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**Nanotechnologies — Multiwall  
carbon nanotubes — Determination  
of carbon impurity content by  
thermogravimetric analysis**

*Nanotechnologies – Nanotubes de carbone multicouches –  
Détermination de la teneur en impureté de carbone par analyse  
thermogravimétrique*

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## Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO document should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see [www.iso.org/directives](http://www.iso.org/directives)).

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This document was prepared by Technical Committee ISO/TC 229, *Nanotechnologies*.

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](http://www.iso.org/members.html).

## Introduction

Multiwall carbon nanotubes (MWCNTs) are quasi-one-dimensional tubular carbon nanomaterials rolled up or coaxial nested by three or more graphene sheets. The production of carbon nanotubes (CNT) generally results in significant amounts of carbon impurities (carbon material content not in the form of CNT, including amorphous carbon and trace amounts of other types of structured carbon), which influence the physical and chemical properties of the nanomaterial. Therefore, the measurement of carbon impurities content in MWCNT samples is highly desirable for the determination of their purity.

Several methods have been reported to characterize carbon impurities in MWCNT samples, including transmission electron microscopy (TEM), temperature programmed oxidation (TPO) and thermogravimetric analysis (TGA), etc., among which TGA can provide quantitative results.<sup>[1][2][3][4][5][6]</sup> This technique makes use of the fact that MWCNTs are more stable than the majority of carbon impurities, so carbon impurities less stable than MWCNTs will react firstly with carbon dioxide in carbon dioxide atmosphere. The oxidation of carbon impurities with carbon dioxide is an endothermal process, which prevents overheating in certain areas and restrains the reaction of MWCNTs at the same time. Therefore, the separation between the oxidation of carbon impurities and those of MWCNTs is enhanced,<sup>[7][8][9][10]</sup> allowing the amount of carbon impurities less stable than MWCNTs to be calculated from the mass loss in thermogravimetric analysis.

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# Nanotechnologies — Multiwall carbon nanotubes — Determination of carbon impurity content by thermogravimetric analysis

## 1 Scope

This document specifies a mild oxidation method to determine the content of carbon impurities (carbon material content not in the form of CNT, including amorphous carbon and trace amounts of other types of structured carbon) less stable than multiwall carbon nanotubes (MWCNTs) by thermogravimetric analysis (TGA) under carbon dioxide atmosphere.

This document is applicable to the characterization of carbon impurities content in MWCNT samples prepared by chemical vapour deposition (CVD). Measurement of carbon impurities in MWCNT samples prepared by other methods can refer to this document. This method is not applicable to functionalized MWCNT samples or MWCNT samples with encapsulant species.

NOTE This method is applicable for the case of TG curves with a single-stage.

## 2 Normative references

There are no normative references in this document.

## 3 Terms, definitions and abbreviated terms

### 3.1 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 <https://www.electropedia.org/>

#### 3.1.1

**multiwall carbon nanotube**

**MWCNT**

**multi-walled carbon nanotube**

carbon nanotube composed of nested, concentric or near-concentric graphene layers with interlayer distances similar to those of graphite

Note 1 to entry: The structure is normally considered to be many single-walled carbon nanotubes nesting each other and would be cylindrical for small diameters but tends to have a polygonal cross-section as the diameter increases.

[SOURCE: ISO/TS 80004-3:2020, 3.3.6<sup>[11]</sup>]

#### 3.1.2

**amorphous carbon**

carbon material without long-range crystalline order

[SOURCE: IUPAC, Compendium of Chemical Terminology<sup>[12]</sup>]

### 3.2 Symbols

|            |                                                        |
|------------|--------------------------------------------------------|
| $T_0$      | temperature of the peak on DTG curve (°C)              |
| $w_{300}$  | mass percentage (%) of the sample at 300 °C            |
| $w_e$      | mass percentage (%) of the sample at temperature $T_e$ |
| $\Delta H$ | is the enthalpy change                                 |

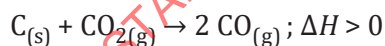
### 3.3 Abbreviated terms

|                 |                              |
|-----------------|------------------------------|
| CO <sub>2</sub> | carbon dioxide               |
| CVD             | chemical vapour deposition   |
| DTG             | derivative thermogravimetric |
| MWCNT           | multiwall carbon nanotube    |
| TG              | thermogravimetric            |
| TGA             | thermogravimetric analysis   |

