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National Standard of the People's Republic of China

GB/T 37782—2019

Metallic materials — Indentation test — Determination of strength, hardness and stress-strain curve

金属材料 压入试验 强度、硬度和应力-应变曲线的测定

(English Translation)

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Contents

Foreword

SAC/TC 183 is in charge of this English translation. In case of any doubt about the contents of English translation, the Chinese original shall be considered authoritative.

This standard is drafted in accordance with the rules given in the GB/T 1.1-2009.

This standard was proposed by China Iron and Steel Association.

This standard was prepared by SAC/TC 183 (Technical Committee on Steel of Standardization Committee of China).

Introduction

By continuous recording the force and depth, instrumented indentation test facilitates the determination of material parameters such as hardness and elastic modulus of metallic materials. However, the methods described in the current national and international standards cannot be used to determine stress-strain curves. This standard has been prepared to enable user to effectively characterize the stress-strain curve within the stage of uniform deformation using instrumented indentation test [1-3]. This standard also covers the principle, test procedure and data processing, in order to achieve the following goals:

— the proposed method provides the users the necessary model to process the indentation force/depth curves, in order to obtain the elastic modulus, tensile strength, hardness and stress-strain curve of test pieces;

—the proposed method allows the conversion between Brinell, Rockwell and Vickers hardness;

—the proposed method allows the conversion between the tensile strength and Brinell, Rockwell and Vickers hardness;

This standard provides an indentation test method for determining elastic modulus, tensile strength, Rockwell hardness and stress-strain curve within the stage of uniform deformation of metallic materials.

Metallic materials — Indentation test - Determination of strength, hardness and stress-strain curve

1 Scope

This standard specifies the principle, equipment, test pieces, test conditions, test procedures, validation of test results and test report for the determination of elastic modulus, tensile strength, hardness and stress-strain curve of metallic materials based on the indentation method.

This standard is applicable to the determination of the elastic modulus, tensile strength, Rockwell hardness and stress-strain curve in the stage of uniform deformation of metallic materials that are homogeneous, isotropic and following power-law strain hardening. It is also applicable to the conversion between the tensile strength and hardness, as well as the conversion between values of Brinell hardness, Rockwell hardness and Vickers hardness.

NOTE When used to determine the stress-strain curve of a metallic material which shows obvious yielding platform or linear strain hardening, significant errors may be found in the obtained results.

2 Normative references

The following referenced documents are indispensable for the application of this standard. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

GB/T 228.1 Metallic materials — tensile testing — Part 1: Method of testing at room temperature

GB/T 7997 Hardmetals — Vickers hardness test

GB/T 10623 Metallic material — Mechanical testing — Vocabulary

GB/T 21838.1 Metallic materials — Instrumented indentation test for hardness and materials parameters — Part 1: Test method

GB/T 21838.2 Metallic materials — Instrumented indentation test for hardness and materials parameters — Part 2: Verification and calibration of testing machines

JJG 139 Tension, compression and universal testing machines

3 Terms and definitions

The following terms and definitions as defined in GB/T 10623, GB/T 21838.1 and GB/T 21838.2

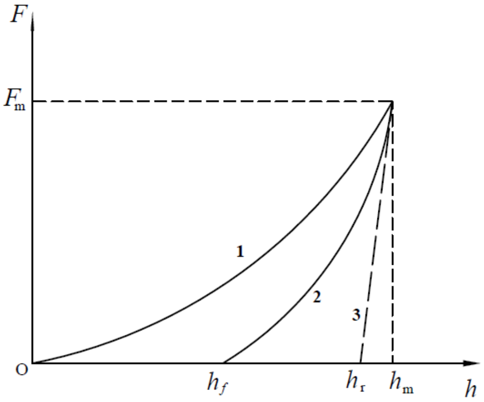
apply to this document.

3.1

force-depth curve

the curve obtained from the relationship between the force applied to the indenter and the depth at which the indenter is pressed vertically into the surface of the material

NOTE Force-depth curve is derived from the data collected during the loading-unloading process. A typical force/depth curve is shown in Figure 1.



Key

1 Loading curve

2 Unloading curve

3 Tangent at the maximum load of the unloading curve

Figure 1 — Schematic diagram of the force/depth curve of a typical spherical indentation test

3.2

referenced stress-strain curve

the stress-strain curve of the reference test piece is measured according to the tensile test method GB/T 228.1

3.3

zero point

the force/displacement/time reference point when the indenter first contacts the test piece and the force is nominally zero

NOTE A zero point is an approximate value used to determine the accurate indentation depth.

3.4

Hollomon model

a mathematical model used to describe the stress-strain curve relationship following the power-law strain hardening

3.5

goodness

it describes the agreement of the stress-strain test curves obtained experimently at different locations on the same test piece according to the method specified in this standard.

4 Symbols and designations

The symbols and designations used in this standard are given in Figure 1 and Table 1.

Table 1 — Symbols and designations

Symbol	Designation	Unit
A_c	effective projected area of contact of spherical indenter to the test piece	mm^2
C	fitting coefficient used in fitting the force-depth loading curve	—
D	spherical indenter diameter	mm
D_B	spherical indenter diameter used for Brinell hardness test	mm
D_R	spherical indenter diameter used for Rockwell hardness test	mm
d	the diameter of the residual indent after unloading	mm
E_I	elastic modulus of the test piece measured by indentation method	GPa
E_i	elastic modulus of the spherical indenter	GPa
F_B	test force for Brinell hardness determination	N
F_V	test force for Vickers hardness determination	N
F_m	maximum test force	N
F_{pr}	real initial force in the force-depth loading curve	N
F_t	main force for Rockwell hardness determination	N
F_0	initial force for Rockwell hardness determination	N
HR_I	Rockwell hardness measured by indentation method recommended in this standard	—
h	indentation depth under applied test force	mm
h_c	depth of the contact of the indenter with the test piece at F_m	mm
h_f	residual indentation depth after unloading	mm
h_m	maximum indentation loading depth allowed for determining the stress-strain curve	mm
h_{pr}	real initial depth in the force-depth loading curve	mm
h_r	the intercept of the tangent at the maximum force of the unloading curve and the depth axis (see Figure 1).	mm
h_{rc}	residual indentation depth at initial test force after removal of main test force when measuring the Rockwell hardness	mm
h_u	indentation depth at the beginning of each stage of unloading in a	mm

