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Rolling bearings — Ceramic bearing balls — Determination of strength by notched ball test

Roulements — Billes en céramique — Détermination de la résistance par test sur bille rainurée

Reference number
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Foreword

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This document was prepared by Technical Committee ISO/TC 4, *Rolling bearings*, Subcommittee SC 12, *Ball bearings.*

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

To determine the strength of components, specially prepared test pieces are usually produced and then tested in flexure.

The transfer of the values measured on standard ceramic bending test pieces to the original components is possible only in some limited cases.

Since the surface finish of the ceramic balls should not be modified, the notched ball test may be successfully applied as a component test for quality control. Moreover, influences of the manufacturing process and service can be quantified.

This testing method is applicable to process and material development, quality assurance, materials characterization and selection, and the determination of design parameters. The measured strength is determined under the following conditions:

a) linear-elastic material behaviour (stress-strain relation);

b) homogeneous and isotropic material behaviour.

This testing method is intended to be conducted at a laboratory using precise processing equipment, measurement device and testing machine. It is intended to be applied by experienced operators paying considerable attention to notch processing and measurement on notch parameters to perform mechanical testing.

Rolling bearings — Ceramic bearing balls — Determination of strength by notched ball test

1 Scope

This document specifies a method for the determination of the strength of finished ceramic balls for ball bearings, preferably made of silicon nitride (Si_3N_4), with ball diameters from 3 mm to 50 mm.

NOTE 1 ISO 26602 specifies the requirements for preprocessed silicon nitride materials for rolling bearing balls. ISO 3290-2 specifies requirements for finished silicon nitride balls for rolling bearings.

NOTE 2 Other test methods to determine ceramic ball strength can be found in Reference [7].

The results of the strength tests slightly depend on the Poisson's ratio. For this reason, all calculations are restricted to a Poisson's ratio ranging from 0,15 to 0,35. This includes the Poisson's ratio of a typical silicon nitride ceramic used as rolling element in ball bearings.

The method can also be used for rolling bearing balls made of other ceramic materials, but the reported prefactors may not be valid.

NOTE 3 Poisson’s ratio of isotropic materials can be determined by one of the methods given in ISO 17561.

Because of the (defect controlled) brittle fracture behaviour of ceramic materials, a significant scatter of individual results in the characterization of a series of nominally identical samples can occur.

NOTE 4 A further statistical analysis according to ISO 20501 can be carried out.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 463, *Geometrical Product Specifications (GPS) — Dimensional measuring equipment — Design and metrological characteristics of mechanical dial gauges*

ISO 3290-2, *Rolling bearings — Balls — Part 2: Ceramic balls*

ISO 3611, *Geometrical product specifications (GPS) — Dimensional measuring equipment: Micrometers for external measurements — Design and metrological characteristics*

ISO 6106, *Abrasive products — Checking the grain size of superabrasives*

ISO 7500-1:2018, *Metallic materials — Calibration and verification of static uniaxial testing machines — Part 1: Tension/compression testing machines — Calibration and verification of the force-measuring system*

ISO 20501, *Fine ceramics (advanced ceramics, advanced technical ceramics) — Weibull statistics for strength data*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
equatorial plane
plane of symmetry of the ball perpendicular to the loading direction

3.2
fracture force
F
applied force at fracture

3.3
ligament cross section
remaining segment of a circle in the equatorial plane of the notched ball

3.4
ligament thickness
h
maximum thickness of the ligament cross section in the *equatorial plane* (3.1) between the *notch root* (3.13) and the ball surface

Note 1 to entry: See Figure 1 and Figure 2.

3.5
mean notch root radius
R_m
arithmetic average of the *notch root radii* (3.10) R_1 and R_2

3.6
nominal width of the cutting wheel
w_{nom}
width of the cutting tool as declared by the producer

3.7
notch centricity
z
quantifiable value of departure from perfect notch midplane, related to the equatorial plane

Note 1 to entry: Practically, the asymmetry of the notch is determined as the notch centricity z; see Figure 2.

3.8
notch depth
l
theoretical depth of the notch

Note 1 to entry: $l = D_w - h$.

Note 2 to entry: See Figure 2.

3.9
notch midplane
imaginary plane through the centre of the real notch perpendicular to the loading direction

Note 1 to entry: See Figure 1 and Figure 2.

3.10
notch root radii
R_1, R_2
radii of the fillet of the *notch root* (3.13)

Note 1 to entry: See Figure 2.

3.11
notched ball
ball with a positioned notch, which is used as the test piece for the notched ball test

Note 1 to entry: See Figure 1.

3.12
notched ball strength
σ_f
theoretical maximum endured fibre stress at the point of the maximum nominal stress at the apex of the *ligament cross section* (3.3) at the time of fracture

Note 1 to entry: See Figure 1. The calculation is performed according to Formula (6).

3.13
notch root
region at the deepest point of the notch

Note 1 to entry: See Figure 1.

3.14
notch width
w
width of the notch, measured at a distance $w_{nom}/2$ away from the *notch root* (3.13)

Note 1 to entry: See Figure 5 and 8.1.

3.15
pole
discrete point of the ball surface where the load is applied

Note 1 to entry: See points B and B´ in Figure 1. The line connecting points B and B' goes through the ball centre and is perpendicular to the notch midplane.

3.16
preload
F_0
force which is applied before the test, in order to fix the test piece in the designated position

3.17
relative notch centricity
ζ
notch centricity (3.7) related to the ball diameter

Note 1 to entry: $\zeta = z/D_w$.

3.18
relative notch depth
λ
notch depth (3.8) related to the ball diameter

Note 1 to entry: $\lambda = l/D_w$.

3.19
relative notch root radius
ρ
mean notch root radius (3.5), related to the *notch width* (3.14)

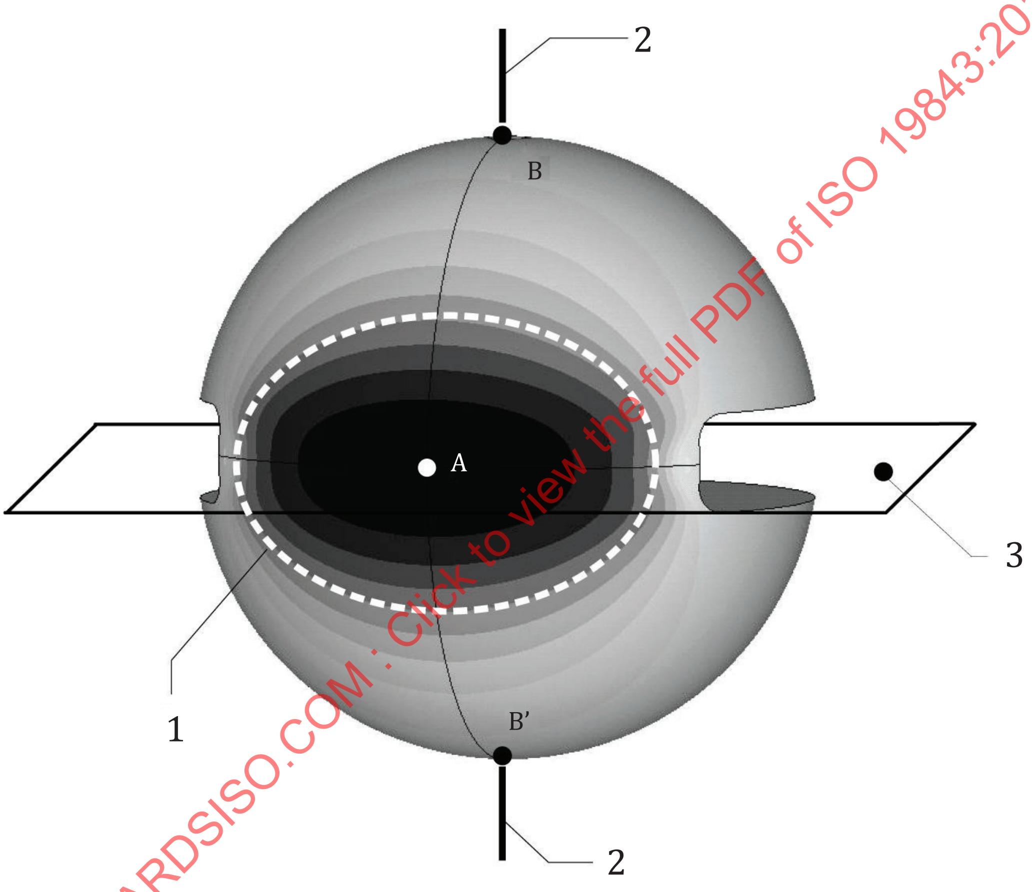
Note 1 to entry: $\rho = R_m/w$.

