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Metallic and other inorganic coatings — Measurement of Young's modulus of thermal barrier coatings by beam bending

Revêtements métalliques et autres revêtements inorganiques — Mesurage du module de Young des revêtements barrières thermiques par flexion de poutre

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Contents

Foreword

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The committee responsible for this document is ISO/TC 107, *Metallic and other inorganic coatings*.

Introduction

Thermal barrier coatings are highly advanced material systems, generally applied to surfaces of hot-section components made of nickel or cobalt-based superalloys, such as combustors, blades, and vanes of power-generation gas turbines in thermal power plants and aero-engines operated at elevated temperatures.

The function of these coatings is to protect metallic components for extended periods at elevated temperatures by employing thermally insulating materials which can sustain an appreciable temperature difference between load bearing alloys and coating surfaces. These coatings permit the high-temperature operation by shielding these components, thereby extending their lives.

Although Young's modulus is an important property of thermal barrier coatings, the existing ISO standard only describes a method for measuring the Young's modulus of monolithic ceramics.

This International Standard specifies a method for measuring the Young's modulus of thermal barrier coatings that consist of multilayers formed on substrate by thermal spraying.

The measuring procedure of this International Standard is applicable for the measurement of the Young's modulus of various thermally sprayed coatings.

Metallic and other inorganic coatings — Measurement of Young's modulus of thermal barrier coatings by beam bending

1 Scope

This International Standard specifies a method for measuring the in-plane Young's modulus, at room temperature, of thermal barrier coatings formed on substrates by thermal spraying.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 1463, *Metallic and oxide coatings — Measurement of coating thickness — Microscopical method*

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

ISO 4287, *Geometrical Product Specifications (GPS) — Surface texture: Profile method — Terms, definitions, and surface texture parameters*

ISO 13385 (all parts), *Geometrical product specifications (GPS) — Dimensional measuring equipment*

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

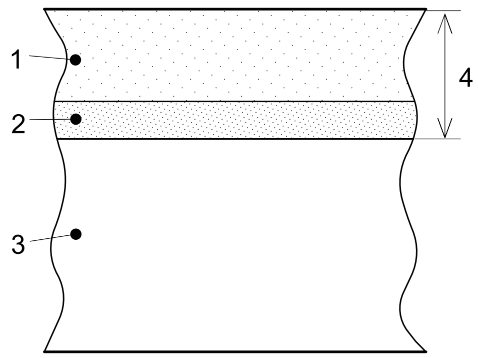
ISO 14188, *Metallic and other inorganic coatings — Test methods for measuring thermal cycle resistance and thermal shock resistance for thermal barrier coatings*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 14188 and the following apply.

3.1
thermal barrier coating
TBC
two-layer coating consisting of a metallic bond coat (BC) and a ceramic top coat (TC), in order to reduce heat transfer from outside of the top coat through the coating to the substrate

Note 1 to entry: See Figure 1.



Key

1 TC
2 BC
3 substrate
4 TBC

Figure 1 — Diagrammatic view of a section of TBC

[SOURCE: ISO 14188:2012, 3.1, modified — a different note to entry and figure has been used.]

3.2
composite beam
beam consisting of multiple layers

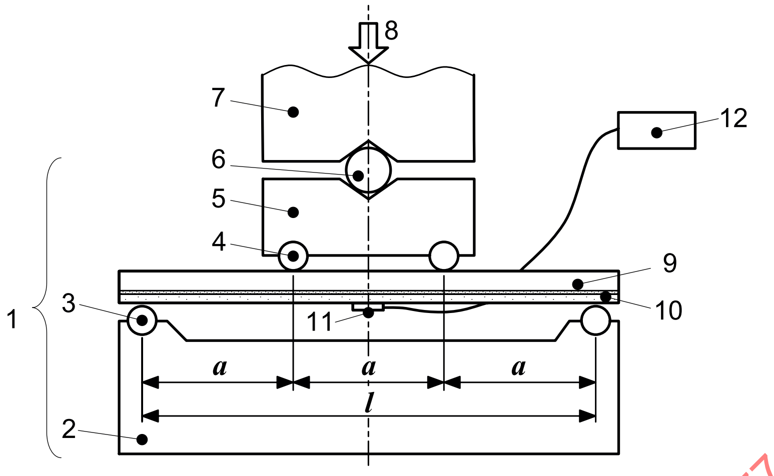
4 Principle

The fundamental procedures for measuring the Young's moduli of the substrate, BC, and TC consist of the measurement of the force–strain diagram of three types of specimens (substrate, substrate with BC, and substrate with TBC) by a four-point bending method and of calculations according to the theory of composite beam.[1][2][3][4][5]

5 Apparatus for measuring Young's modulus

An example of the apparatus for measuring the Young's modulus is schematically shown in Figure 2.