	multi-stage unloading test	
h_0	indentation depth corresponding to the zero force on the loading curve	mm
l	the average length of the indentation diagonal when measuring Vickers hardness	mm
m_1	fitting exponent of indentation test loading force-depth curve	—
m_2	fitting exponent of indentation test unloading force-depth curve	—
k	Rockwell hardness constant for a given scale	—
N	material hardening exponent in Hollomon model	—
R_{mI}	ultimate strength of material measured by indentation method	MPa
r_i	goodness of stress-strain test curve of the *ith* indentation point on the same test piece	—
S	contact stiffness	N/mm
ε	strain	—
v_{i}	Poisson's ratio of the indenter	—
v_{s}	Poisson's ratio of the test piece	—
σ	stress	MPa
σ_{s}	yield stress of the test piece	MPa
σ_{y}	reference yield stress in Hollomon model	MPa

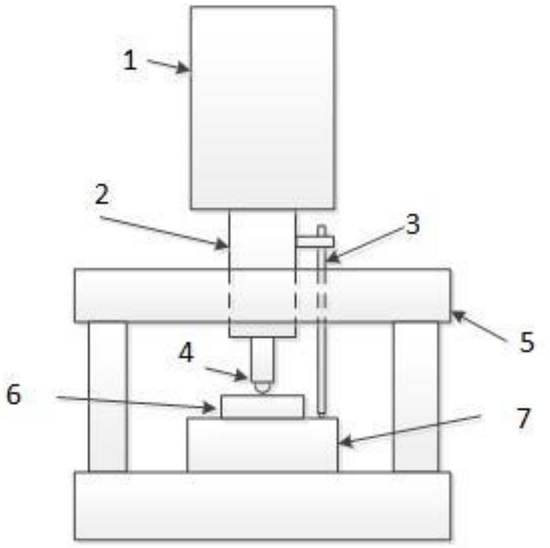
5 Principle

The typical force/depth test curve shown in Figure 1 is obtained by continuously recording the force and depth within an indentation cycle using a spherical indenter. The test piece elastic modulus E_{I} is determined from the unloading part of the force/depth curve. σ_y and N of the test piece are determined from the loading part of the force/depth curve. The stress-strain curve of the test piece is derived from the Hollomon model given in formular (1). The estimated tensile strength and hardness of the material could then be determined from the derived stress-strain curve.

$$\sigma=\begin{cases} E_I\varepsilon & (\sigma\le\sigma_y) \\ E_I^N\sigma_y^{1-N}\varepsilon^N & (\sigma>\sigma_y) \end{cases} \qquad \cdots\cdots\cdots(1)$$

6 Testing equipment

6.1 The testing equipment include driving unit, indenter, fixture, force, displacement applying and measuring devices, etc., which shall meet the requirements in Annex A. The structural schematic diagram of a typical indentation test machine is shown in Figure 2.



Key

1 Driving unit

2 Force measuring system

3 Displacement measuring system

4 Indenter

5 Frame

6 Test piece

7 Fixture

Figure 2 Structural schematic diagram of a typical indentation test machine

6.2 The driving unit shall have the capability of applying continuous test force to the test piece.

6.3 A spherical indenter made of hard metal alloy shall be used and the allowable indenter diameter is between 0.8 mm and 2 mm.

The indenter shall meet the following requirements:

—hardness: the hardness shall not be less than 1500HV10, measured in accordance with GB/T 7997.

—density: ρ = 14.8 g/cm^3 ±0.2 g/cm^3

—diameter tolerance: no more than 0.25 μm

—shape deviation: no more than 0.25 μm

—surface roughness: no more than 0.2 μm

The following chemical composition is recommended:

—cobalt content between 5.0% and 7.0%

—all carbides except tungsten carbide 2.0%

—the remaining should be tungsten carbide (WC)

The diameter of the indenter shall be measured at least three different positions. The difference between the measured diameter of the indenter and its nominal value shall not exceed ±0.0035 mm.

6.4 The fixture shall have the capability of fixing and adjusting the test piece position. Effort shall be made to avoid deforming and warping the test piece during the installation process. There shall be no relative movement between the test piece and the fixture affecting the indentation depth determination. The test piece surface shall be kept vertical to the axial direction of the indenter, meeting the requirements described in 9.1.

6.5 Test equipment shall have the capability of measuring test force and indentation depth. The resolution of the force determination system shall be less than 0.1 N and the accuracy shall be no less than class 0.5. The resolution of the displacement determination system shall be less than 0.1 μm and the accuracy within the determination range of 1 mm shall not be less than class 0.5.

6.6 Test equipment shall have the capability of collecting and storing indentation test data.

6.7 Test equipment shall be calibrated periodically in accordance with JJG 139.

6.8 Before the indentation test on the test piece, a routine inspection shall be performed using a reference test piece that meets the requirements described in Annex B according to the regulations set in Annex A.

7 Test piece

7.1 Unless otherwise specified in the product or material standards, the surface of the test piece shall be flat and smooth and there shall be no scale or foreign matter, especially grease. The surface of the test piece shall be in good conditions to ensure accurate determination of the indentation depth. Surface polishing process is recommended, to achieve a surface roughness better than Ra0.8μm.

7.2 The thickness of the test piece shall be large enough to ensure the test result is not affected by the fixture. The thickness of the test piece shall be at least 20 times of the indentation depth and there shall be no obvious deformation on the bottom side of the test piece after the test.

7.3 The upper and lower surfaces of the test piece shall be parallel and the parallelism shall be no more than 0.02 mm/50 mm.

8 Test conditions

8.1 Unless otherwise specified, the test is generally performed at ambient temperature between 10° C and 35° C. For the test with more restricted temperature requirement, the ambient temperature should be 23° C ± 5° C. The ambient temperature should keep stable during the test.

8.2 Environmental interferences such as shock and vibration can significantly affect the test results, hence shall be avoided.

9 Procedure

9.1 Test piece installation

The test piece shall be fixed in a suitable fixture and the region between the test piece and the fixture shall be free of debris. The test surface of the installed test piece shall be perpendicular to the direction of the test force.