3.20
relative notch width
ω
notch width (3.14) related to the ball diameter

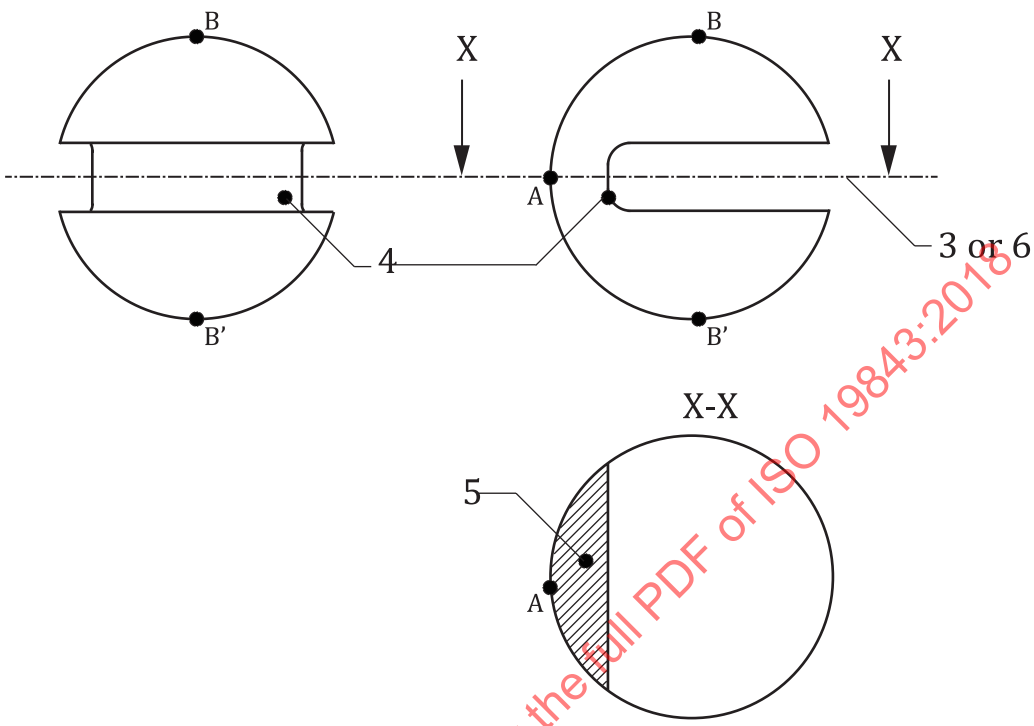
Note 1 to entry: $\omega = w/D_w$.

3.21
test surface
surface area of the *notched ball* (3.11) opposite to the *notch root* (3.13), where the maximum tensile stresses occur during loading

Note 1 to entry: See Figure 1.



a) Volume model illustrated with the stress amplitude

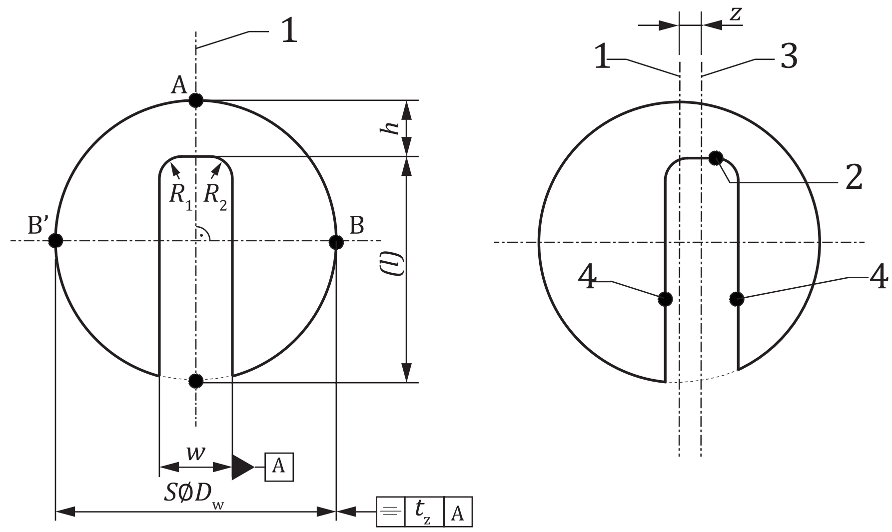


b) Front view, side view and section view (cut)

Key

A	point of maximum nominal stress at the apex of the ligament cross section
B, B’	points where the load is introduced
t_z	tolerance value associated with z
1	test surface
2	loading direction
3	equatorial plane
4	notch root
5	ligament cross section
6	notch midplane

Figure 1 — Notched ball test piece



Key

1 equatorial plane
2 notch root
3 notch midplane
4 notch side faces

NOTE See also Figure 1.

Figure 2 — Notch parameter of the notched ball

4 Symbols

See Table 1.

Table 1 — Symbols

Symbol	Unit	Nomenclature
D_w	mm	ball diameter
F	N	fracture force
F_0	N	preload
f	—	prefactor
f_λ	—	correction factor of the notch depth to calculate the reference strength
f_ω	—	correction factor of the notch width to calculate the reference strength
h	mm	ligament thickness
l	mm	notch depth
m	—	Weibull modulus of a batch
n	—	number of test pieces
p_1, p_2	mm	auxiliary distances for the determination of the notch centricity
R_m	mm	mean notch root radius
R_S	mm	radius of the tip of the measuring gauge
R_1, R_2	mm	notch root radii
r_1, r_2	mm	auxiliary distances for the determination of the notch root radii
S_{eff}	mm^2	effective surface
V_{eff}	mm^3	effective volume

Table 1 *(continued)*

Symbol	Unit	Nomenclature
w	mm	notch width
w_{nom}	mm	nominal width of the cutting wheel
w_S	mm	width of the measuring blade
z	mm	notch centricity
ζ	—	relative notch centricity
λ	—	relative notch depth
ν	—	Poisson's ratio
ρ	—	relative notch root radius
σ_f	MPa	notched ball strength
σ_0	MPa	characteristic strength of a batch
σ_{Ref}	MPa	reference strength
ω	—	relative notch width

5 Test description

During test piece preparation, a notch is centrally ground in the equatorial plane of the ball. In the subsequent strength test, a load is applied at the poles of the notched ball via two parallel anvils. The notch faces are squeezed together, whereby tensile stresses are generated on the surface opposite to the notch root. The load is increased uniformly until fracture. From the fracture force, the notched ball strength is calculated.

NOTE 1 The maximum stress is the first principal stress, the direction of which is parallel to the loading direction.

NOTE 2 Further details can be found in References [8], [9] and [11].

NOTE 3 A similar principle using a C-shaped notch is described in Reference [10], which was derived from Reference [5].

6 Equipment and testing devices

6.1 Loading device

The loading device consists of two parallel plates (testing anvils) and shall meet the following requirements.

The contact areas of the testing anvils shall be made of hard metal or of silicon nitride plates with a thickness of at least 10 mm. The material shall be chosen so that no plastic indentations remain on the anvil faces. The anvil surfaces shall be aligned perpendicular to the loading direction [see item 2 in Figure 1 a)]. The loading direction shall be the same as the moving direction of the crosshead of the testing machine. The anvil surfaces shall be smooth and their parallelism shall be designed in order that the anvil surfaces show a difference in the loading direction of less than 0,05 mm related to a transverse length of 50 mm. While loading, the stiffness shall be sufficient to avoid tilting.