## 4 Principle

Thermogravimetric analysis measures the change in mass of a material as a function of temperature. In order to accomplish this, TGA requires the precise measurements of mass, temperature and temperature change. The change in mass of a material relates to change in composition and structure of the material. Observed mass changes with temperature increases may result from the removal of absorbed moisture, solvent residues, chemically bound moieties and/or the thermal or oxidative decomposition of product. [13] The experiments are carried out in an inert or oxidising atmosphere. The recorded mass change as a function of temperature is a thermogravimetric (TG) curve. Mass change and the extent of these changes of a material in a TG curve are indicators of the thermal stability of the material. [14] Derivative thermogravimetric (DTG) curve is a display of the first derivative of thermogravimetry data with respect to temperature or time [15].

The method specified in this document is based on different reactivity of MWCNTs and carbon impurities under carbon dioxide (CO<sub>2</sub>) atmosphere during heating. Carbon dioxide works as a mild oxidant to first oxidize carbon impurities less stable than MWCNTs. Moreover, the reaction between carbon impurities and CO<sub>2</sub> absorbs heat from environment, [7][8][9] which prevents local overheating, and thus enhances the separation of carbon impurities and MWCNTs. The amount of carbon impurities in MWCNT samples can be calculated from the mass loss in thermogravimetric analyser. See the reaction formula below.



where

- $C_{(s)}$  is the carbon impurities in solid state;
- $CO_{2(g)}$  is the carbon dioxide in gaseous state;
- $CO_{(g)}$  is the carbon monoxide in gaseous state;
- $\Delta H$  is the enthalpy change.



## 5 Sample preparation

MWCNT sample should be of good quality. MWCNT sample is first placed in a thermostatic vacuum drying furnace for 2 h at 150 °C to remove unwanted volatile components.<sup>[16]</sup> Then the sample is transferred to a desiccator to cool down to room temperature and it is stored there until used.

## 6 Measurement

### 6.1 Apparatus

#### 6.1.1 Thermogravimetric analyser

Thermogravimetric analyser should consist of a furnace, which is capable of heating from room temperature to 1 000 °C or above. Heating rate during experiment should be controlled by temperature programme set in software<sup>[14]</sup>.

The linear heating rate should be controllable in the range from 1 °C min<sup>-1</sup> to 50 °C min<sup>-1</sup>. The balance sensitivity should be at least 1 µg, and the temperature controller sensitivity less than or equal to 0,01 °C.

A crucible should be used as a sample container. The crucible is generally made of alumina, platinum, quartz or other materials, which does not change or react under the measurement conditions.

#### 6.1.2 Drying furnace

A drying furnace capable of controlled heating to at least 150 °C is used.

#### 6.1.3 Analytical balance

An analytical balance capable of weighing 0,1 mg or lower is used.

#### 6.1.4 Desiccator

A dessicator containing a desiccant such as dried silica gel impregnated with cobalt chloride is used. The drying agent shall not react with MWCNT samples.

### 6.2 Reagents

#### 6.2.1 Inert gas

Dry, commercially available inert gas, such as nitrogen gas or argon gas, with minimum volume fraction of 99,999 % should be used in the measurement.

#### 6.2.2 Carbon dioxide

Dry, commercially available carbon dioxide gas with minimum volume fraction of 99,999 % should be used in the measurement.

### 6.3 Measurement procedures

The thermogravimetric analyser should be calibrated according to the manufacturer's protocol to ensure proper temperature and mass measurement.