9.2 The selection of indentation position

The distance between the center of any indentation and the edge of the test area shall not be less than 4.5 times the indentation diameter. The distance between the centers of neighbouring indentations shall not be less than 5 times the indentation diameter.

9.3 Test procedure

9.3.1 Selected indenter diameter should match the test piece material type. For light alloys, indenter diameter not less than 1.5875 mm is recommended. For common steels, indenter diameter not less than 1 mm is recommended.

9.3.2 Perform single loading and unloading testing cycle on the test piece. The loading shall be under displacement control and the displacement applying rate shall be kept between 1 μm/s and 5 μm/s. The unloading shall be under force control and the force removal rate shall be kept between 40 N/s and 100N/s.

9.3.3 Record continuously the test force F and depth h during the entire test. The relationship between the maximum indentation depth h_{m} and the indenter diameter D shall satisfy the requirement in formular (2):

$$\frac{h_{\mathrm{m}}}{D} \geq 0.04 \quad \text{..(2)}$$

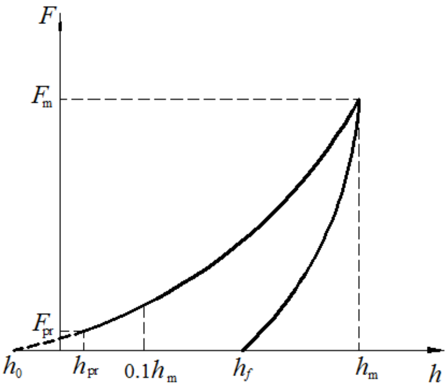
9.3.4 The first indentation test for each test piece is considered as a pre-test and shall not be included in the final test results. At least four effective indentation points shall be guaranteed for a valid test.

9.4 Data processing

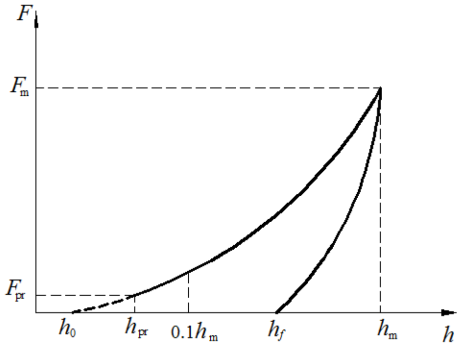
9.4.1 Determination of zero point

9.4.1.1 The zero point shall be assigned individually to each test. In order to effectively determine the zero point, enough data points should be collected within the initial 10% of the force-depth curve.

9.4.1.2 As shown in Figure 3, a quadratic polynomial is used to fit the data in the range of 0-10%h_{m}, then extrapolated to determine the zero point.



a) $h_0<0$



b) $h_0>0$

Figure 3 — Schematic diagram of zero point determination

9.4.1.3 When the zero point is determined by the above extrapolation method, the intercept of the extrapolation curve on indentation depth axis is defined as h_0.

9.4.1.4 Apply the zero point correction by shifting the force-depth test curve along the depth axis by h_0.

9.4.2 Determination of elastic modulus

The following steps are recommended to determine the elastic modulus:

a) apply the zero point correction, then fit the unloading force/depth curve:

$$F = B\left(h - h_f\right)^{m_1} \qquad (3)$$

where B and k are fitting parameters. The fitting range is selected between the beginning of unloading and a point on the unloading curve between 25% and 50%.

b) differentiate formular (3) at h_m, the contact stiffness S yields:

$$S = \left.\frac{dF}{dh}\right|_{h=h_\mathrm{m}} = Bk\left(h_\mathrm{m} - h_\mathrm{f}\right)^{m_1 - 1} \qquad (4)$$

c) calculate the contact depth h_c:

$$h_\mathrm{c} = h_\mathrm{m} - \eta \frac{F}{S} \qquad (5)$$

where η=0.75. The effective contact area A_c can be obtained when h_c is determined:

$$A_\mathrm{c} = \pi\left(Dh_\mathrm{c} - h_\mathrm{c}^2\right) \qquad (6)$$

d) calculate the reduced indentation modulus E_r:

$$E_{\mathrm{r}}=\frac{\sqrt{\pi}}{2\beta}\frac{S}{\sqrt{A_{\mathrm{c}}}} \qquad (7)$$

where, β is a parameter related to the material, geometric shape of the indenter and indentation depth and is determined by the Annex A.

e) calculate the elastic modulus E_I:

$$E_{\mathrm{I}}=\frac{1-\nu_{\mathrm{s}}^{2}}{\frac{1}{E_{\mathrm{r}}}-\frac{1-\nu_{\mathrm{i}}^{2}}{E_{\mathrm{i}}}} \qquad (8)$$

NOTE 1 If ν_s is unknown, published data can be referred. If there is no reference data, set ν_s=0.3.

NOTE 2 Annex C.1 depicts some examples of elastic modulus determination.

9.4.3 Determination of stress-strain curve

9.4.3.1 For a metallic material exhibiting a power-law strain hardening as described in formular (1), the elastic modulus E_I is initially determined according to the method described in 9.4.2, using the unloading part of the indentation force/depth curve after the zero point correction as shown in Figure 1.

9.4.3.2 In the range of $h/D \le 0.04$, the zero-point-corrected loading curve is fitted by:

$$F=Ch^{m_2} \qquad (9)$$

NOTE When $h/D > 0.04$, this fitting may lead to the convex of force-depth curve in the loading stage, which is not applicable to determine the plastic parameters of the material hence not covered by this standard.

9.4.3.3 When the fitting coefficient C and the exponent m is determined, the material plasticity parameters σ_y and N in formular (1) can be determined using the following iterative method:

a) set an arbitrary iterative initial value $\sigma_{y(i)}$ of the reference yield stress to obtain the reference yield strain using $\varepsilon_{y(i)}=\sigma_{y(i)}/E$, then substitute in formular (10) to obtain a hardening exponent $N_{(i)}$ and a new reference yield stress $\sigma_{y(i+1)}$.

$$\begin{cases} N_{(i)}=2m_c-2.2 \\ \sigma_{y(i+1)}=\left[\dfrac{C\left(1+N_{(i)}\right)}{6.88\left(1+m_c\right)\left(\dfrac{E}{5}\right)^{N_{(i)}}D^{2-m_2}}\right]^{\frac{1}{1-N_{(i)}}} \end{cases} \qquad (10)$$

where $m_c=\left(b_1\varepsilon_{y(i)}^{2}+b_2\varepsilon_{y(i)}+b_3\right)\left(m_2-b_4\right)+b_5$, the values of b_1-b_5 are shown in Table 2.