The design of the test anvils shall be selected so that the positioning of the test piece is not hindered. An example is shown in Annex D. The points of the load application B and B' shall be axial in line with the anvil, i.e. they shall lie in the centre of the anvil faces. The dimensions of the anvil-surfaces shall be at least the ball diameter.

It shall be ensured that frictional constraints and maladjustments of the test piece are minimized.

6.2 Testing machine

The testing machine shall be able to apply a force with a constant crosshead displacement speed. The machine shall be equipped with a device for recording the applied force at any time of the test. The uncertainty of the testing machine shall be consistent with ISO 7500-1:2018, class 1 (1 % of indicated load) and the record shall have a sensitivity higher than 0,1 % of the maximum applied force.

6.3 Measuring devices

6.3.1 General

The following measurement equipment is required for the determination of the parameters:

— micrometer for external measurement (see 6.3.2);

— mechanical dial gauge (see 6.3.3);

— light microscope (see 6.3.4);

— measuring gauge to measure the ligament thickness (see 6.3.5).

If other measurement equipment is used, it shall be agreed beforehand.

6.3.2 Micrometer for external measurement

A micrometer in accordance with ISO 3611, but with an accuracy of ±2 µm or better, shall be used for measuring the test piece dimensions. The measuring surfaces of the micrometer shall be flat. Sharp measurement tips shall not be used to avoid damaging the sample. For all alternative length measuring devices, similar restrictions shall be observed.

6.3.3 Mechanical dial gauge

A mechanical dial gauge in accordance with ISO 463, but with an accuracy of ±10 µm, shall be used to measure the notch centricity.

6.3.4 Light microscope

For the recording of calibrated micrographs to determine the notch parameter, a measuring microscope is required [see also Figure C.1 c)].

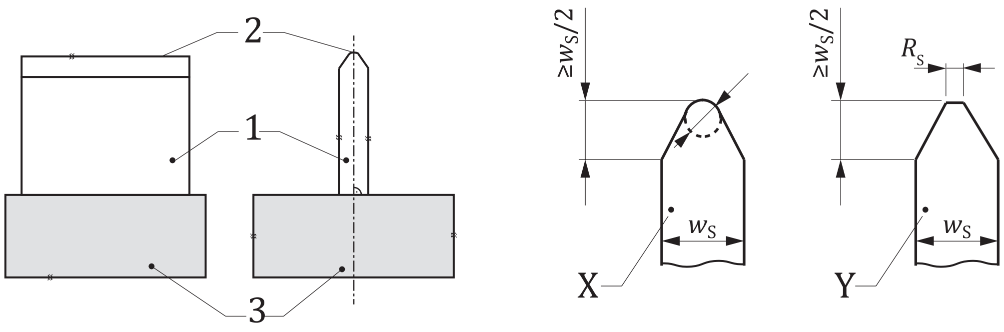
6.3.5 Measuring gauge for the determination of the ligament thickness

With the special measuring tool (measuring gauge or blade) and a corresponding bracket (as shown in Figure 3), the ligament thickness can be determined with sufficient accuracy. The blade edge has the shape of a "blunt knife edge" and may have a rounded or small top flat edge. In order to avoid influencing the measurement by the notch root radius and a strong tilting of the notch ball in the measurement, the measuring blade shall fulfil the geometry conditions given by Formula (1) and Formula (2).

$$R_S \leq w/10 \tag{1}$$

$$0{,}7\ w \leq w_S \leq 0{,}95\ w \tag{2}$$

The procedure for the measurement of the ligament thickness is illustrated in Figure 4.



Key

1 measuring gauge

2 measuring edge

3 bracket

X variant 1 for the measuring edge

Y variant 2 for the measuring edge

NOTE Details of the measuring edge can be executed either according to variant X or according to variant Y.

Figure 3 — Measuring gauge for the determination of the ligament thickness and a corresponding bracket

6.4 Grinding machine

The notch should preferably be produced with a reciprocating grinding machine using a cutting wheel with diamond abrasive layer (see also Reference [7]).

6.5 Psychrometer

A psychrometer for measuring the humidity with a measurement error of ±2 % of the relative humidity shall be used.

A recommended measurement method can be found in Reference [6].

6.6 Dryer

A drying cabinet capable of being maintained at a temperature of 110 °C ± 5 °C shall be used.

7 Preparation of the notched ball

7.1 Number of test pieces *n*

For material characterization and quality assurance, at least n = 10 valid test results shall be obtained. For the statistical evaluation of strength values (e.g. Weibull parameters), the minimum number of test pieces is n = 30.

NOTE If the number of nominally identical test pieces is less than 30, the calculated Weibull parameters can have significant uncertainty. Because of the inaccuracy of these parameters, a comparison of different batches is not suitable in this case. Further information is provided in ISO 20501 and Reference [9].

7.2 Diameter determination

The diameters of the tested balls are specified by the manufacturer or shall be determined in accordance with ISO 3290-2.

7.3 Preparation of the notch

7.3.1 General

The test surface shall not be damaged by notch manufacturing. For the manufacturing of the notch by cutting, large forces are generally required, which results in high contact stresses at the contact points. This can lead to defects in the test surface (such as scratches, cracks, plastic deformation), which can affect the resulting surface strength. Furthermore, high loads perpendicular to the notch shall be avoided (e.g. fixing or clamping the balls) to prevent pre-damage.

The notch shall be produced with a diamond cutting wheel with a grit size between D64 and D151 in accordance with ISO 6106 and with appropriate cooling (e.g. emulsion).

In general, a polymer bonded diamond wheel is recommended. For cutting wheels with a width less than about 1 mm, the diamond coating is often applied by electroplating, which can result in higher and non-constant wear rates of the cutting wheel.

NOTE A simple and proven method is presented in Annex C.

The feed and the feed rate control shall be chosen in such a way that the notch is prepared as carefully as possible and without chipping. Rejection criteria for chipped and/or partially cracked test pieces shall be as specified in Annex F. However, if chipped and/or partially cracked test pieces (exceeding the rejection criteria defined in Annex F) are tested, it shall be proven via fractographical analysis that the fracture origin is not related to notch root damage.

An in-depth feed rate (depth of cut) between 5 µm and 10 µm per cycle is recommended.

7.3.2 Notch geometry

To generalize the notch ball test, the absolute geometry parameters of the notch l, w and R_m are converted into the relative (dimensionless) parameters λ, ω and ρ. Furthermore, the notch should be symmetrically and centrally located with respect to the equatorial plane.

The relative dimensions of the standard notch are given in Table 2. These values (geometry of the notch) shall be the target for the notch preparation. For a valid evaluation of the strength using the notched ball test, all parameters shall be within the acceptance range specified in Table 2.

NOTE For statistical analysis, the approximation given by Formula (A.1) is applicable only within the parameter range in Table 2 .

Table 2 — Acceptable notch geometries for evaluation of a single test piece

Parameter	Symbol	Standard notch	Acceptance range
Relative notch depth	λ	0,80	0,78 to 0,82
Relative notch width	ω	0,10	0,05 to 0,15
Relative notch root radius	ρ	0,25	0 to 0,5
Relative notch centricity	ζ	0	0 to 0,01

The Weibull parameters of a test series (e.g. 30 samples) shall be determined in accordance with ISO 20501 and the difference between the notch parameters of all tested samples shall not be larger than specified in Table 3.

For the comparison of the Weibull parameters of two batches with the same nominal ball diameter, the maximum difference of the relative notch parameters λ, ω and ρ of all individual test pieces are given in Table 3. If one or more of these values are exceeded, a correction shall be carried out in accordance with Annex B.

Table 3 — Preconditions for statistical analysis

Parameter	Symbol	Maximum permitted difference Δ (for the determination of the Weibull parameter)	
		Within one batch	Comparison of two batches
Relative notch depth difference	$\Delta\lambda$	0,005	0,01
Relative notch width difference	$\Delta\omega$	0,02	0,05
Relative notch root radius difference	$\Delta\rho$	0,3	Not restricted

7.4 Cleaning

For testing, the test pieces shall be free of dust and grease. After each machining process, the test pieces shall be cleaned in water or an appropriate solvent. If glue or other adhesive agent is used, all residues shall be removed using a suitable solvent which does not affect the mechanical properties of the ceramic ball material. It is recommended to avoid contact between the test pieces, if an ultrasonic cleaning device is used.