The apparatus consists of four-point bending jig, testing machine, and strain measuring equipment.



Key

1 four-point bending jig
2 support bed
3 support roller
4 load roller
5 load bed
6 ball
7 testing machine
8 force
9 specimen
10 TBC
11 strain gauge
12 strain measuring equipment
a distance between load rollers
l distance between support rollers

Figure 2 — Typical apparatus for measuring the Young's modulus (in the case that the tensile force is applied to the TBC)

5.1 Testing machine

The testing machine is specified according to ISO 7500-1.

5.2 Four-point bending jig

The four-point bending jig consists of the load bed, load roller, support bed, support roller, and ball, as follows.

a) The load bed, load roller, support bed, support roller, and ball shall have sufficient rigidity to prevent their plastic deformation during testing.

b) The width of load bed, load roller, support bed, and support roller shall be larger than that of specimen.

c) The distance between load rollers shall be between 15 mm and 30 mm.

d) The distance between support rollers shall be three times the distance between load rollers.

e) The radii of support rollers and load rollers shall be the same and shall be between 2,0 mm and 3,0 mm.

f) The surface roughness of rollers shall be ≤0,4 μm Ra according to ISO 4287.

g) The ball is used to ensure that the force is distributed evenly between the left and right load rollers.

5.3 Strain measuring equipment

The strain measuring equipment shall be specified as follows.

a) The strain measuring equipment shall be capable of identifying, to the accuracy of ±1 %, the strain to be measured with the strain gauge.

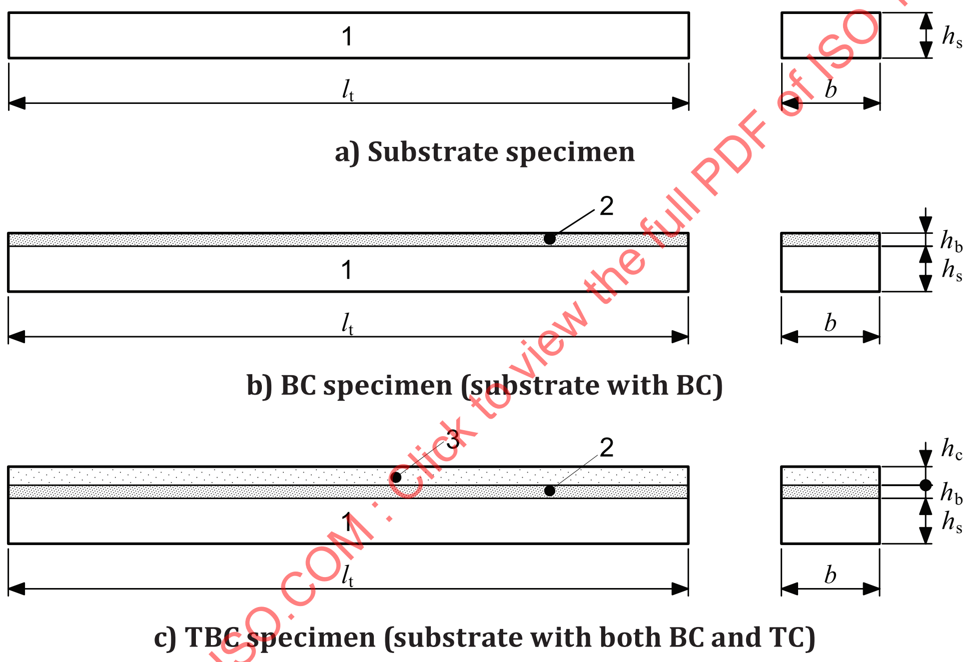
b) The strain gauge length should normally be ≤5 mm.

6 Specimen

The specimens shall be specified as follows.

a) The three types of specimens, the substrate, BC, and TBC specimens shall be used.

b) The specimen shape is a beam type (see Figure 3) and the dimensions of the specimen shall be as given in Table 1.



