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Measurement uncertainties in mechanical tests on metallic materials — The evaluation of uncertainties in tensile testing

Incertitudes de mesure dans les essais mécaniques sur matériaux métalliques — Évaluation des incertitudes pour les essais de traction

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Foreword

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This document was prepared by Technical Committee ISO/TC 164, *Mechanical testing of metals*, Subcommittee SC 1, *Uniaxial testing*.

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

This document is based on a CEN Workshop Agreement which was issued in 2005 following a trilogy of documents concerned with measurement uncertainties in mechanical tests on metallic materials. The trilogy includes three documents, one concerned with the evaluation of uncertainties in low cycle fatigue testing, one with creep testing and this document focused on tensile testing.

For a meaningful estimate of uncertainty, all primary sources of uncertainty are to be included and their effects are to be properly quantified in the analyses. Reporting and interpreting the results of the calculations is also of utmost importance.

The calculations given in this document only capture the uncertainty associated with the uncertainty of the testing equipment's sensors over a short time scale. The uncertainty of a test result is dependent on much more than the uncertainty of the testing equipment's sensors.

Contributions to uncertainty due to misalignment, long-term environmental effects, and intermittent procedural errors, to name a few, are not included in these analyses. This is demonstrated by the results of the interlaboratory reproducibility in Annex C compared to the example given in Annex B.

A more realistic value of the uncertainty of the properties of material can be estimated using reproducibility data from laboratory intercomparisons involving several laboratories.

Results from reproducibility tests also include contributions to uncertainty from material inhomogeneity, different testing machines, controlling, and processing software together with the influence of different operators.

This document is based on CWA 15261-2[1)] and UNCERT CoP 07[1]. It describes a method for evaluating the uncertainty in tensile test results obtained from a series of tests that are performed in accordance with ISO 3534-3,[2] ISO 5725 series,[3] ISO 6892-1,[4] ISO 6892-2,[5] ISO 9513,[6] ISO Guides 33[7] and 35[8]. For a general introduction on the subject of uncertainty in measurement and testing refer to References [12] and [13].

1) Withdrawn

Measurement uncertainties in mechanical tests on metallic materials — The evaluation of uncertainties in tensile testing

1 Scope

This document describes how the evaluation of uncertainties in tensile tests can be obtained from tests at room temperature (ISO 6892-1) or elevated temperature (ISO 6892-2).

This document reports how it can be applied to tests performed at ambient and elevated temperatures under axial loading conditions with a digital acquisition of force and displacement.

NOTE 1 As CWA 15261-2[2)] and UNCERT CoP 07[1] reports, the tests are assumed to run continuously without interruptions on test pieces that have uniform gauge lengths.

NOTE 2 Annex C gives for information an indication of the typical scatter in tensile test results for a variety of materials that have been reported during laboratory inter-comparison exercises.

2 Normative references

There are no normative references in this document.

3 Terms, definitions and symbols

3.1 Terms and definitions

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

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

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

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

3.1.1
coverage factor
number that, when multiplied by the combined standard uncertainty, produces the expanded uncertainty

Note 1 to entry: It is dependent on the confidence level (e.g., 95 % probability). It also depends on the effective degrees of freedom.

3.1.2
level of confidence
probability that the value of the measurand lies within the quoted range of uncertainty

3.1.3
measurand
specific quantity being reported as the measurement result

Note 1 to entry: A measurand can be a direct test reading or an estimate of a material property from other readings.

2) Withdrawn.

3.1.4
measurement
set of operations having the object of determining a value of the measurand

3.1.5
result
distinction is made between:

3.1.5.1
result of a measurement
value attributed to the measurand, obtained by measurement

3.1.6
standard deviation
positive square root of the variance

3.1.7
uncertainty of measurement
parameter, associated with the result of a measurement, that defines the range within which a specific fraction of the distribution of values that could reasonably be attributed to the measurand is estimated to fall (within a given confidence)

3.1.8
standard uncertainty
estimated standard deviation or estimated positive square root of the variance

3.1.9
expanded uncertainty
value obtained by multiplying the combined standard uncertainty by a coverage factor

3.1.10
variance
measure of the dispersion of a set of *n* measurement results. It is the sum of the squares of the deviations of the measurement results from the average, divided by *n-1*

3.2 Symbols

The symbols used in this document and corresponding designations are given in Table 1.

Table 1 — Symbols and corresponding designations

Symbol	Unit	Designation
a_o	mm	Original thickness of a flat test piece
a_u	mm	Minimum thickness after fracture
b_o	mm	Original width of the parallel length of a flat test piece
b_u	mm	Minimum width after fracture
d_o	mm	Original diameter of the parallel length of a circular test piece
d_u	mm	Minimum diameter of a circular test piece after fracture
m_E	MPa	Slope of the elastic part of the stress-extension curve
E	GPa [a]	Young's modulus (modulus of elasticity)
F	N	Force
ΔF	N	Force increment
F_{eH}	N	Force at R_{eH}
F_{eL}	N	Force at R_{eL}

[a] 1 MPa = 1 N/mm^2; 1 GPa = 1 kN/mm^2.

[b] Depends on the property concerned.

Table 1 *(continued)*

Symbol	Unit	Designation
F_p	N	Force at R_p
F_m	N	Maximum force
L_o	mm	Original gauge length
L_e	mm	Extensometer gauge length
L_u	mm	Gauge length after fracture
n	-	Number of readings or results or evaluated data pairs in the linear regression or numerical coefficient NOTE This is also used for other parameters e.g., number of samples in a batch. (See 3.4.2).
R	MPa [a]	Stress
R_{eH}	MPa	Upper yield strength
R_{eL}	MPa	Lower yield strength
R_m	MPa	Tensile strength
R_p	MPa	Proof strength, plastic extension (e.g., 0,2 %, $R_{p0,2}$)
A	%	Percentage elongation after fracture
S_o	mm^2	Original cross-sectional area
S_u	mm^2	Smallest cross-sectional area after fracture
Z	%	Percentage reduction of area after fracture
u	[b]	Standard uncertainty (in general)
$u(x_i)$	[b]	Standard uncertainty on measurement x_i
u_c	[b]	Combined uncertainty (in general)
y	[b]	Test (or measurement) mean result
$u_c(y)$	[b]	Combined uncertainty on the mean result of a measurement
Y	[b]	Evaluated value of the measurand
d_v	-	Divisor associated with the assumed probability distribution
c	[b]	Sensitivity coefficient (in general)
c_i	[b]	Sensitivity coefficient associated with uncertainty on measurement x_i
c_T	[b]	Temperature sensitivity coefficient
x_i	[b]	Individual value
$\bar{x}$	[b]	Arithmetic mean
s	[b]	Sample standard deviation
a , δ	[b]	Mid-point value between the upper and lower limits NOTE Subscripts corresponding to the concerned property, e.g., δ_{ao}.
k, k_p	-	Coverage factor
U	[b]	Expanded uncertainty
ν_{eff}	-	Effective degrees of freedom given by the Welsh-Satterthwaite method
f	-	Degree of freedom (n – 1)
Y	[b]	Evaluated value of the measurand
p	%	Coverage probability; confidence level
t	-	Factor of Student's distribution
m	[b]	Slope of the regression line or strain rate sensitivity NOTE Subscript corresponding to the concerned property, e.g., m_E.
b	[b]	Intercept in the regression line

[a] 1 MPa = 1 N/mm^2; 1 GPa = 1 kN/mm^2.

[b] Depends on the property concerned.