NOTE The use of ultrasonic cleaning of the notched balls can cause surface damage in the test surface due to contact between the test pieces (i.e. between sharp edges of the notch side faces of one ball and the test surface of a second ball).

After cleaning, the test pieces shall be dried in a drying cabinet for at least 2 h at 110 °C ± 5 °C.

8 Test procedure

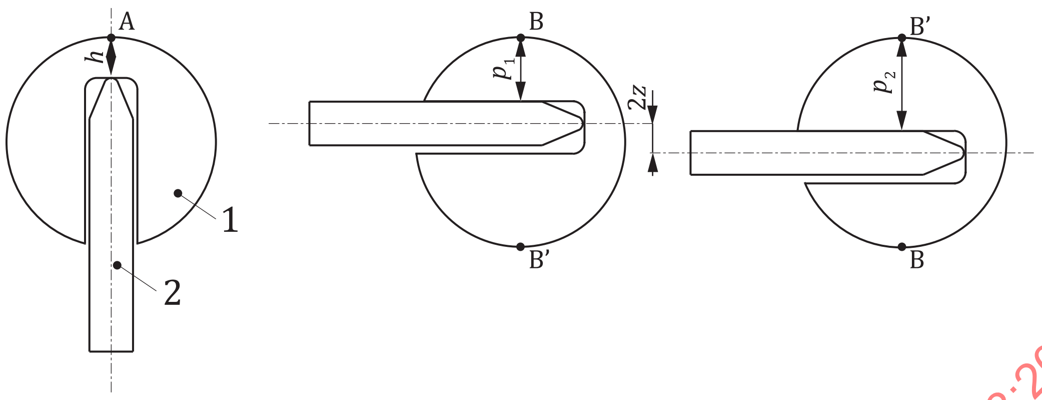
8.1 Measurement of notch parameters

The ligament thickness, h, has the strongest influence on strength and therefore it shall be measured for each test piece separately.

The measurement of the ligament thickness, h, and the notch centricity, z, are shown in Figure 4. Their determinations shall be performed using a measuring gauge as shown in Figure 3.

Place the ball notch onto the horizontal measuring gauge and measure height p_1. Remove the notched ball and replace it resting the other notch face on the measuring gauge. Measure height p_2. Calculate the notch centricity z using Formula (3). Reject any test piece for which $\zeta = z / D_{\mathrm{w}} \geq 0{,}01$.

$$z = |p_1 - p_2| / 2 \tag{3}$$



a) Schematic illustration for the measurement of the ligament thickness *h*

b) Schematic illustration for the measurement of the auxiliary distance p_1

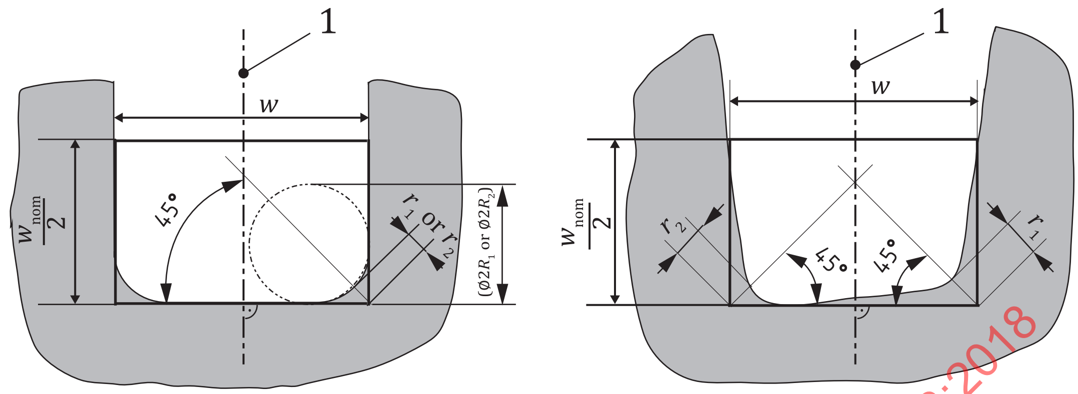
c) Schematic illustration for the measurement of the auxiliary distance p_2

Key

1	notched ball
2	measuring gauge
A	point of maximum nominal stress at the apex of the ligament cross section
B, B'	points where the load is introduced

Figure 4 — Schematic illustration for the measurement of the ligament thickness and the auxiliary distance of the notched ball for the calculation of the notch centricity using the measuring gauge

The determination of the notch root radius and the notch width shall be carried out in a plane which lies parallel to the plane A-B-B' (see Figure 1). For convenience, it is permitted to perform the measurement using a comparative test piece (e.g. rectangular bars, produced in the same cutting step) made of a material with similar material properties or to measure a central cross section of a ball which is perpendicular to the plane A-B-B'. The measurement is schematically illustrated in Figure 5 and shall be conducted with both notch root radii R_1 and R_2. A practical way is presented in Figure C.1 c).



a) Example for a symmetric notch and parallel notch side faces **b) Example for an asymmetric notch and non-parallel notch side faces**

Key

1 notch midplane

NOTE See also Figure 1.

Figure 5 — Cross section of the notch for the determination of the notch root radii and of the notch width *w* using the auxiliary distance r_1, $r_{,2}$

The notch shall be positioned according to Figure 5, i.e. the notch side faces shall be approximately vertical and the notch root shall be located at the bottom side (not necessarily horizontal). The notch shall be circumscribed by a rectangle, the edges of which are parallel and perpendicular regarding the notch midplane. Its height dimension shall be approximately $w_{nom}/2$. Its lower side shall touch the notch root. Both upper corners shall lie on the corresponding notch side face. The notch width, *w*, may then be determined by this rectangle — it is equal to the length of the resulting rectangle. The auxiliary distances r_1, r_2 are measured as the distances between each lower corner and the point of intersection of notch contour and the angle bisecting line.

The mean notch root radius, R_m, can be calculated using Formula (4) and Formula (5):

$$R_{1,2} = r_{1,2} / (\sqrt{2} - 1) \tag{4}$$

$$R_m = (R_1 + R_2)/2 \tag{5}$$

It is recommended to save the picture of the notch root measurement.

8.2 Mechanical testing

At least 2 h before mechanical testing, the test pieces shall be stored in the test atmosphere in order to adapt to the environment. The ambient temperature and relative humidity shall be recorded. The temperature shall be between 15 °C and 30 °C and shall not fluctuate by more than 3 °C and the relative humidity shall not be more than 10 % during the entire test series.

It shall be ensured that the loading device is not damaged and that the anvils are free from fracture parts from other test pieces.

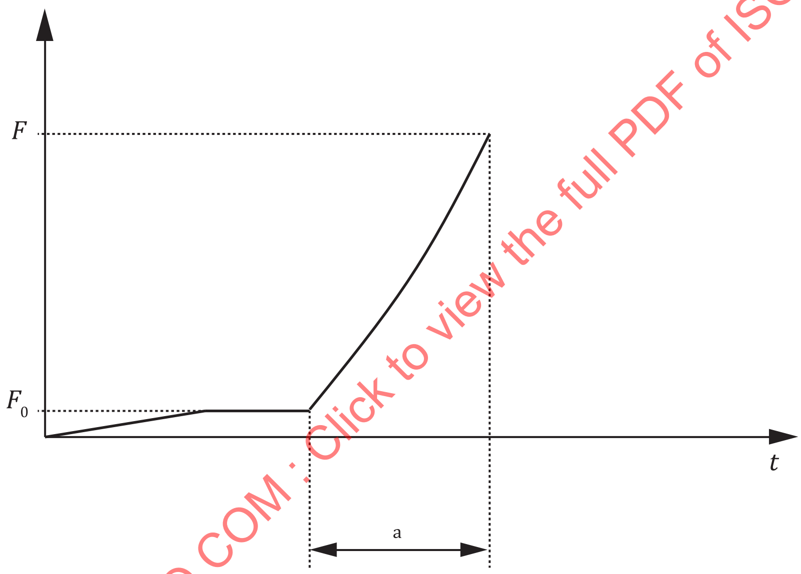
Each test piece shall be positioned centrally between the anvils (i.e. the load application points shall be located on the axis of loading direction). The line perpendicular to the notch midplane shall be within 3° of the load application direction.