Key

1 substrate
2 BC
3 TC
l_t total length
b width
h_s substrate thickness
h_b BC thickness
h_c TC thickness

Figure 3 — Shape of specimens

Table 1 — Dimensions of specimen

Symbol	Designation	Dimension
l (mm)	distance between support rollers	3 a
l_t (mm)	total length	$l + 6 \leq l_t$
b (mm)	width	$4 \leq b \leq (1/6)\ l$
h_s (mm)	substrate thickness	$1{,}5 \leq h_s \leq 3{,}0$
h_b (mm)	BC thickness	$0{,}10 \leq h_b$ and $h_s /20 \leq h_b$ for BC specimen
h_c (mm)	TC thickness	$0{,}20 \leq h_c$ and $(h_s + h_b) /10 \leq h_c$ for TBC specimen

c) The thickness tolerance of the substrate shall be ±0,01 mm.

d) The side surface of the BC and TBC specimens shall be polished to remove the coating deposited on the side surface. The polishing shall be done cautiously so that it does not damage the coating.

7 Measuring procedure

7.1 Specimen dimension

The dimensions of the specimen shall be measured as follows.

a) The total length of the specimen shall be measured according to ISO 13385.

b) The width of the specimen shall be measured according to ISO 3611.

c) The thickness of the substrate shall be measured according to ISO 3611.

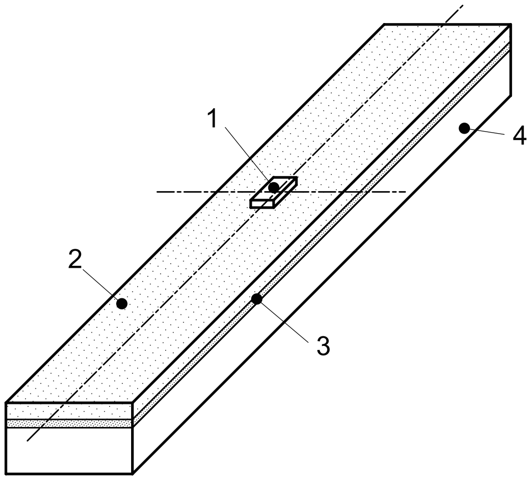
d) The thickness of BC and TC shall be measured on an image of the coating cross section according to ISO 1463.

7.2 Force–strain diagram

a) The strain gauge shall be attached to the coating surface for the BC and TBC specimens.

b) The strain gauge shall be attached at the middle portion of the specimen, parallel to the longitudinal direction, as shown in Figure 4.

For the TBC specimen with significant porosity, where adhesive for fixing the strain gauge might significantly penetrate into the coating, measurement should be done according to Annex A.

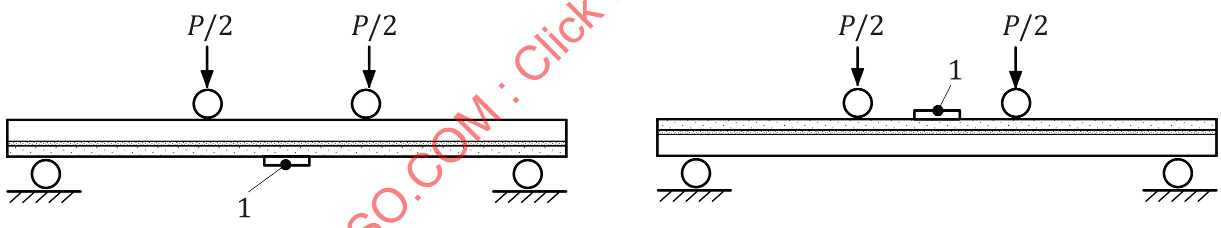


Key

1 strain gauge
2 TC
3 BC
4 substrate

Figure 4 — Position of strain gauge

c) The specimen shall be placed into the four-point bending jig, as shown in Figure 5 a), when tensile force is applied to the coating or as in Figure 5 b) when compressive force is applied. The direction of the force applied to the coating shall be decided according to the agreement between parties involved in the transaction.



a) Tensile force **b) Compressive force**

Key

1 strain gauge
P force applied to specimen

Figure 5 — Direction of force applied to the coating by four-point bending

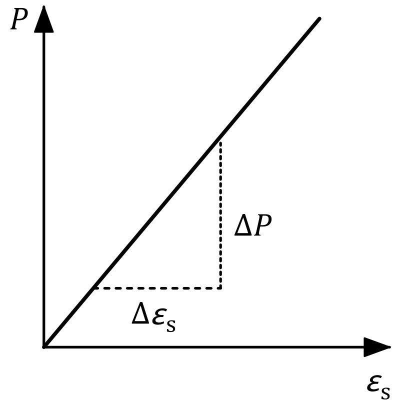
d) The test speed shall be ≤0,5 mm/min.

e) For the BC and TBC specimens, the force range shall be low enough to prevent damage to the coating and to prevent plastic deformation of the substrate.

f) The strain range applied to the coating shall be decided according to the agreement between parties involved in the transaction.

g) The force shall be applied to the specimen repeatedly until the force–strain diagram is stable within the specified force range.

h) For the substrate specimen, the force–substrate strain diagram shall be measured and its slope determined (see Figure 6). The measurement shall be carried out three times on one specimen. The average of their slopes shall be used in the calculation of Young's modulus. This measurement shall be carried out for three specimens prepared using the same procedures.