Table 1 *(continued)*

Symbol	Unit	Designation
S_{xy}	b	Empirical covariance in the linear regression
S_x	b	Standard deviation of x-values in the linear regression
S_y	b	Standard deviation of y-values in the linear regression
r	-	Correlation coefficient in the linear regression
S_m	b	Standard deviation of the slope of the regression line
S_b	b	Standard deviation of the intercept of the regression line
$S_{m(\text{rel})}$	-	Bound regarding the upper and the lower proportional limit for the determination of Young's modulus in the linear regression
ΔL	mm	Displacement increment based on initial gauge length
ΔL_{pl}	mm	Plastic displacement
ΔL_{z}	mm	Calculated zero-point
ΔL_{el}	mm	Elastic displacement
$A_{(a)}$	%	Elongation automatically given by an extensometer
$A_{(m)}$	%	Elongation determined manually
e	-	Strain / extension
$\dot{e}$	s^{-1}	Strain rate
e_{pl}	-	Plastic strain
$e_{(\text{rupt})}$	-	Strain at fracture
$R_{(\text{rupt})}$	MPa	Stress at fracture
$C_{A(m)}$	%	Correction in comparison with the percentage elongation value measured manually
σ	MPa	True stress
ε	-	True plastic strain
$\dot{\varepsilon}$	s^{-1}	True plastic strain rate
m'		Strain rate sensitivity
K'	MPa	Material flow stress at a true strain rate of unity
T	°C	Ambient temperature during testing
n', σ_{yo}, T_1, C_{o}	b	Numerical coefficients

a 1 MPa = 1 N/mm²; 1 GPa = 1 kN/mm².

b Depends on the property concerned.

4 Steps for the evaluation of uncertainty

4.1 General

Figure 1 shows the different steps for the evaluation of uncertainty.

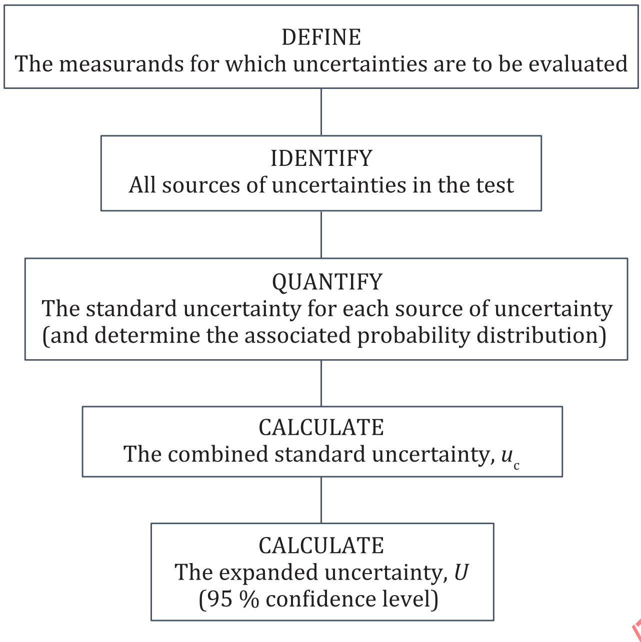

Figure 1 — Steps for the evaluation of uncertainty

4.2 Step 1 — Defining the measurands for which uncertainty is to be evaluated

The measurands (quantities) for which the uncertainties are to be calculated are listed.

Table 2 shows the measurands that can be reported in tensile testing. These measurands are measured directly or are not measured directly and are determined from other quantities (or measurements).

Table 2 — Measurands, measurements and their units and symbols

Measurand	Unit	Symbol
Original cross-sectional area	mm^2	S_o
Slope of the elastic part of the stress-extension curve	MPa	m_E
Proof strength at 0,2 % plastic extension	MPa	$R_{p0,2}$
Upper yield strength	MPa	R_{eH}
Lower yield strength	MPa	R_{eL}
Tensile strength	MPa	R_m
Percentage elongation after fracture	%	A
Percentage reduction of area	%	Z
Test piece original thickness (rectangular test piece)	mm	a_o
Test piece original width (rectangular test piece)	mm	b_o
Test piece original diameter (circular test piece)	mm	d_o
Original gauge length	mm	L_o
Force applied during test	N	F
Axial displacement during the test	mm	ΔL
Final gauge length	mm	L_u
Minimum diameter of a circular test piece after fracture	mm	d_u

[a] The Young's-modulus is not usually reported in tensile testing (only if ISO 6892-1:2019, Annex G is applied).

The measurands not measured are calculated with Formulae (1) to (9):

for rectangular test piece see Formula (1):

$$S_o = a_o \cdot b_o \tag{1}$$

for circular test piece see Formula (2):

$$S_o = d_o^2 \cdot \pi/4 \tag{2}$$

for slope of beginning of stress-extension curve see Formula (3):

$$m_E = \Delta R/\Delta e = (\Delta F \cdot L_o)/(\Delta L \cdot S_o) \tag{3}$$

for proof strength see Formula (4):

$$R_p = F_p/S_o \tag{4}$$

for upper yield strength see Formula (5):

$$R_{eH} = F_{eH}/S_o \tag{5}$$

for lower yield strength see Formula (6):

$$R_{eL} = F_{eL}/S_o \tag{6}$$

for tensile strength see Formula (7):

$$R_m = F_m/S_o \tag{7}$$

for percentage elongation after fracture see Formula (8):

$$A = (L_u - L_o) \cdot 100/L_o \tag{8}$$

for percentage reduction of area see Formula (9):

$$Z = (S_o - S_u) \cdot 100/S_o \tag{9}$$

4.3 Step 2 — Identifying all sources of uncertainty in the test

All possible sources of uncertainty that can have an effect (either directly or indirectly) on the test are identified.

The list cannot be identified comprehensively beforehand as it is associated uniquely with the individual test procedure and apparatus used. A new list can be prepared each time a particular test parameter changes. To help the user list all sources, four categories have been defined. Table 3 lists these categories and gives some examples of the sources of uncertainty in each category.

Table 3 — An example of sources of uncertainty and their likely contribution to the uncertainties in tensile testing measurands for a cold rolled steel (sheet type test piece) at ambient temperature performed by a screw driven tensile testing machine [a]

Source of uncertainty	Type [b]	m_E	$R_{p0,2}$	R_{eH}	R_{eL}	R_m	A	Z
1. Test piece								
Variability of specimen dimensions	B	1	1	1	1	1	1	1
Surface finish	B	0	2	2	2	2	2	2
Residual stresses	B	0	2	2	2	?	?	?
Shape and size of test piece	B	1	1	1	1	2	1-2	1-2
Shape of fracture	B	0	0	0	0	0	1	1
Location of failure	B	0	0	0	0	0	1	1-2
2. Test system								
Cross-sectional area measuring unit	B	1	1	1	1	1	0	1
Original gauge length	B	1	1	0	0	0	1	0
Extensometer positioning	B	1	1	0	0	0	1	0
Load train alignment	B	1	1	1	1	1	1	2
Test machine stiffness	B	1	1	1	1	2	2	2
Uncertainty in force measurement	B	1	1	1	1	1	0	0
Uncertainty in displacement measurement	B	1	1	0	0	0	1	0
3. Environment								
Ambient temperature and humidity	B	2	2	2	2	2	2	2
4. Test Procedure								
Zeroing	B	2	1	1	1	1	1	2
Stressing rate	B	2	1	1	1	1	1-2	2
Straining rate	B	2	1	1	1	1	1	1
Digitizing	B	1	1	1	1	1	1	1
Sampling frequency	B	1	1	1	1	2	2	0
Uncertainty in fracture area measurement	B	0	0	0	0	0	0	1
Software	B	1	1	1	1	2	2	0

NOTE This table is not exhaustive and is for guidance only; relative contributions can vary according to the material tested and the test conditions. Individual laboratories are encouraged to prepare their own list to correspond to their own test facility and assess the associated significance of the contributions.

[a] 1 = major contribution, 2 = minor contribution, 0 = insignificant or no contribution (zero effect), ? = unknown.

[b] See 4.4 and References [1] and [9].

To simplify the uncertainty calculations, it can be advisable to regroup the significant sources affecting the tensile testing results in Table 3 into one of the following four categories:

— Uncertainty due to the measurement of cross-sectional area

— Uncertainty due to the force measurement

— Uncertainty due to the displacement measurement

— Uncertainty due to evaluated quantities (e.g. proof strength)

The worked examples in Annex B use the above categorisation when assessing uncertainties.