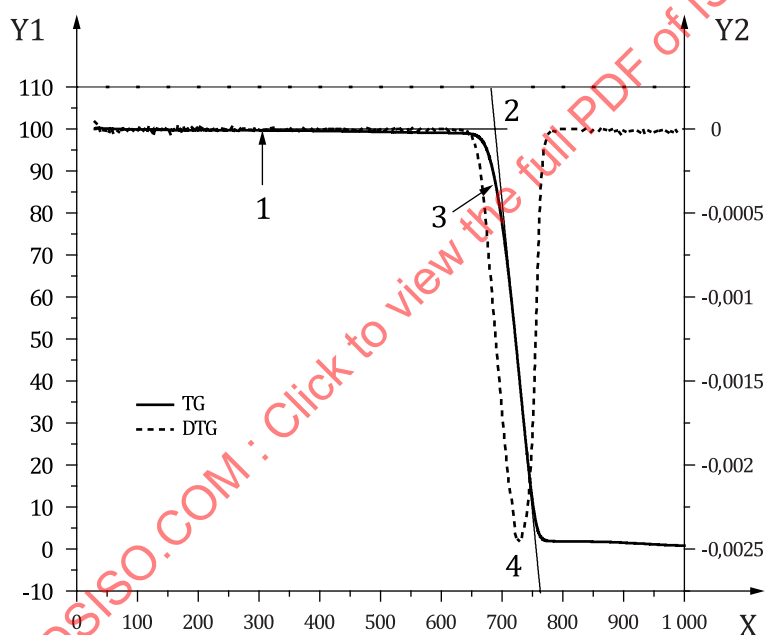
- a) Turn on the thermogravimetric analyser and wait until equilibrium is reached. Then inert gas and carbon dioxide gas are introduced.

- b) Obtain a baseline correction file using empty crucibles at the same experiment conditions to be used for the MWCNT sample. Specifically, set the flow rate of gas to the furnace according to the instrument type. The recommended inert gas flow is 10 ml min<sup>-1</sup> to 20 ml min<sup>-1</sup> and carbon dioxide gas flow is 20 ml min<sup>-1</sup> to 40 ml min<sup>-1</sup>; set the heating rate as 10 °C min<sup>-1</sup> within the temperature range from room temperature to 1 000 °C.
- c) Weigh an appropriate amount of MWCNT sample (3 mg to 5 mg) using an analytical balance and transfer the sample into the crucible.
- d) Before starting the measurement, keep the MWCNT sample in a closed thermogravimetric analyser under a gas flow for at least 15 min and wait until the signal (mass, temperature, gas flow) is stable.
- e) Test the sample under the same conditions as in b). Thermogravimetric analyser will automatically record the mass change of MWCNT sample with temperature.

Repeat the measurement at least three times for one MWCNT sample.

## 7 Data analysis and interpretation of results

TG and DTG curves of one MWCNT sample are shown in [Figure 1](#).



### Key

- X temperature (°C)
- Y<sub>1</sub> mass percentage (%)
- Y<sub>2</sub> derivative mass percentage (%/°C)
- 1 mass percentage of the MWCNT sample at 300 °C,  $w_{300}$  (%)
- 2 extrapolated initial temperature of MWCNT component oxidation in one MWCNT sample,  $T_e$  (°C)
- 3 mass percentage of the sample at  $T_e$ ,  $w_e$  (%)
- 4 temperature of the peak on DTG curve,  $T_o$  (°C)

**Figure 1 — TG and DTG curves of one MWCNT sample**

The mass loss below 300 °C is due to the loss of volatile components<sup>[16]</sup>.

$T_e$  is the intersection point between the base line and the tangent line at the maximum mass loss rate point, where the maximum mass loss rate point is provided in the DTG curve and the tangent line is obtained by ordinary analysis software.

Calculate the content of carbon impurities in MWCNT sample by [Formula \(1\)](#),

$$w = w_{300} - w_e \quad (1)$$

where  $w$  is the mass percentage (%) of the carbon impurities.

Conduct three independent TGA measurements for one MWCNT sample. The three measurements results are referred as  $w_1$ ,  $w_2$  and  $w_3$ , respectively. Calculate mass percentage of carbon impurities in MWCNT sample according to [Formula \(1\)](#). Calculate the average value of the three measurements by [Formula \(2\)](#):

$$\bar{w} = \frac{w_1 + w_2 + w_3}{3} \quad (2)$$

where  $\bar{w}$  is the average mass percentage (%) of the carbon impurities in one MWCNT sample.

[Annex A](#) and [Annex B](#) provide the case studies of repeatability and reproducibility, respectively. [Annex C](#) provides the detailed procedures for the analysis of the TG curve.

NOTE This method is applicable for the case of a TG curve with a single stage.