Table 2 — The values of parameters b_1-b_5

Material Range	b_1	b_2	b_3	b_4	b_5
E≤120GPa	-3928	127.7	0.6528	1.444	1.457
E>120GPa	6243	75.91	0.7040	1.454	1.453

b) if $\left|\frac{\sigma_{y(i+1)}-\sigma_{y(i)}}{\sigma_{y(i)}}\right| \le 0.002$, $\sigma_{y(\mathrm{i})}$ and the hardening index $N_{(\mathrm{i})}$ are taken as the plastic parameters of the material; if $\left|\frac{\sigma_{y(i+1)}-\sigma_{y(i)}}{\sigma_{y(i)}}\right| > 0.002$, $\sigma_{y(\mathrm{i+1})}$ is taken as the new iteration initial value and the iterative calculation step a) is repeated until $\left|\frac{\sigma_{y(i+1)}-\sigma_{y(i)}}{\sigma_{y(i)}}\right| \le 0.002$ is satisfied. The iterative calculation is then terminated.

c) after the elastic modulus E_{I} and the plastic parameters (σ_y and N) are determined, the stress-strain curve can be derived according to formular (1).

NOTE Annex C.2 depicts some examples of stress-strain curve determination.

9.4.4 Determination of tensile strength

The tensile strength R_{mI} is calculated by:

$$R_{\mathrm{mI}} = E_I^N \sigma_y^{1-N} \left(\frac{N}{e}\right)^N \quad \cdots\cdots(11)$$

where e is the natural constant.

NOTE Annex C.3 depicts some examples of tensile strength determination.

9.4.5 Determination of Rockwell hardness

The Rockwell hardness is calculated by:

$$HR_{\mathrm{I}} = 0.91996k - 459.98\frac{F_t^{1/m_2} - F_0^{1/m_2}}{C^{1/m_2}} + 11.803 \quad \text{(Spherical scale: B, E, F, G, H, K)}\cdots\cdots(12)$$

where k=130, F_0=98.07 N and the parameter F_{t} is shown in Table 3.

NOTE Annex C.4 depicts some examples of Rockwell hardness determination.

Table 3 — Related parameters of Rockwell hardness at different scales

Scale	F_t(N)
HRB	980.7
HRE	980.7
HRF	588.4
HRG	1471
HRH	588.4
HRK	1471

9.4.6 Conversion between different hardness scales

9.4.6.1 Brinell hardness HBW and Rockwell hardness HR (spherical scale: B, F) can be converted by:

$$\mathrm{HBW}=\frac{\alpha_{11}\left(\alpha_{12}^{1/m_2}-\alpha_{13}^{1/m_2}\right)}{k-\mathrm{HR}} \qquad \text{......................................(13)}$$

where α_{11}, α_{12} and α_{13} are constants, as shown in Table 4.

Table 4 — Values of constant parameters used in hardness scale conversion formulars

Hardness symbol	α_{11}	α_{12}	α_{13}	/
HBW10/3000–HRB	7580	0.1322	0.1322	/
HBW10/500–HRB	1263	7.934	0.7934	/
HBW10/500–HRF	1263	4.759	0.7934	/
Hardness symbol	α_{21}	α_{22}	α_{23}	α_{24}
HBW10/3000–HV	25.42	0.02768	0.1578	0.0575
HBW10/500–HV	4.236	0.1661	0.1578	0.0575
Hardness symbol	α_{31}	α_{32}	α_{33}	α_{34}
HR–HV	298.2	0.0575	20.52	0.1578

9.4.6.2 Brinell hardness HBW and Vickers hardness HV can be converted by:

$$\mathrm{HBW}=\frac{\alpha_{21}\left[\alpha_{22}\alpha_{23}^{N}\left(1+m\right)\right]^{1/m_2}}{\alpha_{24}^{N}}\left(\frac{E^{N}\sigma_y^{1-N}}{1+N}\right)^{1/m_2-1}\mathrm{HV} \qquad \text{....................(14)}$$

where α_{21}, α_{22}, α_{23} and α_{24} are constants, as shown in Table 4.

9.4.6.3 Rockwell hardness HR spherical scale (B, E, F, G, H, K, etc.) and Vickers hardness HV can be converted by:

$$\mathrm{HV}=\frac{\alpha_{31}\alpha_{32}^{N}\left(F_t^{1/m_2}-F_0^{1/m_2}\right)}{\left[\alpha_{33}\alpha_{34}^{N}\left(1+m_2\right)\right]^{1/m_2}\left(k-\mathrm{HR}\right)}\left(\frac{E^{N}\sigma_y^{1-N}}{1+N}\right)^{1-1/m_2}\quad\cdots\cdots\cdots\cdots(15)$$

where $\alpha_{31}, \alpha_{32}, \alpha_{33}$ and α_{34} are constants, as shown in Table 4.

NOTE Annex C.5 depicts some examples of the conversion between different hardness scales.

9.4.7 Conversion between hardness and tensile strength

9.4.7.1 Brinell hardness and tensile strength can be converted by:

$$\mathrm{HBW}=\frac{\eta F_{\mathrm{B}}^{1-1/m_2}[\beta_{11}(e\beta_{12}/N)^{N}(1+m)D_{\mathrm{B}}^{2-m_2}R_{\mathrm{m}}]^{1/m_2}}{\pi D_{\mathrm{B}}(1+N)^{1/m_2}}\quad\cdots\cdots\cdots\cdots(16)$$

where η=0.102, e is the natural constant, β_{11}=8.142, β_{12}=0.1578.