4.4 Step 3 — Estimating the standard uncertainty for each source of uncertainty

4.4.1 General

Sources of uncertainty are classified as Type A or Type B, depending on the way their influence is quantified.[1],[9] If the uncertainty is evaluated by statistical means from a number of repeated observations, it is classified as Type A. If it is evaluated by any other means it is classified as Type B. The values associated with Type B uncertainties can be obtained from a number of sources including calibration certificates, manufacturers' information, or an expert's estimation. For Type B uncertainties, it is necessary for the user to estimate for each source the most appropriate probability distribution.

The measurement process can usually be modelled by a functional relationship between the estimated input quantities and the output in the form given by Formula (10):

$$y = f(x_1, x_2, \ldots, x_m) \tag{10}$$

The standard uncertainty requires the determination of the associated sensitivity coefficient, c, which is usually evaluated from the partial derivatives of the functional relationship between the output quantity (the measurand) and the input quantities. The calculations required to obtain the sensitivity coefficients by partial differentiation can be a lengthy process, particularly when there are many individual contributions and uncertainty estimates are needed for a range of values. If the functional relationship for a particular measurement is not known, the sensitivity coefficients can be obtained experimentally. In some cases, the input quantity to the measurement might not be in the same units as the output quantity. For example, one contribution to $R_{p0,2}$ is the test temperature. In this case the input quantity is temperature, but the output quantity is the stress that is in MPa. In such a case, a sensitivity coefficient, c_T (corresponding to the partial derivative of the proof strength/ test temperature relationship), is used to convert from temperature to MPa (for more information see Annex A).

Subsequent calculations will be made clearer if, wherever possible, all components are expressed in the same way (e.g., either in the same units as used for the reported result or in relative terms, i.e., in percent.).

The standard uncertainty is defined as one standard deviation and is derived from the uncertainty of the input quantity divided by a factor, d_v, associated with the assumed probability distribution. Divisors for the typical probability distributions most likely to be encountered are shown in Table 4.

Table 4 — Typical values of the divisor d_v

Probability distribution	d_v
Normal	1
Rectangular	$\sqrt{3}$
Triangular	$\sqrt{6}$

4.4.2 Type A evaluation of standard uncertainty

For a series of n repeated readings, the estimated standard uncertainty, u, of the arithmetic mean, $\bar{x}$, is calculated from the Formula (11):

$$u = \frac{s}{\sqrt{n}} \tag{11}$$

where s is the sample standard deviation given by Formula (12):

$$s = \sqrt{\frac{1}{(n-1)} \sum_{i=1}^{n} (x_i - \bar{x})^2} \tag{12}$$

4.4.3 Type B evaluation of standard uncertainty

The standard uncertainty of an input quantity that has not been obtained from repeated measurements can be evaluated by scientific judgment based on all of the available information on the possible contributing factors. The information can include:

— data provided in calibration and other certificates;

— manufacturer's specification;

— previous measurement data;

— experience with or general knowledge of the behaviour of the relevant materials and instruments;

— uncertainties assigned to reference materials;

— uncertainties assigned to reference data taken from handbooks.

For most Type B evaluations:

— estimate the upper and lower limits of uncertainty, and,

— assume e.g., a rectangular probability distribution (i.e., the value is equally likely to fall anywhere in between the upper and lower limits). The standard uncertainty for a rectangular distribution is by Formula (13):

$$u = \frac{a}{\sqrt{3}} \quad (13)$$

where a is the mid-point value between the upper and lower limits. Rectangular distributions are quite common but other distributions can occur. For example, the uncertainty, U, often stated on an instrument's calibration certificate is usually a normal distribution. In this case, the standard uncertainty is given by Formula (14):

$$u = \frac{U}{k} \quad (14)$$

where k is the coverage factor.

4.4.4 Uncertainty due to repeatability of measurement

Repeatability of measurement is a component that is included in the uncertainty calculations. Simply put, repeatability represents the variability within a single laboratory (otherwise known as intra-laboratory testing). In practice this can involve one or more operators (following the same test procedure) using one or more sets of equipment over a reasonably short period of time during which neither the equipment nor the environment is likely to change appreciably. The variability can be random in nature and due to small changes in equipment, calibration, environment, and operator procedure. In material-dependent, destructive tests such as the subject matter in this practice, this variability will inevitably be affected also by some heterogeneity in the material tested. This can be kept to a minimum by the use of test pieces from a careful choice of test material.

In this practice, in the absence of information on the repeatability of measurement on the particular material or batch being tested, an estimate of the repeatability from a similar material or batch can be used in the uncertainty calculations. This can be included in the uncertainty report.

For a reasonably large set of data (e.g. 10 or more), repeatability is represented by one standard deviation, s. The associated uncertainty in the mean of n measurements is given by Formula (15):

$$u = \frac{s}{\sqrt{n}} \quad (15)$$

NOTE For smaller sample sizes see 4.6.

4.5 Step 4 — Computing the combined uncertainty, u_c

Assuming that individual uncertainty sources are uncorrelated, the measurand's combined uncertainty, $u_c(y)$, can be computed using the root sum squares using Formula (16):

$$u_c(y)=\sqrt{\sum_{i=1}^{n}[c_i u(x_i)]^2} \quad (16)$$

where c_i is the sensitivity coefficient associated with x_i.

This uncertainty corresponds to ± one standard deviation on the normal distribution law representing the studied quantity. The combined uncertainty has an associated confidence level of 68,27 %.

4.6 Step 5 — Computing the expanded uncertainty, *U*

The expanded uncertainty, *U*, is obtained by multiplying the combined uncertainty, u_c, as calculated in 4.5, by a coverage factor, *k* or k_p, which is selected on the basis of the level of confidence required (ISO/IEC Guide 98-3). For a normal probability distribution, the most generally used coverage factor is 2 that corresponds to a confidence interval of 95,45 % (effectively 95 % for most practical purposes). Where a higher confidence level is demanded by the customer (such as for aerospace and electronics industries), a coverage factor of 3 is often used so that the corresponding confidence level increases to 99,73 %.

In cases where the probability distribution of u_c is not normal or where the number of data points used in *Type A* analysis is small, a coverage factor k_p can be determined according to the effective degrees of freedom, ν_{eff}, given by the Welsh-Satterthwaite method in Formula (17) (see also ISO/IEC Guide 98-3:2008, Annex G for details):

$$\nu_{eff}=\frac{u_c^4(y)}{\sum_{i=1}^{n}\frac{u_i^4(y)}{\nu_i}} \quad (17)$$

Table 5 shows the values of the coverage factor k_p for a level of confidence of 95 %.

Table 5 — Student's *t*-distribution table

ν_{eff}	1	2	3	4	5	6	7	8	10	12	14	16
k_p	13,97	4,53	3,31	2,87	2,65	2,52	2,43	2,37	2,28	2,23	2,20	2,17
ν_{eff}	18	20	25	30	35	40	45	50	60	80	100	∞
k_p	2,15	2,13	2,11	2,09	2,07	2,06	2,06	2,05	2,04	2,03	2,02	2,00

Tables B.1 to B.4 show an example format of the calculation worksheets for estimating the uncertainty in Young's modulus and proof strength for a rectangular test piece. Annex A presents the mathematical formulae for calculating uncertainty contributions.

5 Reporting of results

Once the expanded uncertainty has been evaluated, the results can be reported as in Formula (18):

$$Y = y \pm U \quad (18)$$

where

- *Y* is the evaluated value of the measurand;
- *y* is the test (or measurement) mean result;
- *U* is the expanded uncertainty associated with *y*.

An explanatory note, such as that given in the following example can be added (change where appropriate):

EXAMPLE The reported expanded uncertainty is based on a standard uncertainty multiplied by a coverage factor, $k = 2$ (or k_p = state value), which for a normal distribution provides a level of confidence of approximately 95 %. The uncertainty evaluation was carried out in accordance with ISO/TR 15263.

Details describing how the uncertainties were estimated can be appended to the test report. The extent of the details can be agreed between the customer and the testing laboratory and can enable the customer to reproduce the reported uncertainty calculations.