Sample homogeneity should be considered. The homogeneity of MWCNT samples can be evaluated by the constituency, thermal stability and scatter in the oxidation temperature and the residual material content in several separate TGA runs.<sup>[13]</sup> Errors in result calculation can be introduced if the sample is non-homogeneous.

## 8 Measurement uncertainty

### 8.1 Type A uncertainty

**8.1.1** The uncertainty is introduced by the measuring method, such as measurement precision, and method bias. It is calculated by measuring repetitive standard deviation of the reference material, which is used for instrument calibration.

**8.1.2** The uncertainty is introduced by aspects of sample measurement, such as the uniformity of samples, weighing, drying and gridding. It is calculated by measuring repetitive standard deviation of the sample.

### 8.2 Type B uncertainty

The uncertainty is introduced by instrument calibration, such as mass calibration, and temperature calibration<sup>[13]</sup>.

## 9 Test report

The test report shall include the following information:

- a) refer to this document (i.e. ISO/TS 23690:2023);
- b) sample type and name;
- c) tester;
- d) organization, contact address and telephone number;
- e) type of thermogravimetric analyser and model;

- f) test conditions, including crucible type, atmosphere, gas flow, sample mass, temperature range and heating rate;
- g) test results, including the TG and DTG curves, data and calculated content of carbon impurities in MWCNT sample;
- h) any deviations from the procedure;
- i) any unusual features observed;
- j) the date of the test.

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## Annex A (informative)

### Repeatability test: Case study

#### A.1 General

This annex provides three cases for determination of carbon impurities less stable than MWCNTs content by thermogravimetric analysis in CO<sub>2</sub> atmosphere.

#### A.2 Sample preparation

Firstly, MWCNT samples were placed in a thermostatic vacuum drying furnace for 2 h at 150 °C. Then, the samples were transferred to a desiccator to cool down to room temperature and stored there until used.

#### A.3 Measurement conditions

The measurement conditions were as follows:

- a) heating rate was 10 °C min<sup>-1</sup>;
- b) the temperature range was set from room temperature to 1 000 °C;
- c) the inert gas, N<sub>2</sub>, flow rate was set as 20 ml min<sup>-1</sup>;
- d) the CO<sub>2</sub> gas flow rate was set as 30 ml min<sup>-1</sup>.

#### A.4 Measurement procedure

**A.4.1** Obtain the correction baseline file using empty crucible under identical experiment condition.

**A.4.2** Add an appropriate mass of the MWCNT sample into the crucible.

**A.4.3** Put crucible into sample holder of thermogravimetric analyser.

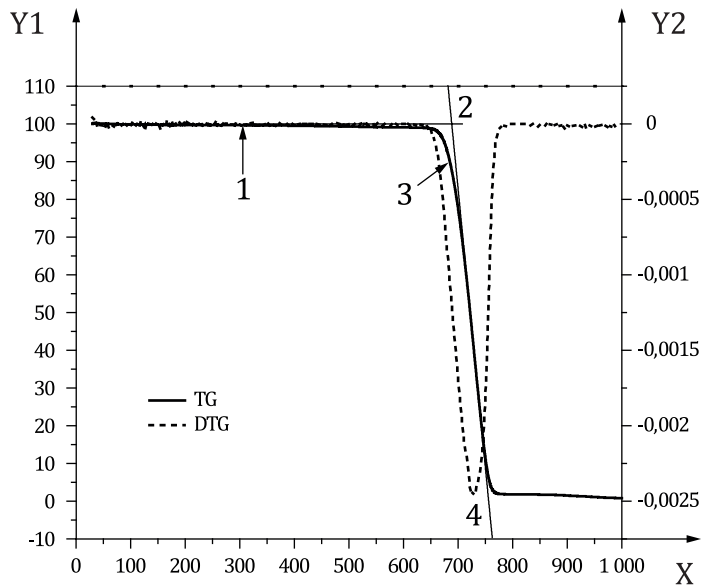
**A.4.4** Set the measurement parameters in accordance with [Clause A.3](#) and start the measurement.

**A.4.5** Repeat the measurement three times for one MWCNT sample and use the results to calculate the average value of carbon impurities content.