9.4.7.2 Rockwell hardness and tensile strength can be converted by:

$$\mathrm{HR}=k-\frac{(F_{\mathrm{t}}^{1/m_2}-F_0^{1/m_2})[\beta_{11}(e\beta_{12}/N)^{N}(1+m)D_{\mathrm{R}}^{2-m_2}R_{\mathrm{m}}]^{-1/m_2}}{S(1+N)^{-1/m_2}}\quad\text{(Spherical scale: B, E, F,etc.)}\ldots(17)$$

9.4.7.3 Vickers hardness and tensile strength can be converted by:

$$\mathrm{HV}=\frac{2\eta\beta_{21}(e\beta_{22}/N)^{N}R_{\mathrm{m}}\sin\frac{\theta}{2}}{1+N}\quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(18)$$

where β_{21}=1.986 and β_{22}=0.05753.

NOTE Annex C.6 depicts some examples of the conversion between hardness and tensile strength.

10 Test results validation

10.1 It is recommended that n (n≥4) valid indentation points from the same test piece should be collected, according to the requirements described in 9.2. As a result, n stress-strain test curves can be obtained.

10.2 The calculated stress-strain curves of each indentation point are discretized into w (w≥20) points using the same interval of strain in the same strain range and the stress-strain data ($\sigma_{j,i}$, $\varepsilon_{j,i}$)(i=1,2,…,n, j=1,2,…,w) is obtained.

10.3 Calculate the mean of the stress $\sigma_{j,\mathrm{mean}}$ at the same strain level ε_j by:

$$\sigma_{j,mean}=\frac{1}{n}\sum_{i=1}^{n}\sigma_{j,i}\quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(19)$$

10.4 Calculate the goodness r_i[4] of the measured stress-strain curve of each indentation point by:

$$r_i = 1 - \sqrt{\frac{\sum_{j=1}^{w}\left(\sigma_{j,i} - \sigma_{j,mean}\right)^2}{\sum_{j=1}^{w}\sigma_{j,i}^2}} \quad \text{……(20)}$$

10.5 When the goodness r_i of all the measured stress-strain curves of n indentation points are not less than 0.95, the test results are considered as valid results. The averaged stress-strain curves of n indentation points is taken as the test result.

10.6 When the goodness r is lower than 0.95, a single stress-strain curve obviously deviates from the test of the curves should be replace by a new indentation data point (see Figure 4). If the goodness including the new data point meets the requirement as described in 10.5, the obtained stress-strain curve is considered as valid; otherwise, the test results are considered as invalid.

10.7 When the goodness r is lower than 0.95 and the stress-strain curves obtained from $n(n\geq4)$ indentation points from the same test piece show relatively large scattering as shown in Figure 5, the test results are considered as invalid.

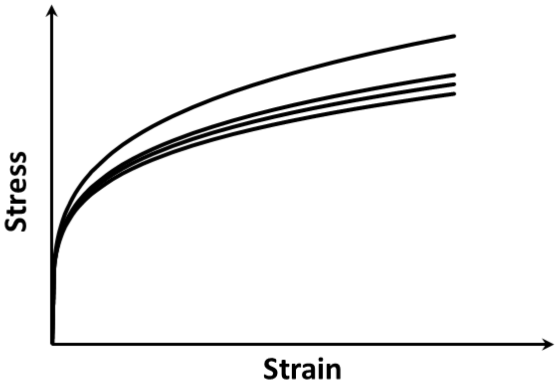


Figure 4 — Example of stress-strain test result deviation

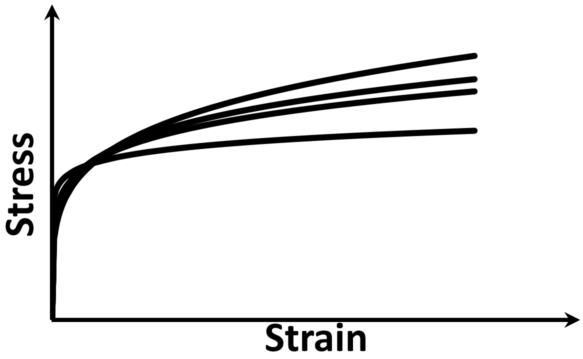


Figure 5 — Example of invalid stress-strain test result

11 Report

The report shall include at least the following information:

a) reference to this standard;

b) test conditions;

c) material type and grade;

d) test piece identification;

e) abnormal behaviour during the test;

f) results obtained.

Annex A
(normative)
Routine inspection of test equipment

A.1 General

A. 1.1 Inspection shall be performed on a regular basis. The equipment shall be inspected before test.

A. 1.2 Routine inspection should be performed at 23° C ± 5° C, using the reference test piece specified in Annex B. If the inspection is performed outside this temperature range, it shall be included in the inspection report.

A.2 Method

A.2.1 The calibration of the parameter β required in the determination of the elastic modulus described in Section 9.4.2 shall be performed first as described in following the steps:

a) perform a multi-stage loading and unloading test on a single indentation point of the reference test piece and adjust the β value according to the method described in Section 9.4.2 so that the indentation elastic modulus calculated using formular (8) coincides with the given elastic modulus of the reference test piece, thereby obtaining a relationship between β and h_u/D.

b) fit the relationship between β and h_u/D:

$$\beta = k_0 + k_1\left(\frac{h_u}{D}\right) + k_2\left(\frac{h_u}{D}\right)^2 \quad \text{......}(A.1)$$

A.2.2 The procedure for routine inspection is performed as follows:

a) select three indentation points on the reference test piece to perform loading and unloading indentation tests and obtain the zero-point-corrected force/depth curve according to the method described in Section 9.4.1.

b) determine the Hollomon model parameters σ_{yi}, $N_i(i=1,2,3,4)$ of the three indentation points of the reference test piece based on Section 9.4.2 and 9.4.3 and obtain the measured stress-strain curves of the three indentation points of the reference test piece according to formular (1).

c) discretize the stress-strain determination curves of the three indentation points into $w(w\geq 20)$ points using the same interval of strain in the same strain range and obtain the stress-strain data $(\sigma_{j,i}, \varepsilon_{j,i})(i=1,2,3, j=1,2,\ldots,w)$. Discretize the reference stress-strain curves of the reference test piece into w data points according to the same rule and obtain the stress-strain data $(\sigma_j, \varepsilon_j)$.

d) calculate the goodness r_i[4] of the measured stress-strain curve of each indentation point by:

$$r_i = 1 - \sqrt{\frac{\sum_{j=1}^{w}\left(\sigma_{j,i} - \sigma_j\right)^2}{\sum_{j=1}^{w}\sigma_{j,i}^2}} \quad \text{......}(A.2)$$

In this case, σ_j is the stress value corresponding to the strain level ε_j of the reference stress-strain curve. $\sigma_{j,i}$ is the stress value corresponding to the strain level ε_j of the stress-strain curves for the three indentation points.

e) when the goodness r_i of the stress-strain curves of the three indentation points exceeds 0.95, it is considered that the overall performance of the test equipment satisfies the requirement.