Annex A
(informative)

Mathematical formulae for calculating uncertainties in tensile testing

NOTE 1 To simplify matters Clauses A.1 to A.11 are limited to uncertainty affected by calibration, determination of cross-sectional area, and evaluation procedure. With the exception of Clauses A.12 and A.13, it was not necessary to study the mechanical behaviour of metallic materials under different conditions or to consult published analyses. Basic concepts can be used. The methods of DOE (Design of Experiments) can be used for further studies to consider the many parameters that affect results.

NOTE 2 The measurement uncertainties stated in calibration certificates of calipers or micrometers employed for dimensional measurments are not representing the full uncertainty budget of their dedicated application and therefore the stated uncertainties are not appropriate for direct use as standard uncertainties u in the above formulae.

A.1 Uncertainty of measurements

A.1.1 General

The x_i, the expectation or expected value of X_i is the midpoint of the range: $x_i = (LL + UL)/2$, with variance given in Formulae (A.1) to (A.3):

$$u^2(x_i) = \frac{(UL - LL)^2}{12} \tag{A.1}$$

If the difference between two bounds, $UL - LL$, is denoted by 2δ, then Formula (A.1) can be written as Formula (A.2):

$$u^2(x_i) = \frac{\delta^2}{3} \tag{A.2}$$

Example Variance of test piece original thickness (rectangular test piece) a_o can be written as Formula (A.3):

$$u^2(a_o) = \frac{\delta_{a_o}^2}{3} \tag{A.3}$$

If the thickness has been measured n times (and at least 5 times), the bounds can be estimated with Formula (A.4) as follows:

— determine the mean value of a_o and the standard deviation s;

— determine the confidence region of the mean value:

$$u(a_o) = \frac{s \cdot t(p, f)}{\sqrt{n}} \tag{A.4}$$

where

t	is the factor of Student's distribution;
p	is the confidence level;
f	is the degrees of freedom (n – 1);
n	is the number of measurements.

For p = 68,27 % and n = 5, the factor t = 1,15.

A.2 Uncertainty due to errors in the measurement of the cross-sectional area

A.2.1 Rectangular test piece

For a rectangular test piece, see Formula (A.5):

$$S_o = a_o \cdot b_o \tag{A.5}$$

Sensitivity coefficients c_i associated with the uncertainty on the measurement x_i, see Formulae (A.6) and (A.7):

$$\frac{\partial S_o}{\partial a_o} = b_o \tag{A.6}$$

$$\frac{\partial S_o}{\partial b_o} = a_o \tag{A.7}$$

Uncertainty in S_o, see Formula (A.8):

$$u_c(S_o) = \sqrt{(b_o)^2 u^2(a_o) + (a_o)^2 u^2(b_o)} \tag{A.8}$$

A.2.2 Circular test piece

For a circular test piece, see Formula (A.9):

$$S_o = \frac{\pi \cdot d_o^2}{4} \tag{A.9}$$

Sensitivity coefficients c_i associated with the uncertainty on the measurement x_i, see Formula (A.10):

$$\frac{\partial S_o}{\partial d_o} = \frac{\pi \cdot d_o}{2} \tag{A.10}$$

Uncertainty in S_o, see Formula (A.11):

$$u_c(S_o) = \sqrt{\frac{d_o^2 \pi^2 u^2(d_o)}{4}} \tag{A.11}$$

A.3 Uncertainty in stress

For calculations of stress values, see Formula (A.12):

$$R = \frac{F}{S_o} \tag{A.12}$$

Sensitivity coefficients c_i associated with the uncertainty on the measurement x_i, of stress values, see Formulae (A.13) and (A.14):

$$\frac{\partial R}{\partial F} = \frac{1}{S_o} \tag{A.13}$$

$$\frac{\partial R}{\partial S_o} = -\frac{F}{S_o^2} \tag{A.14}$$

Uncertainty in R, see Formula (A.15):

$$u_c(R) = \sqrt{\left(\frac{1}{S_o}\right)^2 u^2(F) + \left(-\frac{F}{S_o^2}\right)^2 u^2(S_o)} \tag{A.15}$$

A.4 Uncertainty in strain

For calculations of strain / extension values, see Formula (A.16):

$$e = \frac{\Delta L}{L_o} \tag{A.16}$$

Sensitivity coefficients c_i associated with the uncertainty on the measurement x_i, of strain / extension values, see Formulae (A.17) and (A.18):

$$\frac{\partial e}{\partial \Delta L} = \frac{1}{L_o} \tag{A.17}$$

$$\frac{\partial e}{\partial L_o} = -\frac{\Delta L}{L_o^2} \tag{A.18}$$

Uncertainty in u_e, see Formula (A.19):

$$u_c(e) = \sqrt{\left(\frac{1}{L_o}\right)^2 u^2(\Delta L) + \left(-\frac{\Delta L}{L_o^2}\right)^2 u^2(L_o)} \tag{A.19}$$

A.5 Uncertainty in initial slope of the stress-extension curve m_E

A.5.1 Formulae for linear regression

For calculations of straight lines, see Formula (A.20):

$$y = mx + b \tag{A.20}$$

Slope calculation, see Formula (A.21):

$$m = \frac{n\sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{n\sum_{i=1}^{n} x_i^2 - (\sum_{i=1}^{n} x_i)^2} \tag{A.21}$$

Intercept calculation, see Formula (A.22):

$$b = \frac{\sum_{i=1}^{n} y_i - m\sum_{i=1}^{n} x_i}{n} \tag{A.22}$$

Empirical covariance (S_{xy}), see Formula (A.23):

$$S_{xy} = \frac{1}{n-1}\left[\sum_{i=1}^{n} x_i y_i - \frac{\sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{n}\right] \tag{A.23}$$

Standard deviation of *x*-values, see Formula (A.24):

$$S_x = \sqrt{\frac{1}{n-1}\left[\sum_{i=1}^{n} x_i^2 - \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n}\right]} \tag{A.24}$$

Standard deviation of *y*-values, see Formula (A.25):

$$S_y = \sqrt{\frac{1}{n-1}\left[\sum_{i=1}^{n} y_i^2 - \frac{\left(\sum_{i=1}^{n} y_i\right)^2}{n}\right]} \tag{A.25}$$

Correlation coefficient (r), see Formula (A.26):

$$r = \frac{S_{xy}}{S_x \cdot S_y} \tag{A.26}$$

Standard deviation of the slope (S_m), see Formula (A.27):

$$S_m = \sqrt{\frac{\left(1-r^2\right)S_y^2}{(n-2)S_x^2}} \quad \text{(A.27)}$$

Standard deviation of the intercept (S_b), see Formula (A.28):

$$S_b = \sqrt{S_m^2 \frac{(n-1)S_x^2 + \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n}}{n}} \quad \text{(A.28)}$$

Bound regarding the upper and the lower proportional limit for the determination of the initial slope of the stress-extension curve, see Formula (A.29):

$$S_{m(\text{rel})} = \frac{S_m}{m} \rightarrow \ \text{minimum} \quad \text{(A.29)}$$

The data pair for the minimum of $S_{m(\text{rel})}$ represents the upper and the lower elastic limit.

