σ_{uci} calculated from Eq. (3) and *n* corresponding measured values σ_{ui}(table) from Table 15.8 in [10] is calculated from the formula

$$\bar{\delta} = \frac{100\%}{n}\sum_{i=1}^{n}\frac{|\sigma_{uci} - \sigma_{ui}(\text{table})|}{\sigma_{ui}(\text{table})}. \tag{4}$$

The reliability of the approximation $R^2 \approx 0.9999$. The result $\bar{\delta} \approx 0.377\%$ shows that the relative deviation between the values calculated from Eq. (3) and the measured σ_u values for carbon steel is 5–10 times less than the discreteness (2–4%) in the σ_u values due to discreteness in the *HB* value with 0.05 mm increments in *d* [8]. That permits the use of the measured *HB* values for carbon steel to estimate σ_u from Eq. (3).

However, many measurements of the magnetic properties and hardness of steel after heat treatment are based on the Rockwell scale *HRC* [15, 16]. We now establish an analytical relation between the *HRC* and *HB* values, on the basis of the data in Table 15.11 of [10]. In that table, the *HB* and *d* values are presented accordance with [8, Appendix 3, Table 1]. In this table, which has been repeatedly updated, in contrast to other sources, the numerical values of *HRC* vary monotonically with *HB*, and all possible values of *HRC* (1–72) are covered.

In Fig. 2, we show the dependence of *HB* on *HRC* according to [10]. In the range $9 \le HRC \le 72$, the following function best meets the conditions of simple interpolation and precise approximation of the data from [10, Table 15.11]

$$HB \approx 0.28HRC^{1.8} + 163. \tag{5}$$

In Fig. 3, we show the correlation between the results *HB*(calc) calculated from Eq. (5) and the *HB*(table) data in [10, Table 15.11] for steel with known *HRC*.

When $9 \le HRC \le 72$, the statistical parameters of the relation

$$HB(\text{table}) = HB(\text{calc}), \tag{6}$$

are as follows: $R^2 \approx 0.9987$ and $\bar{\delta} \approx 1.63\%$.

Analysis of the results shows that the mean deviation of the *HB* values given by Eq. (5) from the classical tabular values is less than *HB* 5, which is 1.63% of the total *HB* value. That is about a third of the error in standard measurements of *HB* [12]. A considerable proportion of the relative error in the *HB* value from Eq. (5) is due to the imprecise representation of the relation between *HB* and *HRC* by Eq. (5) for the steel and also the discreteness in the *HRC* data given in [5,

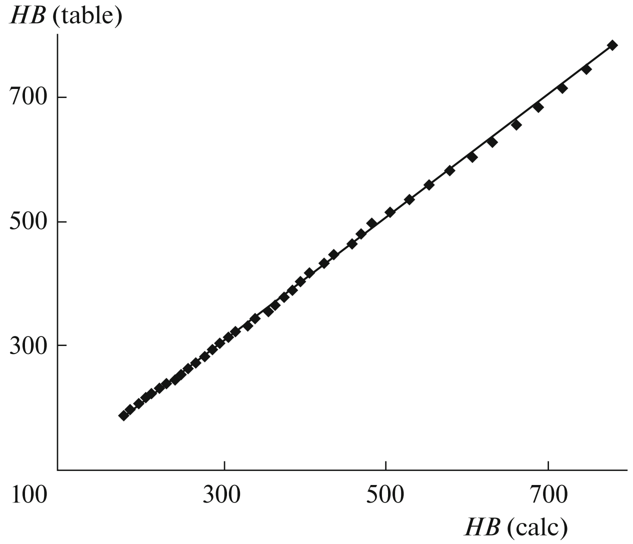

Fig. 3. Correlation between the *HB*(calc) values given by Eq. (5) and *HB*(table) values from Table 15.11 in [10]; the straight line corresponds to Eq. (6).