#### A.5 Data analysis and interpretation of results

##### A.5.1 Sample A

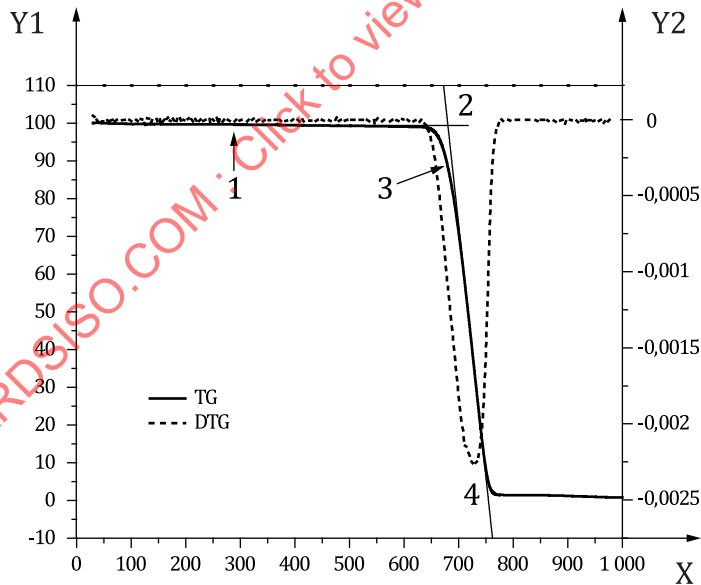
TG and DTG curves of sample A are shown in [Figures A.1](#) to [A.3](#).



Key

- |                |                                   |   |                         |
|----------------|-----------------------------------|---|-------------------------|
| X              | temperature (°C)                  | 2 | $T_e = 688,9\text{ °C}$ |
| Y <sub>1</sub> | mass percentage (%)               | 3 | $w_e = 87,30\text{ %}$  |
| Y <sub>2</sub> | derivative mass percentage (%/°C) | 4 | $T_o = 727,7\text{ °C}$ |
| 1              | $w_{300} = 99,70\text{ %}$        |   |                         |

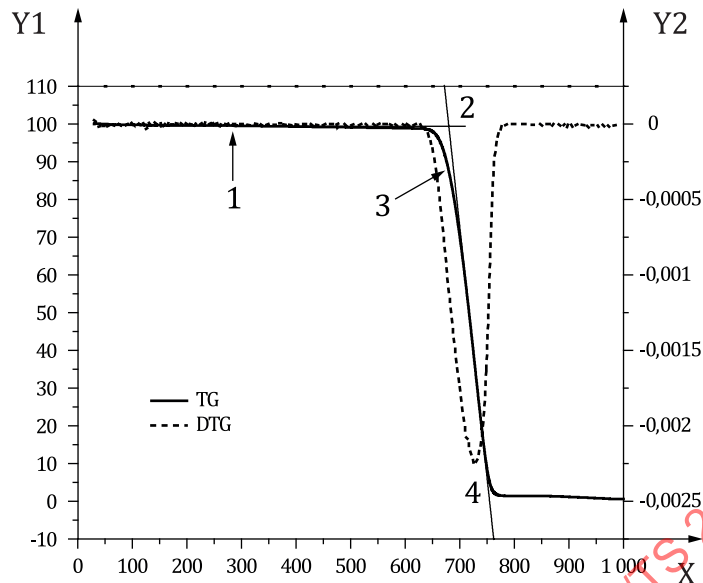
Figure A.1 — TG and DTG curves of sample A in the first run of measurement



Key

- |                |                                   |   |                         |
|----------------|-----------------------------------|---|-------------------------|
| X              | temperature (°C)                  | 2 | $T_e = 681,2\text{ °C}$ |
| Y <sub>1</sub> | mass percentage (%)               | 3 | $w_e = 87,70\text{ %}$  |
| Y <sub>2</sub> | derivative mass percentage (%/°C) | 4 | $T_o = 725,2\text{ °C}$ |
| 1              | $w_{300} = 99,70\text{ %}$        |   |                         |

Figure A.2 — TG and DTG curves of sample A in the second run of measurement

**Key**

|       |                                   |   |                                       |
|-------|-----------------------------------|---|---------------------------------------|
| X     | temperature (°C)                  | 2 | $T_e = 681,0 \text{ } ^\circ\text{C}$ |
| $Y_1$ | mass percentage (%)               | 3 | $w_e = 86,80 \text{ } \%$             |
| $Y_2$ | derivative mass percentage (%/°C) | 4 | $T_o = 725,2 \text{ } ^\circ\text{C}$ |
| 1     | $w_{300} = 99,50 \text{ } \%$     |   |                                       |