A.5.2 Combined uncertainty of m_E

The linear regression is used to determine the linear relationship between force and displacement, see Formulae (A.30) and (A.31):

$$m_E = \frac{F \cdot L_o}{\Delta L \cdot S_o} = m \cdot \frac{L_o}{S_o} \quad \text{(A.30)}$$

$$F = m \cdot \Delta L + b \quad \text{(A.31)}$$

Therefore:

$F = y$ see Formula (A.20)

$\Delta L = x$ see Formula (A.20)

$S_{\Delta L,F} = S_{xy}$ see Formula (A.23)

$S_{\Delta L} = S_x$ see Formula (A.24)

$S_F = S_y$ see Formula (A.25)

Sensitivity coefficients, c_i, associated with the uncertainty on the measurement, x_i, see Formulae (A.32) to (A.35):

$$\frac{\partial m_E}{\partial m} = \frac{L_o}{S_o} \quad \text{(A.32)}$$

$$\frac{\partial m_E}{\partial L_o} = \frac{m}{S_o} \quad \text{(A.33)}$$

$$\frac{\partial m_E}{\partial S_o} = -\frac{m \cdot L_o}{S_o^2} \quad \text{(A.34)}$$

$$u_c(m_E) = \sqrt{\left(\frac{L_o}{S_o}\right)^2 u^2(m) + \left(\frac{m}{S_o}\right)^2 u^2(L_o) + \left(-\frac{mL_o}{S_o^2}\right)^2 u^2(S_o)} \quad \text{(A.35)}$$

A.6 Uncertainty in the determination of proof strengths

The proof strengths are determined by methods using the series of values of force-displacement or force-extension as defined in the relevant testing standards (e.g., ISO 6892-1[4]) and as illustrated by Figure A.1, see also Formulae (A.36) to (A.38).

$$\Delta L_{pl} = \Delta L - \Delta L_z - \Delta L_{el} \text{ (plastic displacement)} \quad \text{(A.36)}$$

where

ΔL is the input data for displacement (e.g. recorded in ASCII-file);

ΔL_z is the calculated zero-point.

$$F = 0 \Rightarrow \Delta L_z = -\frac{b}{m} \quad \text{(A.37)}$$

$$\Delta L_{el} = \frac{F}{m} \text{ (elastic displacement)} \quad \text{(A.38)}$$

F is the input data of force (e.g., recorded in ASCII-file), see Formula (A.39):

$$b \geq 0 \Rightarrow \Delta L_z \leq 0 \Rightarrow \Delta L_{pl} = \Delta L + \frac{b-F}{m} \quad \text{(A.39)}$$

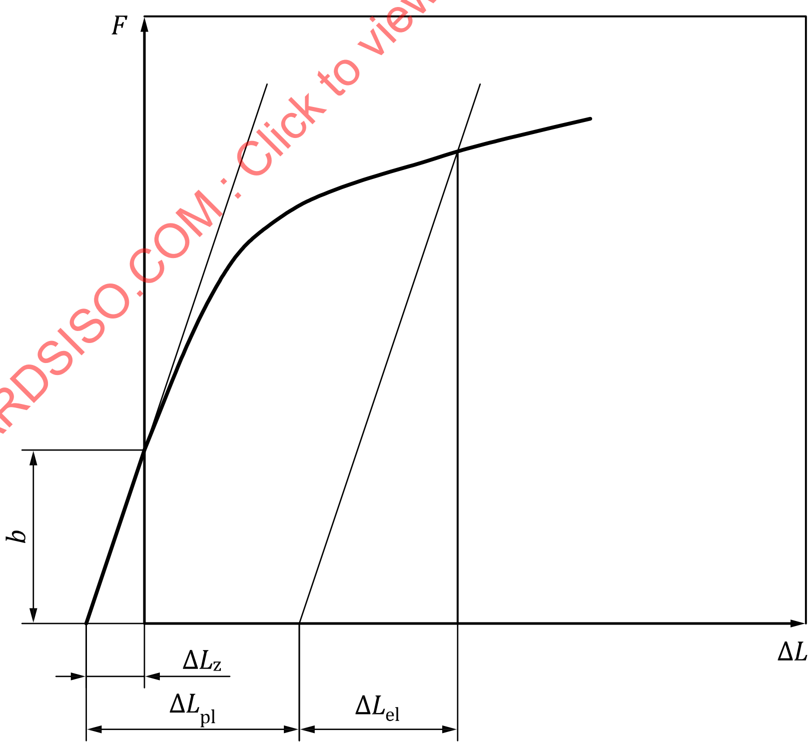

Figure A.1 — Determination of proof strengths

For calculations of plastic strains, see Formula (A.40):

$$e_{pl} = \frac{\Delta L}{L_o} + \frac{b-F}{m \cdot L_o} \tag{A.40}$$

Sensitivity coefficients, c_i, associated with the uncertainty on the measurement x_i, of plastic strain values, see Formulae (A.41) to (A.45):

$$\frac{\partial e_{pl}}{\partial \Delta L} = \frac{1}{L_o} = c_1 \tag{A.41}$$

$$\frac{\partial e_{pl}}{\partial L_o} = -\frac{\Delta L}{L_o^2} - \frac{(b-F)}{m \cdot L_o^2} = c_2 \tag{A.42}$$

$$\frac{\partial e_{pl}}{\partial b} = \frac{1}{m \cdot L_o} = c_3 \tag{A.43}$$

$$\frac{\partial e_{pl}}{\partial F} = -\frac{1}{m \cdot L_o} = c_4 \tag{A.44}$$

$$\frac{\partial e_{pl}}{\partial m} = -\frac{(b-F)}{m^2 \cdot L_o} = c_5 \tag{A.45}$$

Uncertainty in plastic strain e_{pl}, see Formula (A.46):

$$u_c(e_{pl}) = \sqrt{c_1^2 u^2(\Delta L) + c_2^2 u^2(L_o) + c_3^2 u^2(b) + c_4^2 u^2(F) + c_5^2 u^2(m)} \tag{A.46}$$

From the recorded force-displacement diagram (see Figure A.1), we obtain a polynomial to determine $u(F_{e_{pl}})$, see Formulae (A.47) to (A.49):

$$F_{e_{pl}} = \alpha_2 e_{pl}^2 + \alpha_1 e_{pl} + \alpha_o \tag{A.47}$$

$$\frac{\partial F_{e_{pl}}}{\partial e_{pl}} = 2\alpha_2 e_{pl} + \alpha_1 \tag{A.48}$$

$$u(F_{e_{pl}}) = \sqrt{(2\alpha_2 e_{pl} + \alpha_1)^2 u^2(e_{pl})} \tag{A.49}$$

Combined uncertainty in force at e_{pl}, see Formula (A.50):

$$u_c(F_{e_{pl}}) = \sqrt{u^2(F_{e_{pl}}) + u^2(F)} \tag{A.50}$$

Combined uncertainty in proof strength, see Formulae (A.51) and (A.52):

$$R_{p0,2} = \frac{F_{e_{pl}}}{S_o} \tag{A.51}$$

$$u_c(R_{p0,2}) = \sqrt{\left(\frac{1}{S_o}\right)^2 u_c^2(F_{e_{pl}}) + \left(-\frac{F_{e_{pl}}}{S_o^2}\right)^2 u^2(S_o)} \tag{A.52}$$

A.7 Uncertainty in determination of the tensile strength

For calculation of tensile strength values, see Formula (A.53):

$$R_m = \frac{F_m}{S_o} \tag{A.53}$$

and the sensitivity coefficients c_i associated with the uncertainty on the measurement of tensile strength, see Formulae (A.54) and (A.55):

$$\frac{\partial R_m}{\partial F_m} = \frac{1}{S_o} \tag{A.54}$$

$$\frac{\partial R_m}{\partial S_o} = -\frac{F_m}{S_o^2} \tag{A.55}$$

Uncertainty of R_m, see Formula (A.56):

$$u_c(R_m) = \sqrt{\left(\frac{1}{S_o}\right)^2 u^2(F_m) + \left(-\frac{F_m}{S_o^2}\right)^2 u^2(S_o)} \tag{A.56}$$

A.8 Uncertainty in determination of the upper yield strength

The calculation of the uncertainty of R_{eH} follows the same procedure as R_m, see Formula (A.57):

$$R_{eH} = \frac{F_{eH}}{S_o} \tag{A.57}$$

Sensitivity coefficients c_i associated with the uncertainty on the measurement x_i, see Formulae (A.58) and (A.59):

$$\frac{\partial R_{eH}}{\partial F_{eH}} = \frac{1}{S_o} \tag{A.58}$$

$$\frac{\partial R_{eH}}{\partial S_o} = -\frac{F_{eH}}{S_o^2} \tag{A.59}$$

Uncertainty of R_{eH}, see Formula (A.60):

$$u_c(R_{eH}) = \sqrt{\left(\frac{1}{S_o}\right)^2 u^2(F_{eH}) + \left(-\frac{F_{eH}}{S_o^2}\right)^2 u^2(S_o)} \tag{A.60}$$