A.2.3 When the routine inspection result do not meet the requirements, the cause should be examined according to the manufacturer's equipment troubleshooting guide. If the results still do not meet the requirements, the routine inspection fails.

Annex B
(normative)
Reference test piece

B.1 General

B.1.1 Each reference test piece shall have a reference stress-strain curve obtained from tensile test.

B.1.2 For each reference test piece, the applicable range of depth or force shall be specified.

The range of the indentation force is restricted by the test piece's properties. For example, a brittle test piece will crack if the indentation force exceeds a certain threshold value. When the indentation force is less than a certain value, the surface roughness or micro-scale inhomogeneity will cause scattering results.

B.2 Material selection

The selection of reference materials shall consider the chemical and mechanical homogeneity, stable surface condition and no significant viscosity. The tensile stress-strain behaviour can be strictly described by Hollomon model represented in formular (1).

B.3 Machining

B.3.1 The thickness of the reference test piece shall be not less than 2 mm, or 20 times the maximum indentation depth, whichever is bigger.

B.3.2 The parallelism of the upper and lower surfaces of the reference test piece shall be no less than 0.02 mm/50 mm.

B.3.3 The test surface of the reference test piece shall have no defects (such as dents, scratches, scales, etc.) that could significantly affect the indentation depth determination. The test surface shall be as smooth as possible with surface roughness better than R_a0.8.

B.3.4 The machining of the reference test piece shall be performed in a manner that minimizes the influence on its surface properties, to ensure the surface properties of the test piece obtained by the indentation test method as representative of the overall performance of the test piece.

B.3.5 The reference test piece shall be marked at the appropriate location.

B.4 Value determination

B.4.1 Perform the required mechanical tests on the reference test piece and provide the key results.

B.4.2 The method specified in GB/T 228.1 is recommended to perform tensile tests on the reference test piece material. The obtained tensile stress-strain curve is used as the reference stress-strain curve.

B.4.3 The reference test piece report shall contain the following information:

a) reference this Annex of the standard;
b) the date of the value obtained;
c) information about institution performed the tests;
d) information of equipment and method including treacibility ;

e) the values of the Hollomon model parameters E, σ_y, N used to describe the stress-strain curve.

f) the serial number of the reference test piece.

Annex C

(Informative)

Indentation test examples of strength, hardness and stress-strain curve determination

C.1 Examples of stress-strain curve determination

Figure C.1—Figure C.3 presents the indentation test stress-strain curves of various metallic materials.

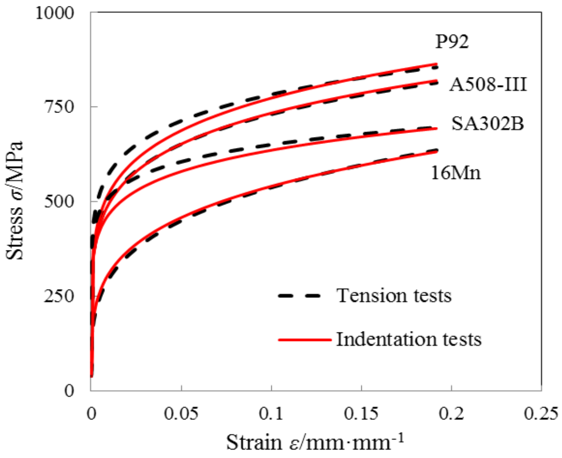


Figure C.1 — Stress-strain curve examples for P92, A508-III, SA302B and 16Mn

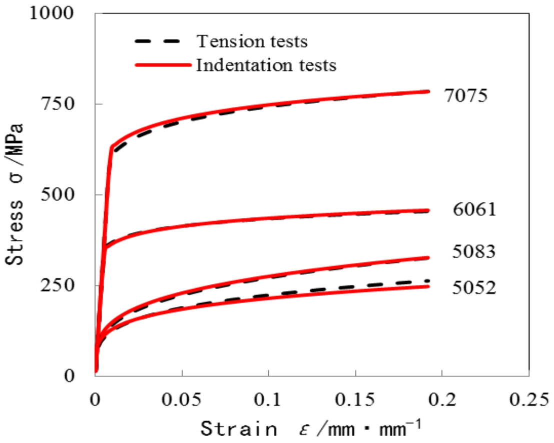


Figure C.2 — Stress-strain curve examples for 7075, 6061, 5083 and 5052 aluminum alloys

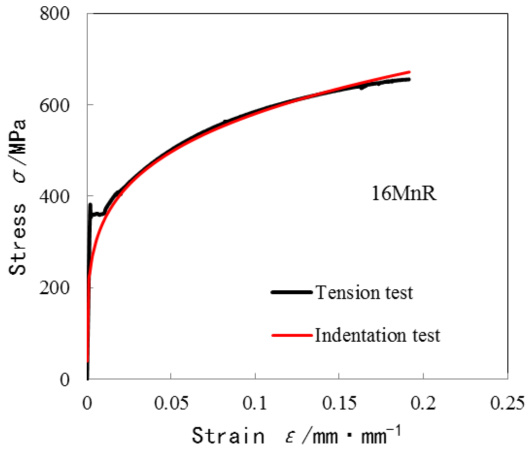


Figure C.3-Stress-strain curve example for 16MnR

C.2 Examples of measured elastic modulus

Table C.1 presents the measured elastic modulus of various metallic materials.