Key

ε_s substrate strain

P force (N)

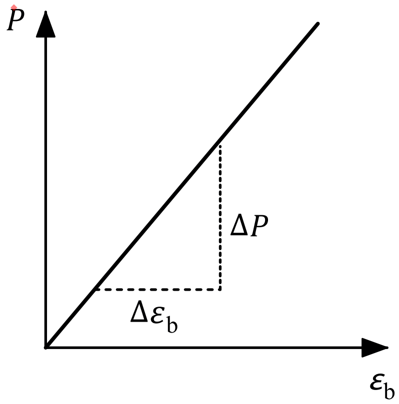
$\Delta \varepsilon_s$ increment of substrate strain

ΔP increment of force

$\Delta P/\Delta \varepsilon_s$ slope of force–substrate strain diagram

Figure 6 — Force–substrate strain diagram

i) For the BC specimen, the force–BC strain diagram shall be measured and its slope determined (see Figure 7). The measurement shall be carried out three times on one specimen. The average of their slopes shall be used in the calculation of Young's modulus. This measurement shall be carried out for three specimens prepared using the same procedures.



Key

ε_b BC strain

P force (N)

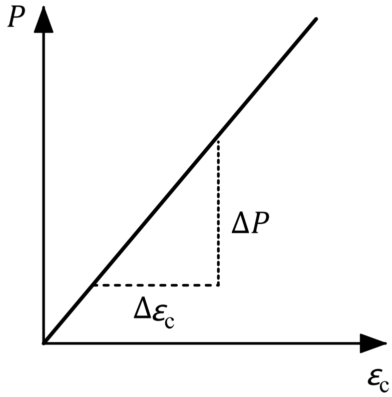
$\Delta \varepsilon_b$ increment of BC strain

ΔP increment of force

$\Delta P/\Delta \varepsilon_b$ slope of force–BC strain diagram

Figure 7 — Force–BC strain diagram

j) For the TBC specimen, the force–TC strain diagram shall be measured and its slope determined (see Figure 8). The measurement shall be carried out three times on one specimen. The average of their slopes shall be used in the calculation of Young's modulus. This measurement shall be carried out for three specimens prepared using the same procedures.



Key

ε_c TC strain
P force (N)
$\Delta\varepsilon_c$ increment of TC strain
ΔP increment of force
$\Delta P/\Delta\varepsilon_c$ slope of force–TC strain diagram

Figure 8 — Force–TC strain diagram

8 Calculation of Young's modulus

The Young's moduli of substrate, BC, and TC shall be calculated as follows.

a) Young's modulus of the substrate

The Young's modulus E_s of substrate shall be calculated according to Formula (1) on the basis of the slope of force–substrate strain diagram measured using the substrate specimen:

$$E_s = \frac{3a}{bh_s^2}\left|\frac{\Delta P}{\Delta\varepsilon_s}\right| \quad (1)$$

b) Young's modulus of BC

The Young's modulus E_b of BC shall be calculated according to Formula (2) on the basis of the slope of force–BC strain diagram measured using the BC specimen and E_s obtained in Formula (1):

$$E_b = \frac{-B+\sqrt{B^2-4AC}}{2A} \quad (2)$$

where

$$\left.\begin{array}{l} A = bh_{\mathrm{b}}^{4} \\ B = 2bE_{\mathrm{s}}h_{\mathrm{b}}h_{\mathrm{s}}\left(2h_{\mathrm{b}}^{2} + 3h_{\mathrm{b}}h_{\mathrm{s}} + 2h_{\mathrm{s}}^{2}\right) - 3ah_{\mathrm{b}}^{2}\left|\dfrac{\Delta P}{\Delta \varepsilon_{\mathrm{b}}}\right| \\ C = E_{\mathrm{s}}h_{\mathrm{s}}\left\{bE_{\mathrm{s}}h_{\mathrm{s}}^{3} - 3a\left|\dfrac{\Delta P}{\Delta \varepsilon_{\mathrm{b}}}\right|\left(2h_{\mathrm{b}} + h_{\mathrm{s}}\right)\right\} \end{array}\right\}$$