A.9 Uncertainty in determination of the lower yield strength

Similarly, for the lower yield strength R_{eL}, see Formula (A.61):

$$R_{eL} = \frac{F_{eL}}{S_o} \tag{A.61}$$

Sensitivity coefficients c_i associated with the uncertainty on the measurement are, see Formulae (A.62) and (A.63):

$$\frac{\partial R_{eL}}{\partial F_{eL}} = \frac{1}{S_o} \tag{A.62}$$

$$\frac{\partial R_{eL}}{\partial S_o} = -\frac{F_{eL}}{S_o^2} \tag{A.63}$$

Uncertainty of R_{eL}, see Formula (A.64):

$$u_c(R_{eL}) = \sqrt{\left(\frac{1}{S_o}\right)^2 u^2(F_{eL}) + \left(-\frac{F_{eL}}{S_o^2}\right)^2 u^2(S_o)} \tag{A.64}$$

A.10 Uncertainty in the determination of the percentage elongation after fracture

A.10.1 Automatic extensometer

For an automatic extensometer, see Formula (A.65):

$$A_{(a)} = \left[e_{(RUPT)} - \frac{R_{(RUPT)}}{m_E} + C_{A(m)}\right] \cdot 100 \tag{A.65}$$

The value of $A_{(a)}$ depends on the location of the fracture within the parallel length of the test piece. $C_{A(m)}$ is the correction in comparison with the percentage elongation value measured by hand.

Sensitivity coefficients c_i associated with the uncertainty on the measurement x_i, see Formulae (A.66) to (A.69):

$$\frac{\partial A_{(a)}}{\partial e_{(RUPT)}} = 100 \tag{A.66}$$

$$\frac{\partial A_{(a)}}{\partial R_{(RUPT)}} = -\frac{1}{m_E} \cdot 100 \tag{A.67}$$

$$\frac{\partial A_{(a)}}{\partial m_E} = -\frac{R_{(RUPT)}}{m_E^{\ 2}} \cdot 100 \tag{A.68}$$

$$\frac{\partial A_{(a)}}{\partial C_{A(m)}} = 100 \tag{A.69}$$

Uncertainty of $A_{(a)}$, see Formula (A.70):

$$u_c(A_{(a)}) = \left[\sqrt{u^2(e_{(RUPT)}) + \left(-\frac{1}{m_E}\right)^2 u^2(R_{(RUPT)}) + \left(-\frac{R_{(RUPT)}}{m_E^{\ 2}}\right)^2 u^2(m_E) + u^2(C_{A(m)})}\right] \cdot 100 \tag{A.70}$$

A.10.2 Manual determination (e.g. vernier calliper)

For manual determination, see Formula (A.71):

$$A_{(m)} = \left(\frac{L_u - L_o}{L_o}\right) \cdot 100 \tag{A.71}$$

Sensitivity coefficients c_i associated with the uncertainty on the measurement are, see Formulae (A.72) and (A.73):

$$\frac{\partial A_{(m)}}{\partial L_u} = \frac{1}{L_o} \cdot 100 \tag{A.72}$$

$$\frac{\partial A_{(m)}}{\partial L_o} = -\frac{L_u}{L_o^2} \cdot 100 \tag{A.73}$$

Uncertainty of $A_{(m)}$, see Formula (A.74):

$$u_c(A_{(m)}) = \left[\sqrt{\left(\frac{1}{L_o}\right)^2 u^2(L_u) + \left(-\frac{L_u}{L_o^2}\right)^2 u^2(L_o)}\right] \cdot 100 \tag{A.74}$$

A.11 Uncertainty in the determination of the percentage reduction of area

A.11.1 Determination of the reduced area — Rectangular test piece

For determination of the reduced area (rectangular test piece), see Formula (A.75):

$$S_u = a_u \cdot b_u \tag{A.75}$$

Sensitivity coefficients c_i associated with the uncertainty on the measurement x_i, see Formulae (A.76) and (A.77):

$$\frac{\partial S_u}{\partial a_u} = b_u \tag{A.76}$$

$$\frac{\partial S_u}{\partial b_u} = a_u \tag{A.77}$$

Uncertainty in S_u, see Formula (A.78):

$$u_c(S_u) = \sqrt{(b_u)^2 u^2(a_u) + (a_u)^2 u^2(b_u)} \tag{A.78}$$

A.11.2 Determination of the reduced area — Circular test piece

For determination of the reduced area (circular test piece), see Formula (A.79):

$$S_u = \frac{\pi \cdot d_u^2}{4} \tag{A.79}$$

Sensitivity coefficients c_i associated with the uncertainty on the measurement x_i, see Formula (A.80):

$$\frac{\partial S_u}{\partial d_u} = \frac{\pi \cdot d_u}{2} \tag{A.80}$$

Uncertainty of S_u, see Formula (A.81):

$$u_c(S_u) = \sqrt{\left(\frac{\pi\, d_u}{2}\right)^2 u^2(d_u)} = \frac{\pi}{2} \cdot d_u \cdot u(d_u) \tag{A.81}$$

A.11.3 Determination of the percentage reduction of area

For determination of the percentage reduction of area, see Formula (A.82):

$$Z=\left(\frac{S_o-S_u}{S_o}\right)\cdot 100 \quad \text{(A.82)}$$

Sensitivity coefficients c_i associated with the uncertainty on the measurement x_i, see Formulae (A.83) and (A.84):

$$\frac{\partial Z}{\partial S_o}=\frac{S_u}{S_o^2}\cdot 100 \quad \text{(A.83)}$$

$$\frac{\partial Z}{\partial S_u}=-\frac{1}{S_o}\cdot 100 \quad \text{(A.84)}$$

Uncertainty of Z, see Formula (A.85):

$$u_c(Z)=\left[\sqrt{\left(\frac{S_u}{S_o^2}\right)^2 u^2(S_o)+\left(-\frac{1}{S_o}\right)^2 u^2(S_u)}\right]\cdot 100 \quad \text{(A.85)}$$

A.12 Strain rate sensitivity

Reference [21] states: There are a number of reasons for the strain rate sensitivity of flow stress, and they are all related to the atomistic and/or microscopic mechanisms of plastic deformation. The strain rate sensitivity of the flow stress is often adequately represented by the empirical Formulae (A.86) to (A.88):

$$\sigma=K^{'}(\dot{\varepsilon})^{m'} \quad \text{(A.86)}$$

where

$\dot{\varepsilon}$	is the true plastic strain rate;
m'	is the strain rate sensitivity; and
K'	is a constant equal to the material flow stress at a true strain rate of unity.

$$\varepsilon=\ln(1+e_{pl}) \quad \text{(A.87)}$$

$$\sigma=R\cdot(1+e) \quad \text{(A.88)}$$

A.13 Temperature uncertainty consideration

A.13.1 Background

Explicit formulae are given here for 0,2 % proof strength, $R_{p0,2}$, (see Formulae (A.89) and (A.90)) but similar relationships are intended to be applicable to other measurands, namely the slope of the stress-extension curve, m_E, and tensile strength, R_m.

It is assumed that for any type of metal and alloy, the following universal relationship to account for temperature (T) dependence is valid.

$$R_{p0,2}=\sigma_{yo}\left\{1-\exp\left[-C\left(\frac{T_1-T}{T+273}\right)\right]\right\} \quad \text{(A.89)}$$

$$C = C_o \left(\frac{\frac{de}{dt}}{\left(\frac{de}{dt} \right)_{max}} \right)^{n'} = C_o \left(\frac{\dot{e}}{\dot{e}_{max}} \right)^{n'} \quad \text{(A.90)}$$

where

$\left(\frac{de}{dt} \right)_{max}$	is the maximum strain rate allowed by the test standard, e.g., $8 \cdot 10^{-3} s^{-1}$ as specified in ISO 6892-1;
T	is the test temperature, in °C;
σ_{yo}	is a coefficient that need not be determined (as relative uncertainties are discussed below, not absolute uncertainties);
n', T_1, and C_o	are numerical coefficients, whose values are reported below.