Table C.1 — Examples of elastic modulus measured by indentation and tensile tests

Materials	Modulus measured by indentation /GPa	Modulus measured by tension /GPa	Relative error *e*/%
16Mn	208.9	214.5	-2.6
A508-III	208.3	210.4	-1.0
316L	192.3	195.0	-1.4
1Cr12Mo	194.7	200.3	-2.8
SA302B	221.8	221.4	0.2
316H	212.4	212.1	0.1
5083 Aluminum alloy	69.7	70.3	-0.8
6061 Aluminum alloy	72.1	71.0	1.6
7075 Aluminum alloy	72.3	73.0	-0.9
7050 Aluminum alloy	71.6	72.7	-1.5
5052 Aluminum alloy	70.7	69.5	1.8
T2	107.9	109.5	-1.5
TA17	107.3	110.2	-2.6

C.3 Examples of tensile strength determination

Table C.2 presents the measured tensile strength of various metallic materials.

Table C.2 — Examples of tensile strength measured by indentation and tensile tests

Material	Tensile strength measured by tension /MPa	Tensile strength measured by indentation /MPa	Relative error *e*/%
T91	833	810	2.8
9Ni	751	798	-5.9
16Mn	521	522	-0.2
P92	769	721	6.7
SA302B	601	592	1.5
5083 Aluminum alloy	270	284	-4.9
6061 Aluminum alloy	402	394	2.0
7075 Aluminum alloy	683	678	0.7
5052 Aluminum alloy	197	203	-3.0
16MnR	556	552	0.7

C.4 Examples of Rockwell hardness tests

Table C.3 presents the measured Rockwell hardness of various metallic materials.

Table C.3 — Examples of Rockwell hardness HRB measured by indentation tests

Material	Rockwell hardness test result	Indentation test prediction result	Relative error *e*/%
16Mn	79.1	81.5	3.1
P92	95.4	96.5	1.1
A508-III	93.4	93.4	0
3Cr13	84.9	87.9	3.5
60Si2Mn	101.0	99.2	1.8
A302B	90.0	92.1	2.3
5083 Aluminum alloy	37.6	36.1	3.9
2024 Aluminum alloy	79.1	77.2	2.4
T91	102.6	101.2	1.4

7050 Aluminum alloy	86.9	88.7	2.0
16MnR	86.1	84.1	2.2

C.5 Examples of conversion between different hardness scales

Figure C.4–Figure C.11 introduced the conversion results between different hardness scales for various metallic materials.

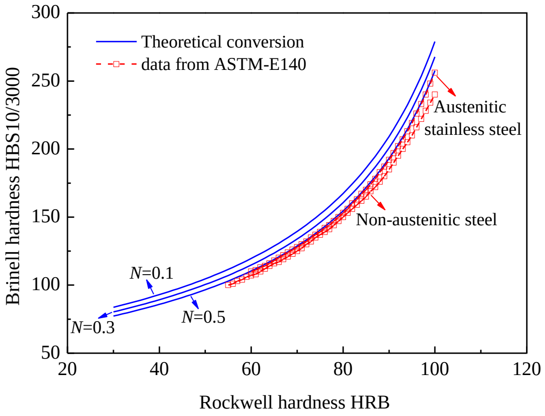


Figure C.4 — Example of steel HBW10/3000 and HRB conversion

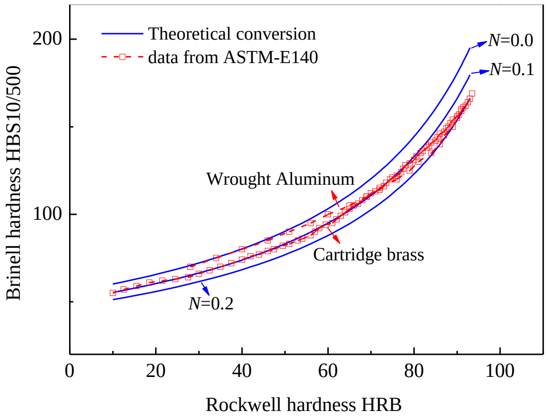


Figure C.5 — Example of HBW10/500 and HRB conversion of wrought aluminium and brass