NOTE 1 A suggestion for a positioning aid is given in Annex D.

To stabilize the test piece in this position, a preload can be applied, which shall not exceed 10 % of the expected fracture force. In any case, the loading rate up to the application of the preload shall be lower than the subsequent testing speed. After the application of the preload, all positioning aids shall be removed and a corresponding splinter protection device shall be positioned around the test piece.

The expected load range should be selected in a way that the expected average breaking forces are roughly in the middle of the permitted range of force measurement. The loading is steadily increased with a testing speed that shall ensure that the fracture occurs within 5 s to 15 s. A recommendation for the initial testing speed is given in Annex G. A schematic plot of the force versus time is shown in Figure 6.

NOTE 2 The loading rate at a given cross head speed can be influenced by the elastic compliance of the loading device, the elastic properties of the material and the geometry of the notched ball.



Key

F fracture force

F_0 preload

t time

a 5 s to 15 s.

Figure 6 — Schematic plot the testing force versus time

The fracture force, F (applied force at fracture), shall be recorded. All fractured parts shall be stored and marked for later investigations. The fracture surface shall be protected against contamination during transport and storage.

9 Evaluation

Calculate the relative notch parameters λ, ω and ρ. Evaluate the notched ball strength according to Formula (6).

$$\sigma_{\mathrm{f}} = f\frac{6F}{h^2}\left(1-0{,}087\left(\nu-0{,}27\right)\right) \tag{6}$$

Function tables and a fitting function for the prefactor f depending on the relative notch parameter (λ, ω and ρ) shall be as given in Annex A. If function tables are used, the values shall be determined by linear interpolation.

For the evaluation, the actual values of the ligament thickness h and the notch depth l and λ (respectively) of every single test piece shall be used. The use of a mean value (e.g. regarding one batch) is not permitted.

10 Potential uncertainties and deviations

An analysis based on Formula (6) may be used to show that the main error sources for the uncertainty of the notched ball strength are the measurements of the fracture force, of the notch centricity and of the thickness of the notch ligament. The accuracy of the force recording, which is influenced by the accuracy of calibration of the load cell, by the noise of the signal and by deviations while data reading, shall be better than ±1 % (see ISO 7500-1).

Assuming the absolute measurement accuracy (Δl = Δh = ±5 µm, Δw = ±10 µm, ΔR_{m} = ±10 µm) and a natural variation of Poisson's ratio of ±0,01, the influence on the notched ball strength values can be calculated. The resulting maximum deviation of the notched ball strength for small balls (e.g. D_{w} = 3 mm) is lower than ±3 % and decreases with increasing ball size (e.g. D_w = 50 mm) to ±0,3 %.

The notch centricity, z, is not included in the analysis. A maximum deviation of 1 % of the ball diameter leads to an increase in the calculated notch ball strength of 0,8 %. The same happens for a tilt of the test piece while positioning. The maximum permissible value of 3° leads to a reduction of the evaluated notch ball strength value of 0,1 %.

Accordingly, the maximum total deviation of the notch ball strength is less than ±5 % with a proper summation of the force and geometry deviations as well as contributions for a given variation of the elastic constants of the material.

NOTE A measurement error of about ±5 % is a typical value for strength testing.

In principle, the deviation can be reduced by an improvement in calibration of the force and precision levels for the length measurement and if the notch is centred and symmetrical.

11 Test report

The test report shall include at least the following information (an example is given in Annex E):

a) information regarding the testing machine;

b) date, start and duration of testing, report number, signature of the operator;

c) anvil material (at least at the load introduction points);

d) reference to this document (e.g. "determined in accordance with ISO 19843:2018");

e) description of the testing sample (material type, ball grade, producer identification number, lot number, receipt date);

f) mean temperature and average relative humidity during the test;

g) mean loading time to fracture of the test piece in seconds or loading rate;

h) number of tested test pieces *n* (invalid test pieces also have to be listed and continuously numbered);

i) individual values of the ball diameters, notch parameters, ligament thicknesses, notch centricities, fracture forces in N and values of the nominal notched ball strength in MPa with an accuracy of at least four significant digits;

j) mean value of all valid notched ball strength values and the standard deviation (if not specified);

k) remarks on delivery, cleaning or thermal treatment (if they differ from this document);

l) remarks on testing or results, notes for the type of fracture and type and position of the fracture origin.

Annex A
(normative)

Function tables for prefactor f

For usage of Tables A.1 to A.6, a linear interpolation between the given values shall be conducted, if necessary.

Table A.1 — Prefactor, f, for the calculation of the notched ball strength according to Formula (6) with ρ = 0 as a function of the relative notch width, ω, and the relative notch depth, λ

ω	f								
	λ = 0,780	λ = 0,785	λ = 0,790	λ = 0,795	λ = 0,800	λ = 0,805	λ = 0,810	λ = 0,815	λ = 0,820
0,05	0,568 1	0,584 1	0,600 7	0,618 0	0,635 9	0,654 4	0,673 7	0,693 7	0,714 6
0,06	0,581 7	0,598 2	0,615 2	0,632 9	0,651 3	0,670 4	0,690 2	0,710 8	0,732 3
0,07	0,594 3	0,611 1	0,628 6	0,646 7	0,665 5	0,685 0	0,705 2	0,726 3	0,748 2
0,08	0,605 9	0,623 1	0,640 9	0,659 3	0,678 5	0,698 3	0,718 9	0,740 3	0,762 6
0,09	0,616 7	0,634 1	0,652 2	0,670 9	0,690 3	0,710 4	0,731 3	0,752 9	0,775 5
0,1	0,626 6	0,644 2	0,662 5	0,681 4	0,701 0	0,721 3	0,742 4	0,764 3	0,786 9
0,11	0,635 7	0,653 5	0,671 9	0,691 0	0,710 7	0,731 2	0,752 4	0,774 4	0,797 1
0,12	0,644 0	0,661 9	0,680 4	0,699 6	0,719 5	0,740 0	0,761 3	0,783 3	0,806 2
0,13	0,651 5	0,669 5	0,688 1	0,707 4	0,727 3	0,747 9	0,769 2	0,791 3	0,814 1
0,14	0,658 3	0,676 4	0,695 1	0,714 3	0,734 3	0,754 9	0,776 2	0,798 2	0,821 0
0,15	0,664 5	0,682 6	0,701 3	0,720 6	0,740 5	0,761 1	0,782 4	0,804 4	0,827 1

Table A.2 — Prefactor, f, for the calculation of the notched ball strength according to Formula (6) with ρ = 0,1 as a function of the relative notch width, ω, and the relative notch depth, λ