A.13.2 Uncertainty evaluation

This document reports values of uncertainties in tensile data due to temperature uncertainties, and as reported, the results can be applied to tests at room temperature and above for four classes of metals and alloys (see below).

Evaluation of uncertainties on tensile test results due to temperature uncertainties can be neglected, provided that the temperature and the strain rate limits indicated in the test standard procedure (e.g., ISO 6892-1[4] and ISO 6892-2[5]) are followed, and provided that the test temperature is lower than:

300 °C for iron and low alloy steels;

300 °C for austenitic steels;

600 °C for Ni and Ni base superalloys;

100 °C for aluminium and its alloys.

At higher temperatures, or when slower strain rates or larger temperature errors than those in standards are involved in a test, the uncertainty in tensile test results due to temperature uncertainties can be evaluated using the uncertainty Formula (A.91).

In this specific context U means the absolute uncertainty, u means the relative uncertainty, e.g. multiplied by 100 %:

$$\frac{U_{R_{p0,2}}}{R_{p0,2}} = u_{R_{p0,2}} = -\frac{C \frac{T_1 + 273}{(T + 273)^2}}{\exp\left(\frac{T_1 - T}{T + 273} \right) - 1} U_T \quad \text{(A.91)}$$

The sign − (minus) applicable to the whole expression is from the partial derivative, it can be dropped.

Formula (A.91) provides the relative uncertainty (e.g., multiplied by 100, in %) due to the uncertainty of T, e.g., U_T = 3 °C or 5 °C.

A.13.3 Explicit values for the coefficients

Explicit values of the material dependent coefficients T_1 and C_o are given in Table A.1. They were evaluated from an analysis of actual tensile test results at several temperatures reported in Reference [7], with some additional tensile data on 1CrMoV steels, particularly for strain rate dependence. The upper temperature limits of validity of this method are also indicated in Table A.1.

Table A.1 — Table of coefficient values

Values of the coefficients *n´*, T_1 and C_o for evaluating the uncertainties of measurands $R_{p0,2}$, R_m and m_E						
Material	for $R_{p0,2}$			for R_m and m_E		
	n´	T_1	C_o	*n´*	T_1	C_o
Iron and low alloy steels 25 – 600 °C	0,1	870	3,2	0,1	930	2,5
Austenitic steels 25 – 600 °C	0,1	870	3,2	0,1	930	2,5
Ni and its alloys 25 – 900 °C	0,1	950	18,0	0,1	1 000	8,0
Al and its alloys 25 – 400 °C	0,1	a	a	0,1	a	a

[a] Not available.

Using the above coefficients, the uncertainty values calculated are themselves judged to be subject to a relative uncertainty not greater than 15 %.

Annex B
(informative)

Worked example for calculating uncertainty in the determination of proof strength at ambient temperature

B.1 General

The subject of this worked example is a sheet type test piece of a cold-rolled steel. It is an example of an uncertainty study of a single test in comparison to the uncertainty of the mean value of a test series consisting of 7 test pieces at a confidence level of 95 %. The test piece for the study lies near the mean value of the test series.

B.2 Testing conditions

Testing conditions are as given in Table B.1.

Table B.1 — Testing conditions

Testing means	Details
Load cell (F)	Class 1 Cell according to ISO 7500-1; 100 kN nominal range
Extensometer (ΔL)	Class 0,5 Extensometer according to ISO 9513 System 1: 5 mm nominal range System 2: 60 mm nominal range
Cross-sectional area	Robot measuring unit in the testing system. The thickness and the width are measured with an accuracy of ±5 µm
Original gauge length, L_o	80 mm
Tooling alignment (angular)	The equipment used guarantees conformance to standard
Tooling alignment (coaxiality)	The equipment used guarantees conformance to standard
Test machine stiffness	Also dependant on a clamping system, i.e. parallel (hydraulic) clamping device
Test method	**Details**
Zero check frequency	Automatic zeroing
Calibration	It is calibrated at the same time once a year (according to ISO 7500-1)
Software	Based on ISO 6892-1:2019, Annex A
Test environment	**Details**
Temperature	Air/conditioned laboratory (23 °C ± 2 °C)
Operator	—
Choice of limits on graph, slope of beginning stress-extension curve	Normally automatic calculation is used
Extensometer angular positioning	Precision positioning is given by automatic alignment
Test piece	**Details**
Section (S_o, mm^2)	S_o = 23,81 mm^2
Tolerance of shape	±0,05 mm; based on ISO 6892-1
Parallelism	±0,1 mm; based on ISO 6892-1
Cylindricity	—
Surface finish	R_z is less than 6,3 µm

B.3 Example of uncertainty calculations and reporting of results

All calculations are based on the formulae in Annex A. Every table is produced for a certain measurand or evaluated quantity. The worked example shows the procedure for 0,2 % proof strength.

The test pieces have been prepared in two steps, as follows, and the material is a Bake-Hardening Steel (ZSTE 220 BH).

— Punch in the shape according to ISO 6892-1.

— Finish by milling under cooling medium.

Table B.2 — Test results

No.	a_o (mm)	b_o (mm)	S_o (mm^2)	$R_{p0,2}$ (MPa)
1	1,185	20,057	23,768	241,2
2	1,185	20,073	23,787	241,6
3	1,183	20,085	23,761	241,8
4	1,185	20,093	23,810	241,4
5	1,185	20,092	23,809	240,7
6	1,179	20,081	23,675	241,6
7	1,177	20,067	23,619	241,8
Mean value $\bar{x}$				**241,4**
Standard deviation s_x				0,39
Uncertainty of $\bar{x}$, see Formula A.4 t = 2,45; p = 95 %				**0,36**
Calculated uncertainty of Annex B based on test piece no. 4				
Expanded uncertainty				**3,06**

Table B.3 — Uncertainty budget calculations for the cross-sectional area — Rectangular test piece n°4

Symbol	**Measurands or evaluated quantities**	**Symbol of uncertainty**	**Value**	**Type**	**Probability distribution**	**Divisor** d_v	**Sensitivity coefficient**[a] c_i	$c_i u(x_i)$	v_i or v_{eff}
a_o	Thickness	$u(a_o)$	±0,005 mm	B	Rectangular	$\sqrt{3}$	20,093	±5,81E-2 mm^2	∞
b_o	Width	$u(b_o)$	±0,005 mm	B	Rectangular	$\sqrt{3}$	1,185	±3,42E-3 mm^2	∞
S_o	Cross-sectional area	$u(S_o)$	Combined uncertainty	B	Triangular	±0,24 %		±5,82E-2 mm^2	∞

a The sensitivity coefficient is not dimensionless (see Annex A).

Steps:

δ_{a_o} = 0,005 mm, see Formula (A.3), leads to $u(a_o)$ = 2,89 · 10^{-3} mm

δ_{b_o} = 0,005 mm, see Formula (A.3), leads to $u(b_o)$ = 2,89 · 10^{-3} mm

Sensitivity coefficient, see Formula (A.6), leads to 20,093 mm

Sensitivity coefficient, see Formula (A.7), leads to 1,185 mm

1st term (not squared) of Formula (A.8): 2,89 · 10^{-3} · 20,093 = 5,81 · 10^{-2} mm^2

2^{nd} term (not squared) of Formula (A.8): $2,89 \cdot 10^{-3} \cdot 1,185 = 3,42 \cdot 10^{-3}$ mm^2

Formula (A.8): square root of (1^{st} term^2 + 2^{nd} term^2) leads to $5,82 \cdot 10^{-2}$ mm^2

Table B.4 — Uncertainty budget calculations for the 0,2 % plastic strain

Symbol	Measurands or evaluated quantities	Symbol of uncertainty	Value	Type	Probability distribution	Divisor d_v	Sensitivity coefficient [a] c_i	$c_i u(x_i)$	v_i or v_{eff}
ΔL	Measured displacement	$u(\Delta L)$	±1,5E-3 mm	*B*	Rectangular	$\sqrt{3}$	1,25E-2	±1,083E-5	∞
L_o	Original gauge length	$u(L_o)$	±0,4 mm	*B*	Rectangular	$\sqrt{3}$	-2,51E-5	±5,798E-6	∞
b	Intercept value	S_b	±0,337 N	*A*	Normal	1	2,02E-7	±6,81E-8	∞
F	Measured force	$u(F)$	±57,5 N	*B*	Rectangular	$\sqrt{3}$	-2,02E-7	±6,71E-6	∞
m	Slope	S_m	±99,1 N/mm	*A*	Normal	1	-1,82E-8	±1,8E-6	∞
e_{pl}	Plastic strain	$u(e_{pl})$	Combined uncertainty	*A+B*	Normal	±0,71 %		±1,41E-5	∞
[a] The sensitivity coefficient is not dimensionless (see Annex A).									