c) Young's modulus of TC

The Young's modulus E_{c} of TC shall be calculated according to Formula (3) on the basis of the slope of force–TC strain diagram measured using the TBC specimen, E_{s} obtained in Formula (1) and E_{b} obtained in Formula (2):

$$E_{\mathrm{c}} = \frac{-B + \sqrt{B^{2} - 4AC}}{2A} \tag{3}$$

where

$$\left.\begin{array}{l} A = bh_{\mathrm{c}}^{4} \\ B = 2bE_{\mathrm{b}}h_{\mathrm{c}}h_{\mathrm{b}}\left(2h_{\mathrm{c}}^{2} + 3h_{\mathrm{c}}h_{\mathrm{b}} + 2h_{\mathrm{b}}^{2}\right) + 2bE_{\mathrm{s}}h_{\mathrm{c}}h_{\mathrm{s}}\left\{2h_{\mathrm{c}}^{2} + 3h_{\mathrm{c}}h_{\mathrm{s}} + 2h_{\mathrm{s}}^{2} + 6h_{\mathrm{b}}\left(h_{\mathrm{c}} + h_{\mathrm{b}} + h_{\mathrm{s}}\right)\right\} - 3ah_{c}^{2}\left|\dfrac{\Delta P}{\Delta \varepsilon_{\mathrm{c}}}\right| \\ C = b\left\{E_{\mathrm{b}}^{2}h_{\mathrm{b}}^{4} + 2E_{\mathrm{b}}E_{\mathrm{s}}h_{\mathrm{b}}h_{\mathrm{s}}\left(2h_{\mathrm{b}}^{2} + 3h_{\mathrm{b}}h_{\mathrm{s}} + 2h_{\mathrm{s}}^{2}\right) + E_{\mathrm{s}}^{2}h_{\mathrm{s}}^{4}\right\} - 3a\left|\dfrac{\Delta P}{\Delta \varepsilon_{\mathrm{c}}}\right|\left\{E_{\mathrm{b}}h_{\mathrm{b}}\left(2h_{\mathrm{c}} + h_{\mathrm{b}}\right) + E_{\mathrm{s}}h_{\mathrm{s}}\left(2h_{\mathrm{c}} + 2h_{\mathrm{b}} + h_{\mathrm{s}}\right)\right\} \end{array}\right\}$$

9 Test report

The test report shall contain the following items:

a) specimen:

1) material of substrate;

2) materials and spraying conditions of BC and TC;

3) shape and dimensions of substrate;

4) thickness of substrate, BC, and TC;

5) width of specimen;

b) measurement conditions:

1) strain gauge length;

2) distance between load rollers of four-point bending jig;

3) applied force range and strain range applied to coating;

4) test speed;

5) direction of force applied to coating;

c) results of measurement

1) force–strain diagrams of the substrate, BC, and TBC specimens;

2) Young's moduli of substrate, BC, and TC.

Annex A
(informative)

Measurement method of Young's modulus of TBC specimen with significant porosity

A.1 Force–substrate strain method

a) TBC specimen

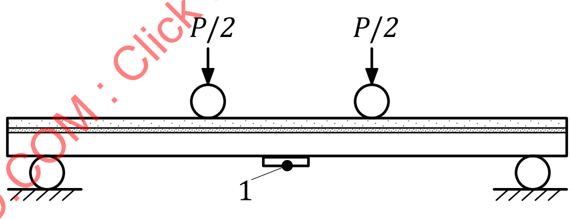
The TC thickness shall be specified in Table A.1. For all other conditions of the specimen, see Clause 6.

Table A.1 — Dimensions of TBC specimen

Symbol	Designation	Dimension
h_c (mm)	TC thickness	$0{,}30 \leq h_c$ and $(3/20)(h_s + h_b) \leq h_c$

b) Measuring procedure

1) The strain gauge shall be attached to the substrate surface (Figure A.1). The force–substrate strain diagram shall be measured and its slope determined. The measurement shall be carried out three times on one specimen. The average of their slopes shall be used in the calculation of Young's modulus. This measurement shall be carried out for three specimens prepared using the same procedures.



Key

1 strain gauge to measure the strain (ε_s) of substrate

P force applied to specimen

Figure A.1 — Force–substrate strain method

2) The Young's modulus E_c of TC shall be calculated according to Formula (A.1) on the basis of the slope of the force–substrate strain diagram measured using the TBC specimen, E_s obtained in Formula (1) and E_b obtained from Formula (2):

$$E_c = \frac{-B + \sqrt{B^2 - 4AC}}{2A} \tag{A.1}$$