ω	f								
	λ = 0,780	λ = 0,785	λ = 0,790	λ = 0,795	λ = 0,800	λ = 0,805	λ = 0,810	λ = 0,815	λ = 0,820
0,05	0,561 9	0,577 7	0,594 1	0,611 0	0,628 6	0,646 9	0,665 8	0,685 5	0,706 1
0,06	0,574 2	0,590 5	0,607 3	0,624 7	0,642 7	0,661 4	0,680 9	0,701 1	0,722 2
0,07	0,585 8	0,602 4	0,619 5	0,637 3	0,655 7	0,674 9	0,694 8	0,715 4	0,737 0
0,08	0,596 5	0,613 4	0,630 9	0,649 0	0,667 8	0,687 3	0,707 5	0,728 5	0,750 4
0,09	0,606 5	0,623 7	0,641 4	0,659 8	0,678 8	0,698 6	0,719 1	0,740 4	0,762 6
0,1	0,615 8	0,633 2	0,651 1	0,669 7	0,689 0	0,709 0	0,729 7	0,751 2	0,773 6
0,11	0,624 4	0,642 0	0,660 1	0,678 9	0,698 3	0,718 5	0,739 4	0,761 0	0,783 5
0,12	0,632 4	0,650 0	0,668 3	0,687 2	0,706 8	0,727 1	0,748 1	0,769 9	0,792 5
0,13	0,639 7	0,657 5	0,675 9	0,694 9	0,714 5	0,734 9	0,756 0	0,777 9	0,800 5
0,14	0,646 4	0,664 3	0,682 8	0,701 8	0,721 6	0,742 0	0,763 1	0,785 0	0,807 7
0,15	0,652 6	0,670 6	0,689 1	0,708 2	0,728 0	0,748 4	0,769 6	0,791 5	0,814 2

Table A.3 — Prefactor, f, for the calculation of the notched ball strength according to Formula (6) with ρ = 0,2 as a function of the relative notch width, ω, and the relative notch depth, λ

ω	f								
	λ = 0,780	λ = 0,785	λ = 0,790	λ = 0,795	λ = 0,800	λ = 0,805	λ = 0,810	λ = 0,815	λ = 0,820
0,05	0,553 3	0,568 8	0,584 8	0,601 4	0,618 6	0,636 4	0,655 0	0,674 2	0,694 3
0,06	0,564 3	0,580 1	0,596 5	0,613 5	0,631 1	0,649 4	0,668 4	0,688 1	0,708 7
0,07	0,574 6	0,590 7	0,607 5	0,624 8	0,642 8	0,661 5	0,680 8	0,701 0	0,721 9
0,08	0,584 2	0,600 7	0,617 7	0,635 4	0,653 7	0,672 6	0,692 4	0,712 9	0,734 2
0,09	0,593 2	0,610 0	0,627 3	0,645 2	0,663 7	0,683 0	0,703 0	0,723 8	0,745 4
0,1	0,601 7	0,618 7	0,636 2	0,654 3	0,673 1	0,692 6	0,712 8	0,733 8	0,755 7
0,11	0,609 6	0,626 8	0,644 5	0,662 8	0,681 8	0,701 5	0,721 9	0,743 1	0,765 1
0,12	0,617 0	0,634 3	0,652 2	0,670 7	0,689 8	0,709 7	0,730 2	0,751 6	0,773 8
0,13	0,624 0	0,641 4	0,659 4	0,678 0	0,697 3	0,717 2	0,737 9	0,759 4	0,781 7
0,14	0,630 4	0,647 9	0,666 0	0,684 8	0,704 2	0,724 2	0,745 0	0,766 6	0,789 0
0,15	0,636 4	0,654 1	0,672 3	0,691 1	0,710 5	0,730 7	0,751 5	0,773 2	0,795 6

Table A.4 — Prefactor, f, for the calculation of the notched ball strength according to Formula (6) with ρ = 0,3 as a function of the relative notch width, ω, and the relative notch depth, λ

ω	f								
	λ = 0,780	λ = 0,785	λ = 0,790	λ = 0,795	λ = 0,800	λ = 0,805	λ = 0,810	λ = 0,815	λ = 0,820
0,05	0,544 0	0,559 1	0,574 8	0,590 9	0,607 7	0,625 1	0,643 1	0,661 9	0,544 0
0,06	0,553 4	0,568 8	0,584 8	0,601 3	0,618 4	0,636 1	0,654 6	0,673 7	0,553 4
0,07	0,562 2	0,577 9	0,594 2	0,611 0	0,628 4	0,646 5	0,665 3	0,684 8	0,562 2
0,08	0,570 5	0,586 5	0,603 0	0,620 1	0,637 8	0,656 2	0,675 3	0,695 1	0,570 5
0,09	0,578 4	0,594 6	0,611 3	0,628 7	0,646 6	0,665 3	0,684 6	0,704 7	0,578 4
0,1	0,585 7	0,602 1	0,619 1	0,636 7	0,654 9	0,673 7	0,693 3	0,713 7	0,585 7
0,11	0,592 7	0,609 3	0,626 4	0,644 2	0,662 6	0,681 6	0,701 4	0,722 0	0,592 7
0,12	0,599 3	0,616 0	0,633 3	0,651 2	0,669 8	0,689 0	0,709 0	0,729 7	0,599 3
0,13	0,605 5	0,622 4	0,639 8	0,657 9	0,676 6	0,696 0	0,716 1	0,736 9	0,605 5
0,14	0,611 4	0,628 4	0,645 9	0,664 1	0,682 9	0,702 5	0,722 7	0,743 7	0,611 4
0,15	0,616 9	0,634 0	0,651 7	0,670 0	0,688 9	0,708 5	0,728 9	0,750 0	0,616 9

Table A.5 — Prefactor, *f*, for the calculation of the notched ball strength according to Formula (6) with ρ = 0,4 as a function of the relative notch width, ω, and the relative notch depth, λ

ω	*f*								
	λ = 0,780	λ = 0,785	λ = 0,790	λ = 0,795	λ = 0,800	λ = 0,805	λ = 0,810	λ = 0,815	λ = 0,820
0,05	0,534 0	0,548 7	0,563 9	0,579 6	0,595 9	0,612 7	0,630 2	0,648 4	0,667 3
0,06	0,541 6	0,556 5	0,572 0	0,588 0	0,604 6	0,621 7	0,639 5	0,658 0	0,677 3
0,07	0,548 7	0,563 9	0,579 6	0,595 9	0,612 7	0,630 1	0,648 2	0,667 0	0,686 6
0,08	0,555 5	0,570 9	0,586 8	0,603 3	0,620 3	0,638 0	0,656 4	0,675 4	0,695 2
0,09	0,561 8	0,577 4	0,593 5	0,610 2	0,627 5	0,645 4	0,664 0	0,683 3	0,703 3
0,1	0,567 9	0,583 6	0,599 9	0,616 8	0,634 2	0,652 3	0,671 1	0,690 6	0,710 8
0,11	0,573 6	0,589 5	0,605 9	0,622 9	0,640 5	0,658 8	0,677 8	0,697 4	0,717 9
0,12	0,579 0	0,595 0	0,611 6	0,628 7	0,646 5	0,664 9	0,684 0	0,703 9	0,724 5
0,13	0,584 1	0,600 3	0,617 0	0,634 3	0,652 2	0,670 7	0,690 0	0,710 0	0,730 7
0,14	0,589 0	0,605 3	0,622 1	0,639 5	0,657 6	0,676 2	0,695 6	0,715 7	0,736 6
0,15	0,593 6	0,610 0	0,627 0	0,644 5	0,662 7	0,681 5	0,700 9	0,721 2	0,742 2

Table A.6 — Prefactor, *f*, for the calculation of the notched ball strength according to Formula (6) with ρ = 0,5 as a function of the relative notch width, ω, and the relative notch depth, λ

ω	*f*								
	λ = 0,780	λ = 0,785	λ = 0,790	λ = 0,795	λ = 0,800	λ = 0,805	λ = 0,810	λ = 0,815	λ = 0,820
0,05	0,523 1	0,537 4	0,552 1	0,567 3	0,583 0	0,599 3	0,616 2	0,633 8	0,652 0
0,06	0,528 7	0,543 1	0,558 0	0,573 5	0,589 4	0,605 9	0,623 0	0,640 8	0,659 2
0,07	0,533 9	0,548 5	0,563 6	0,579 2	0,595 3	0,612 0	0,629 3	0,647 3	0,666 0
0,08	0,538 8	0,553 6	0,568 8	0,584 5	0,600 8	0,617 7	0,635 2	0,653 3	0,672 2
0,09	0,543 4	0,558 3	0,573 7	0,589 5	0,606 0	0,623 0	0,640 6	0,658 9	0,677 9
0,1	0,547 8	0,562 8	0,578 2	0,594 2	0,610 8	0,627 9	0,645 7	0,664 2	0,683 3
0,11	0,551 8	0,566 9	0,582 5	0,598 6	0,615 3	0,632 6	0,650 5	0,669 0	0,688 3
0,12	0,555 7	0,570 9	0,586 6	0,602 8	0,619 6	0,636 9	0,654 9	0,673 6	0,693 0
0,13	0,559 4	0,574 6	0,590 4	0,606 7	0,623 6	0,641 0	0,659 1	0,677 9	0,697 4
0,14	0,562 9	0,578 2	0,594 1	0,610 5	0,627 4	0,645 0	0,663 1	0,682 0	0,701 6
0,15	0,566 2	0,581 6	0,597 5	0,614 0	0,631 0	0,648 7	0,666 9	0,685 9	0,705 6