Steps:

$\delta_{\Delta L} = 1,5 \cdot 10^{-3}$ mm (Class 0,5 according to ISO 9513), see Formula (A.3), leads to $u(\Delta L) = 8,66 \cdot 10^{-4}$ mm

ΔL and F obtained from the recorded ASCII-file

Sensitivity coefficient, see Formulae (A.40) and (A.41), leads to $1,25 \cdot 10^{-2}$

Sensitivity coefficient, see Formulae (A.40) and (A.42), leads to $-2,51 \cdot 10^{-5}$

Sensitivity coefficient, see Formulae (A.40) and (A.43), leads to $2,02 \cdot 10^{-7}$

Sensitivity coefficient, see Formulae (A.40) and (A.44), leads to $-2,02 \cdot 10^{-7}$

Sensitivity coefficient, see Formulae (A.40) and (A.45), leads to $-1,82 \cdot 10^{-8}$

1^{st} term (not squared) of Formula (A.46): $8,66 \cdot 10^{-4}$ $1,25 \cdot 10^{-2} = 1,083 \cdot 10^{-5}$

2^{nd} term (not squared) of Formula (A.46): $2,31 \cdot 10^{-1}$ $2,51 \cdot 10^{-5} = 5,798 \cdot 10^{-6}$

3^{rd} term (not squared) of Formula (A.46): 0,337 $2,02 \cdot 10^{-7} = 6,81 \cdot 10^{-8}$

4^{th} term (not squared) of Formula (A.46): 33,2 $2,02 \cdot 10^{-7} = 6,71 \cdot 10^{-6}$

5^{th} term (not squared) of Formula (A.46): 99,1 $1,82 \cdot 10^{-8} = 1,8 \cdot 10^{-6}$

Formula (A.46): square root of (1^{st} term^2 + 2^{nd} term^2 + ... +5^{th} term^2) leads to $1,41 \cdot 10^{-5}$

Table B.5 — Uncertainty budget calculations for the proof strength

Symbol	Measurands or evaluated quantities	Symbol of uncertainty	Value	Type	Probability distribution	Divisor d_v	Sensitivity coefficient[a] c_i	$c_i u(x_i)$	v_i or v_{eff}
$F_{e_{pl}}$	Force at e_{pl} = 0,002	$u_{F_{e_{pl}}}$	±33,49 N	*A*+*B*	Normal	1	0,042	±1,41 MPa	∞
S_o	Original cross-sectional area	u_{S_o}	±5,82 mm^2	*B*	Rectangular	1	10,14	±0,59 MPa	∞
$R_{p0,2}$	Proof strength	$u_c(R_{p0,2})$	Combined uncertainty	*A*+*B*	Normal	±0,63 %		±1,53 MPa	∞
		$U(R_{p0,2})$	Expanded uncertainty	*A*+*B*	Normal	k = 2	±1,27 %	±3,06 MPa	∞

[a] The sensitivity coefficient is not dimensionless (see Annex A).

Steps:

$F_{e_{pl}} = -6,59 \cdot 10^7\, e_{pl}^2 + 3,19 \cdot 10^5\, e_{pl} + 5370$ obtained by analytical fitting according to Formula (A.47) of the force-displacement data coming from the testing machine in the form of an ASCII-file

$$u(F_{e_{pl}}) = \sqrt{(2 \cdot (-6,59 \cdot 10^7) \cdot 0,002 + 3,19 \cdot 10^5)^2 \cdot (1,41 \cdot 10^{-5})^2} = 0,78\ \text{N}$$ (Formulae (A.47) and (A.49)

$$u_c(F_{e_{pl}}) = \sqrt{4,5^2 + u^2(F)}\ ; \quad u(F) = \sqrt{\frac{\delta^2}{3}} = \sqrt{\frac{(0,01 \cdot 5749)^2}{3}} = 33,19\ \text{N}$$ (class 1 according to ISO 7500-1)

$$u_c(F_{e_{pl}}) = \sqrt{4,5^2 + 33,19^2} = 33,49\ \text{N}$$

Sensitivity coefficient, see Formulae (4) and (A.13), leads to 4,2 · 10^{-2}

Sensitivity coefficient, see Formulae (4) and (A.14), leads to 10,14

1st term (not squared) of Formula (A.52): 33,49 · 4,2 · 10^{-2} = 1,41

2nd term (not squared) of Formula (A.52): 5,82 · 10^{-2} · 10,14 = 0,59

Formula (A.52): square root of (1st term^2 + 2nd term^2) leads to 1,53

B.4 Reported results

$R_{p0,2}$ = 241,5 MPa ± 3,1 MPa (±1,27 %)

The above reported expanded uncertainties are based on standard uncertainties multiplied by a coverage factor k = 2, providing a level of confidence of approximately 95 %.

Annex C
(informative)

Interlaboratory scatter

An indication of the typical scatter in tensile test results for a variety of materials that have been reported during laboratory inter-comparison exercises (LabEx), which include both material scatter and measurement uncertainty are shown in Tables C.1 to C.4. The results for the reproducibility are expressed in % calculated by multiplying by 2 the standard deviation for the respective parameter (e.g. R_p, R_m, etc.) and dividing the result by the mean value of the parameter, thereby giving values of reproducibility which represent the 95 % confidence level.

Table C.1 — Yield strengths (0,2 % proof strengths or upper yield strengths) — Reproducibility from laboratory inter-comparison exercises

Material	Code	Yield or proof strength MPa	Reproducibility $\pm U_{LabEx}$, %	Reference
Aluminium				
	AA5754	105,7	3,2	TENSTAND WP4, 2004 [32]
	AA5182-O	126,4	1,9	Aegerter et al, 2003 [29]
	AA6016-T4	127,2	2,2	Aegerter et al, 2003 [29]
	EC-H 19	158,4	4,1	ASTM Report, 1994 [11]
	2024-T 351	362,9	3,0	ASTM Report, 1994 [11]
Steel				
Sheet	DX56	162,0	4,6	TENSTAND WP4, 2004 [32]
Low Carbon, Plate	HR3	228,6	8,2	Roesch et al, 1993 [31]
Sheet	ZStE 180	267,1	9,9	TENSTAND WP4, 2004 [32]
AISI 105	P245GH C22	367,4 402,4	5,0 4,9	Roesch et al, 1993 [31] ASTM Report, 1994 [11]
Plate	S355	427,6	6,1	TENSTAND WP4, 2004 [32]
Austenitic S S	SS316L	230,7	6,9	TENSTAND WP4, 2004 [32]
Austenitic S S	X2CrNi18-10	303,8	6,5	Roesch et al, 1993 [31]
Austenitic S S	X2CrNiMo18-10	353,3	7,8	Roesch et al, 1993 [31]
AISI 316	X5CrNiMo17-12-2	480,1	8,1	ASTM Report, 1994 [11]
Martensitic S S	X12Cr13	967,5	3,2	ASTM Report, 1994 [11]
High Strength.	30NiCrMo16	1039,9	2,0	Roesch et al, 1993 [31]
Nickel Alloys				
INCONEL 600	NiCr15Fe8	268,3	4,4	ASTM Report, 1994 [11]
Nimonic 75	(CRM661)	298,	4,0	Ingelbrecht and Loveday, 2000 [30]
Nimonic 75	(CRM661)	302,1	3,6	TENSTAND WP4, 2004 [32]