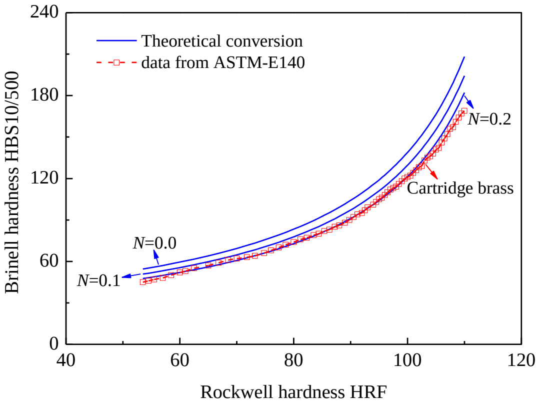


Figure C.6 — Example of brass HBW10/500 and HRF conversion

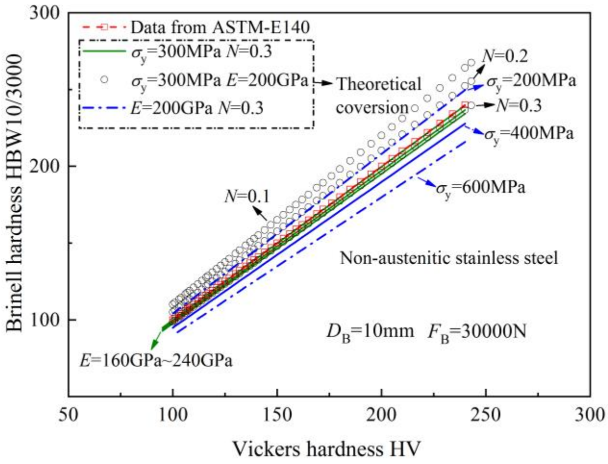


Figure C.7 — Example of non-austenitic steel HBW10/3000 and HV conversion

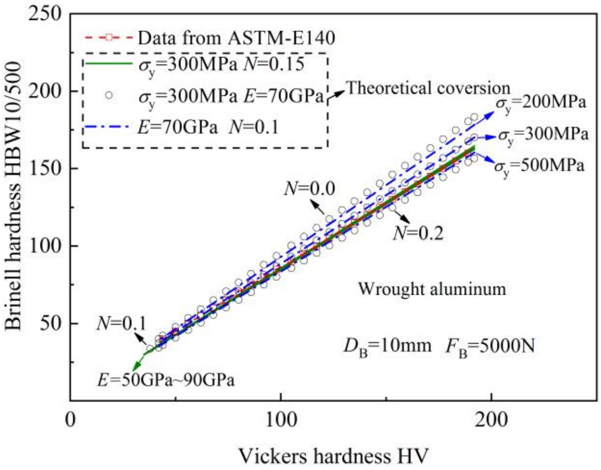


Figure C.8 — Example of wrought aluminum HBW10/500 and HV conversion

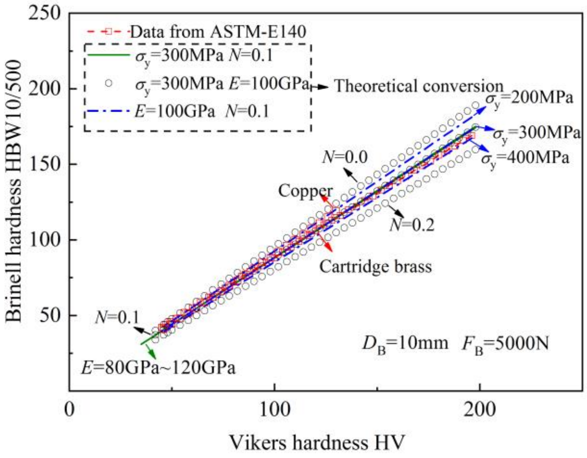


Figure C.9 — Example of brass HBW10/500 and HV conversion

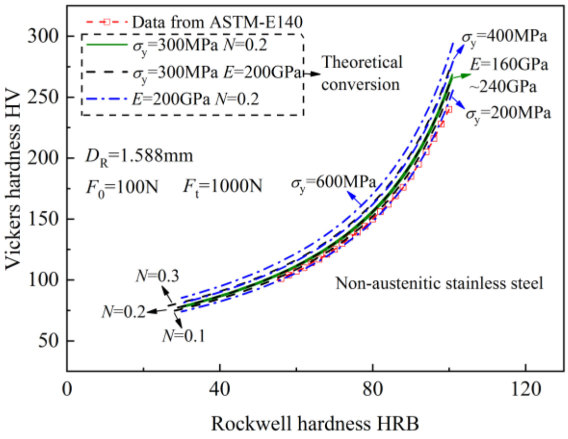


Figure C.10 — Example of steel HV and HRB conversion

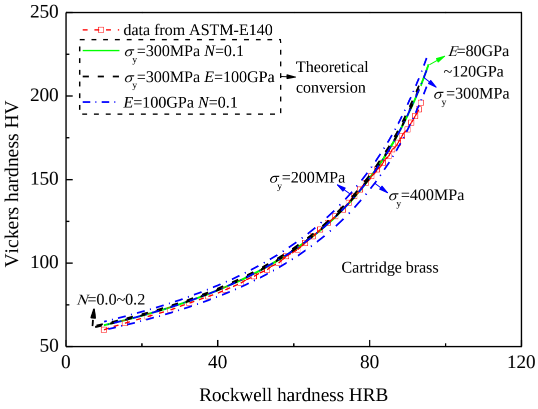


Figure C.11 — Example of brass HV and HRB conversion

C.6 Examples of conversion between tensile strength and different hardness scales

Figure C.12–Figure C.14 presents the conversion results between different hardness scales of various metallic materials.

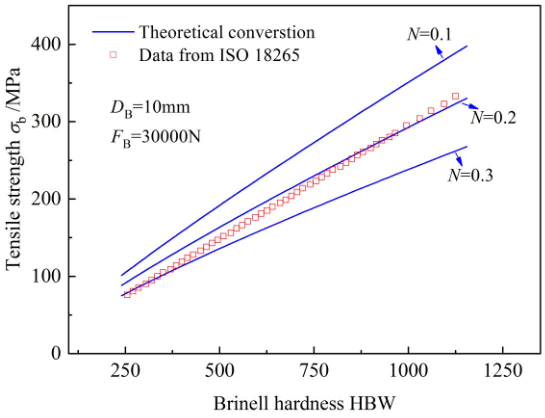


Figure C.12 — Example of tensile strength and HBW conversion

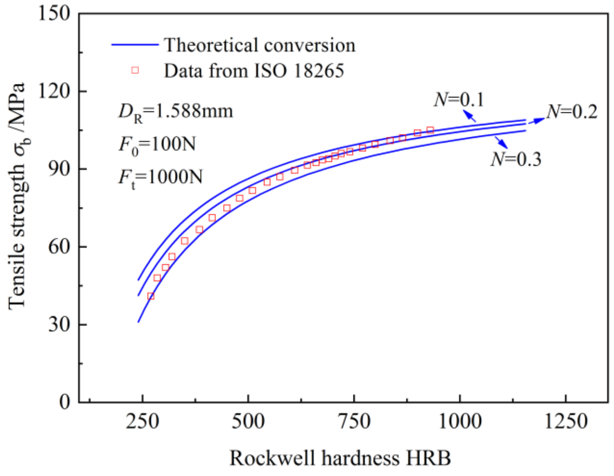


Figure C.13 — Example of tensile strength and HRB conversion

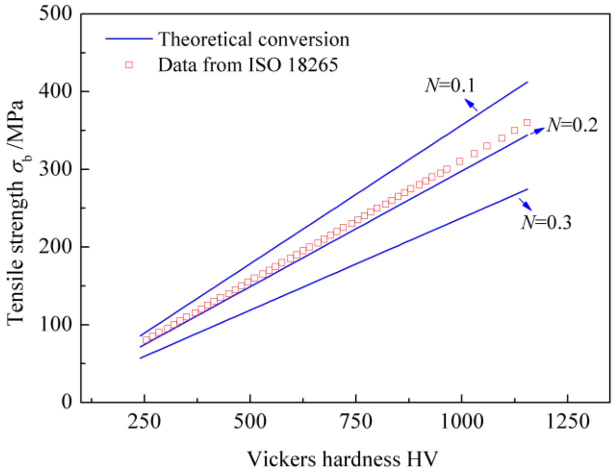


Figure C.14 — Example of tensile strength and HV conversion

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