For ease of use (e.g. automated data calculation, mathematic programs), prefactor *f* may be approximated by Formula (A.1). The fitting error is less than ±0,25 % in any case for the allowed parameter intervals of the notch.

$$f(\lambda,\omega,\rho)=1{,}747\,1+\lambda\left(-0{,}394\,58-0{,}972\,99\rho-4{,}901\,2\rho^2\right)\left(0{,}787\,27+0{,}833\,36\omega-3{,}089\,7\omega^2\right)$$
$$+\lambda^2\left(3{,}779\,1-0{,}861\,71\rho-4{,}787\,1\rho^2\right)\left(-2{,}311\,8-1{,}515\,1\omega+6{,}819\,9\omega^2\right)$$
$$+\lambda^3\left(2{,}821\,7-0{,}433\,76\rho-2{,}36\,46\rho^2\right)\left(3{,}213\,9+4{,}074\,1\omega-15{,}259\omega^2\right) \quad \text{(A.1)}$$

Annex B
(normative)

Comparability of notched ball strength results

In case of different relative notch geometries, the size of the loaded area (and volume) will change and this will result in different characteristic strength values according to Weibull-theory. In order to compare the characteristic strength of two batches (same ball diameter, but different notch geometry), it is possible to reduce both characteristic strength values using Formula (B.1) to a reference case, i.e. a reference strength σ_{Ref} for a standard geometry. For the correction factors $f_\omega(\omega, m)$ and $f_\lambda(\lambda, m)$ in Table B.1 and Table B.2, respectively, the mean values of the notch parameters λ and ω of each batch shall be used.

$$\sigma_{Ref} = \sigma_0 \frac{f_\omega(\omega, m)}{f_\omega\left((\omega=0{,}1), m\right)} \cdot \frac{f_\lambda(\lambda, m)}{f_\lambda\left((\lambda=0{,}8), m\right)} \quad \text{(B.1)}$$

The condition for the permissibility of the conversion in Formula (B.1) is the determination of the Weibull parameters (characteristic strength and Weibull modulus) according to ISO 20501 and thus the minimum amount of test pieces (sample size) is 30 in each batch.

NOTE 1 For the standard parameters (λ = 0,8, ω = 0,1, ρ = 0,25 and m = 10), the size of the effective surface is 2,038 % and the effective volume is 0,120 % related to the full sphere (see References [8] and [11]). The relative notch radius ρ has almost no effect (≤0,1 %) on the notched ball strength, and was therefore neglected.

Table B.1 — Correction factor, f_ω, for the calculation of the reference strength according to Formula (B.1) as a function of the relative notch width, ω, and the Weibull modulus, m

m	f_ω				
	ω = 0,05	ω = 0,075	ω = 0,100	ω = 0,125	ω = 0,150
5	1,093	1,101	1,113	1,128	1,147
6	1,054	1,059	1,069	1,080	1,095
7	1,029	1,034	1,041	1,050	1,063
8	1,013	1,016	1,022	1,030	1,041
9	1,002	1,004	1,009	1,016	1,026
10	0,994	0,996	1,000	1,006	1,014
11	0,988	0,990	0,993	0,998	1,006
12	0,984	0,985	0,988	0,993	0,999
13	0,980	0,981	0,984	0,988	0,994
14	0,978	0,978	0,981	0,985	0,990
15	0,976	0,976	0,978	0,982	0,987
16	0,974	0,974	0,976	0,980	0,984
17	0,973	0,973	0,975	0,978	0,982
18	0,972	0,972	0,974	0,976	0,981
19	0,971	0,971	0,973	0,975	0,979
20	0,971	0,971	0,972	0,974	0,978
21	0,970	0,970	0,971	0,974	0,977
22	0,970	0,970	0,971	0,973	0,976
23	0,970	0,969	0,970	0,972	0,976
24	0,969	0,969	0,970	0,972	0,975
25	0,969	0,969	0,970	0,972	0,975
26	0,969	0,969	0,970	0,972	0,974
27	0,969	0,969	0,970	0,971	0,974
28	0,969	0,969	0,970	0,971	0,974
29	0,969	0,969	0,970	0,971	0,974
≥30	0,969	0,969	0,970	0,971	0,974

Table B.2 — Correction factor, f_λ, for the calculation of the reference strength according to Formula (B.1) as a function of the relative notch depth, λ, and the Weibull modulus, m

m	f_λ				
	λ = 0,78	λ = 0,79	λ = 0,80	λ = 0,81	λ= 0,82
5	1,151	1,132	1,113	1,094	1,075
6	1,099	1,084	1,069	1,053	1,037
7	1,066	1,054	1,041	1,028	1,015
8	1,044	1,033	1,022	1,011	1,000
9	1,029	1,019	1,009	0,999	0,989
10	1,018	1,009	1,000	0,991	0,982
11	1,009	1,001	0,993	0,985	0,977
12	1,002	0,995	0,988	0,980	0,973
13	0,997	0,991	0,984	0,977	0,970
14	0,993	0,987	0,981	0,974	0,968
15	0,990	0,984	0,978	0,972	0,966
16	0,987	0,982	0,976	0,971	0,965
17	0,985	0,980	0,975	0,969	0,964
18	0,983	0,978	0,974	0,969	0,963
19	0,982	0,977	0,973	0,968	0,963
20	0,981	0,976	0,972	0,967	0,963
21	0,980	0,975	0,971	0,967	0,962
22	0,979	0,975	0,971	0,967	0,962
23	0,978	0,974	0,970	0,966	0,962
24	0,978	0,974	0,970	0,966	0,962
25	0,977	0,973	0,970	0,966	0,962
26	0,977	0,973	0,970	0,966	0,963
27	0,976	0,973	0,970	0,966	0,963
28	0,976	0,973	0,970	0,966	0,963
29	0,976	0,973	0,970	0,966	0,963
≥30	0,976	0,973	0,970	0,967	0,963

One approach for the relationship between characteristic strength of test pieces of different sizes and/or stress fields is based on the effective volume, V_{eff} (appropriate for volume distributed flaws), or on the effective surface, S_{eff} (appropriate for surface distributed flaws only). The conversion procedure can be found in Reference [11] or Reference [8]. Typically, this conversion is performed in order to compare the characteristic strength of the test pieces with bending bars or components in application.

Due to the complex geometry of the notched ball test piece, no analytical solution for V_{eff} and S_{eff} may be derived. However, in Formula (B.2) and Formula (B.3) give approximations for V_{eff} and S_{eff}, respectively. In both cases, the fitting error is less than 8,5 % for $4 < m < 20$ and less than 18 % for $4 < m < 50$. These statements are correct for the acceptable notch geometry parameters given in Table 2 and for a Poisson's ratio of $0{,}15 < \nu < 0{,}35$.