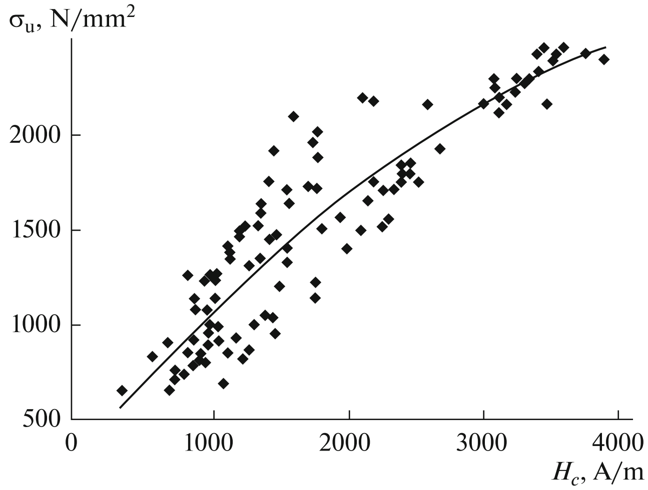

Fig. 4. Correlation between the measured coercive force H_c for 30, 35, 45, U8, U10, and U12 carbon steel with different heat treatments and the σ_u values calculated from Eq. (7) on the basis of *HRC* measurements; the curve corresponds to Eq. (8).

Table 15.11]. Accordingly, we may recommend Eq. (5) for the assessment of the hardness *HB* of steel from the known *HRC* values and for analysis of the relation between these two hardness scores, instead of the existing tables, which are inconvenient and relatively uninformative.

From Eqs. (5) and (3), it follows that for carbon steel

$$\sigma_u \approx \tau\left(0.9886HRC^{1.8} + 575.5\right). \tag{7}$$

The coercive force H_c of ferromagnetic components is the only magnetic parameter that may be measured in an open magnetic system [15]. To plot the correlation between H_c and σ_u for carbon steel , we use measurements of H_c and *HRC* for 30, 35, 45, U8, U10, and U12 steel after quenching and tempering at different temperatures [16, 17]. The σ_u values for the carbon steel are calculated from Eq. (7). In all, we use measurements of H_c and *HRC* for 110 carbon steels with different heat treatment [16, Fig. 21; 17, Tables 1.1, 2.1, 2.2, 2.2, 3.1, 4.1–4.3, 5.1, 5.2, and 6.1].

In Fig. 4, We show the correlation between H_c measurements for the carbon steels and their σ_u values calculated from Eq. (7) on the basis of *HRC* values. These results correspond to a polynomial curve

$$\sigma_u \approx \tau\left[293.3 + 852.1\gamma H_c - 80(\gamma H_c)^2\right], \tag{8}$$

where γ is a dimensional factor: $\gamma = 1$ m/kA.

On the basis of Eq. (8), σ_u may be calculated from H_c measurements. We may assume a very close correlation between these physical quantities when $|R| > 0.7$ [18]. In fact, the correlation coefficient between the σ_u values calculated from Eq. (8) and values obtained in destructive tests is high: $R = 0.9125$. Hence, given the small mean relative error in determining σ_u from Eq. (8) ($\bar{\delta} \approx 13.6\%$), we may recommend the use of Eq. (8) in the nondestructive assessment of σ_u for carbon steel components on the basis of H_c data.

For example, the coercive force H_c of cold-worked carbon steel 20 is 624 ± 40 A/m, according to [7, Table 3]. The range of σ_u for this steel is estimated at 736–834 N/mm^2. Calculation from Eq. (8) gives practically the same possible range of σ_u for steel 20: 766–826 N/mm^2.

CONCLUSIONS

(1) We have established the constant of proportionality between the strength σ_u and hardness *HB* in Eq. (3) for carbon steel. The relation between the hardness scores *HB* and *HRC* of carbon steel is given in Eq. (5). This relationship is physically correct and precise for practical purposes over the realistic range of hardness values for structural steel. On the basis of Eqs. (3) and (5), we have established the relation between the strength σ_u and hardness *HRC* of carbon steel.

(2) Using Eq. (7) and measurements of the coercive force H_c and hardness *HRC* of 30, 35, 45, U8, U10, and U12 steel with different heat treatments, we have established the correlation between H_c and σ_u for carbon steel. By means of Eq. (8), nondestructive assessment of σ_u for carbon steel is possible on the basis of H_c measurements, with a mean relative error of 13.6%.

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