NOTE 2 The error in extrapolated strength due to the fitting error in Formula (B.2) and Formula (B.3) is in any case <1,6 % due to the strong influence of the Weibull modulus, i.e. power ($1/m$).

$$V_{\mathrm{eff}}(\lambda,\omega,\rho,\nu,m)=\left(\frac{1}{6}D_{\mathrm{w}}^{3}\,\pi\right)(m+1)^{-1{,}863}\;0{,}893(1-1{,}063\,\lambda)^{2}(\omega+1{,}544)^{3}$$
$$\left(1+0{,}083\,7\left(\left(\frac{\omega}{0{,}05}\right)-1\right)^{2}(1{,}01-\rho)^{3}\left(\frac{\lambda}{0{,}8}\right)^{10}\right)\left(1+0{,}19\left(\frac{m}{30}\right)^{0{,}5}\left(\frac{\nu}{0{,}27}\right)^{2}\right)\left(1+\frac{\rho}{10}\right)^{1{,}27} \tag{B.2}$$

$$S_{\mathrm{eff}}(\lambda,\omega,\rho,\nu,m)=\left(D_{\mathrm{w}}^{2}\,\pi\right)(m+1)^{-0{,}938}\;0{,}020\,6\,(1-0{,}988\,\lambda)^{2}(\omega+5{,}465)^{3}$$
$$\left(1+0{,}09\left(\left(\frac{\omega}{0{,}05}\right)-1\right)^{2}(1{,}02-\rho)^{3}\left(\frac{\lambda}{0{,}8}\right)^{10}\right)\left(1+0{,}269\,5\left(\frac{m}{30}\right)^{0{,}5}\left(\frac{\nu}{0{,}27}\right)^{2}\right)\left(1+\frac{\rho}{10}\right)^{1{,}31} \tag{B.3}$$

Annex C
(informative)

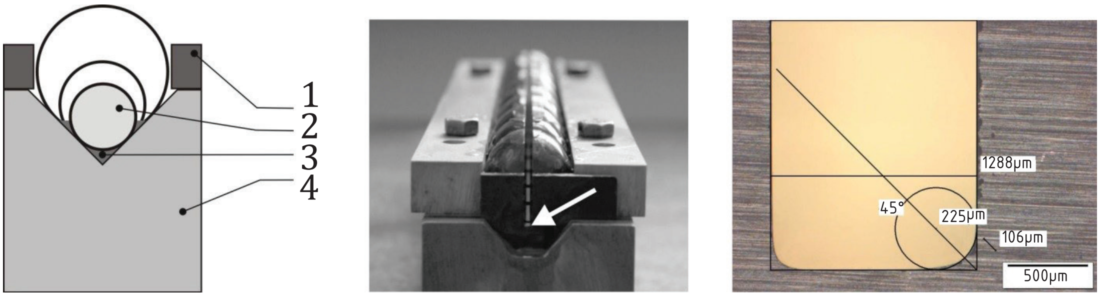
V-block system for preparation of the notch

The V-block system to produce defined notches in balls is shown in Figure C.1. Here, a series of balls is glued in a V-groove of a rail and afterwards slotted with a diamond blade. This means that many test pieces are prepared in a process step with the same notch geometry. The V-block system essentially consists of the following three components:

a) The rail with V-groove (90° prism block) is schematically sketched in Figure C.1 a) (Key 4). By this type of support, the test surface and in particular point A (see Figure 1 and Figure 2) of the balls are not in contact with another surface and therefore cannot be damaged. The V-groove shall be parallel to the cutting direction and shall be free from dust and grease. The groove in the rail may be also made in trapezoidal shape, as in Figure C.1 b), to reduce the amount of necessary glue (it shall be guaranteed that the test surface at the bottom of the ball does not touch the ground of the rail). There may be auxiliary rails (key item 1) used to form the additional fixing points for stabilizing the glue. It shall be ensured that these auxiliary rails do not clamp the balls mechanically in any way.

b) The end plate is cut together with the balls in the same preparation step and serves at the same time as a stop and to fix the balls (see arrow in Figure C.1 b)). A corresponding device for positioning of the end plate (e.g. notch at the end of the rail transversely to the groove) is recommended. If the end plate is in proper alignment to the cutting direction, it is allowed to measure the notch root geometry at this end plate (see Figure C.1 c)).

c) The glue is used to fix the balls in the V-groove during the preparation. It shall wet the balls, rail and end plate sufficiently. The glue shall be soluble in a suitable solvent in order to ensure a good cleaning. If a thermal treatment is required, it is recommended to use a thermoplastic that can be easily processed at a temperature of about 150 °C (i.e. no decomposition and sufficient reduction of viscosity).



a) Schematic cross section of the V-groove rail and ball

b) Example for a batch of notched balls incl. end plate (marked by white arrow) for measuring the notch root geometry

c) Example for measuring the notch root geometry

Key

1 auxiliary rails

2 test pieces (balls) before notching

3 glue

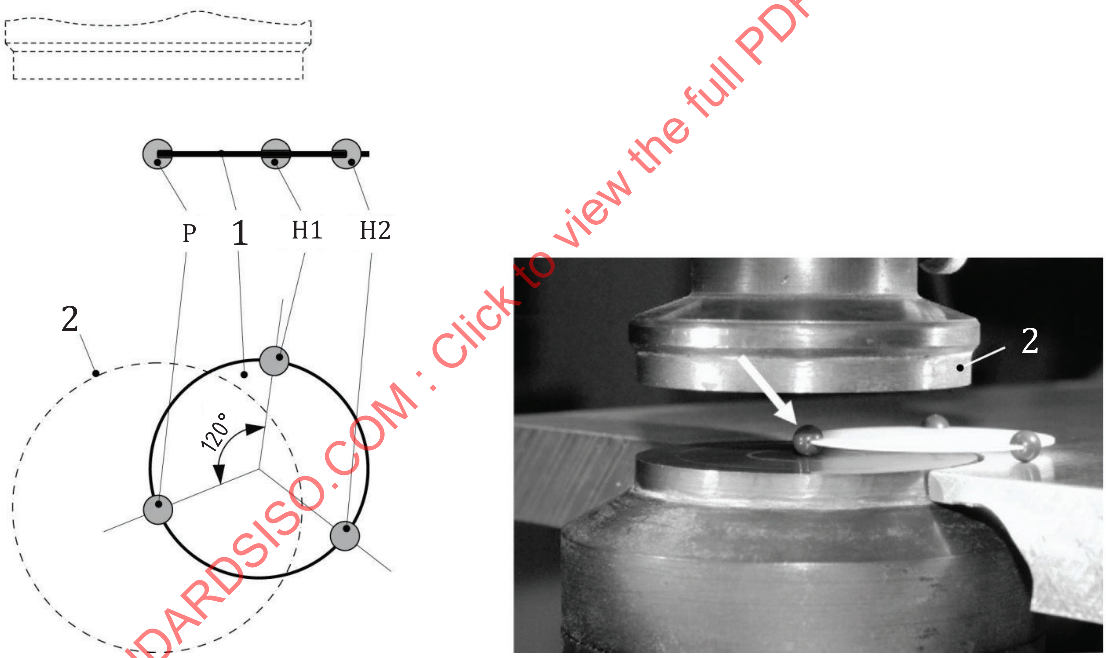
4 rail with V-groove

Figure C.1 — V-block system for preparation of the notch

Annex D
(informative)

Positioning aid

For the horizontal orientation of the notch in the notched ball test, a "tripod" can be used as a simple and sufficiently accurate positioning aid (see also Reference [8]). For this purpose, a circular plate is used with a diameter of about 10 D_W and a thickness of about 0,9 w. Position three balls equidistantly slotted onto the edge of the plate with the test ball in the loading position (see Figure D.1). The plate and thus also the notches in the ball can be aligned parallel to a horizontal reference surface (e.g. lower punch surface or flush auxiliary surface). The three notched balls shall stably rest on the reference surface; they should have the same diameter and very similar notch geometries; preferably, they should be produced in the same preparation step. Previously, a cleaning of the balls and the plate is required. The auxiliary balls can also be fixed on the plate. This can also be modified such that it serves as a centering aid to ease a centered positioning of the test piece in the loading device. The positioning aid shall be removed immediately before the start of the test, i.e. after application of the preload F_0.



a) **Front view and ground view** b) **Positioning example**

Key

P test piece (marked with an arrow in Figure D.1 b))

H1, H2 auxiliary balls

1 (circular) plate

2 anvil(s)

NOTE The notch midplane is parallel regarding the anvil surface.

Figure D.1 — Positioning aid for positioning the test piece in the loading device