**Figure A.3 — TG and DTG curves of sample A in the third run of measurement**

The content of carbon impurities in the MWCNT sample was calculated according to [Formulae \(1\)](#) and [\(2\)](#) in [Clause 7](#).

$$w_1 = w_{300-1} - w_{e-1} = 99,7 \text{ } \% - 87,3 \text{ } \% = 12,4 \text{ } \%$$

$$w_2 = w_{300-2} - w_{e-2} = 99,7 \text{ } \% - 87,7 \text{ } \% = 12,0 \text{ } \%$$

$$w_3 = w_{300-3} - w_{e-3} = 99,5 \text{ } \% - 86,8 \text{ } \% = 12,7 \text{ } \%$$

$$\bar{w} = \frac{w_1 + w_2 + w_3}{3} = \frac{12,4 \text{ } \% + 12,0 \text{ } \% + 12,7 \text{ } \%}{3} = 12,4 \text{ } \%$$

where

- $w_1$  is the mass percentage (%) of the carbon impurities of sample A in the first run of measurement;
- $w_{300-1}$  is the mass percentage (%) of sample A in the first run of measurement at 300 °C;
- $w_{e-1}$  is the mass percentage (%) of sample A in the first run of measurement at temperature  $T_e$ ;
- $w_2$  is the mass percentage (%) of the carbon impurities of sample A in the second run of measurement;
- $w_{300-2}$  is the mass percentage (%) of sample A in the second run of measurement at 300 °C;
- $w_{e-2}$  is the mass percentage (%) of sample A in the second run of measurement at temperature  $T_e$ ;
- $w_3$  is the mass percentage (%) of the carbon impurities of sample A in the third run of measurement;

- $w_{300-3}$  is the mass percentage (%) of sample A in the third run of measurement at 300 °C;
- $w_{e-3}$  is the mass percentage (%) of sample A in the third run of measurement at temperature  $T_e$ ;
- $\bar{w}$  is the average mass percentage (%) of the carbon impurities in the measured MWCNT sample.

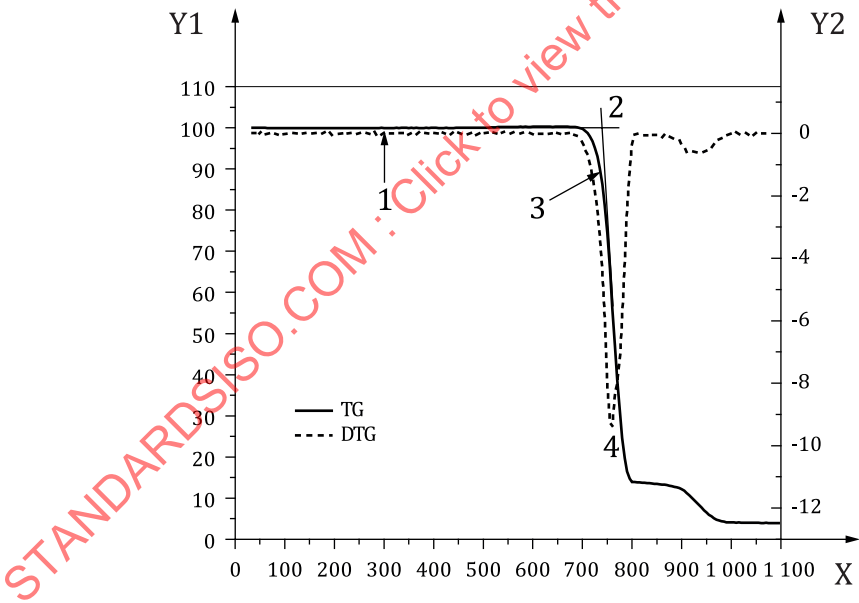
The average value of the  $w$  and the standard deviation from multiple runs were calculated as shown in [Table A.1](#). The standard deviation value of the mass percentage (%) of the carbon impurities should be less than or equal to 1,5 %, showing repeatability of multiple TG runs.

**Table A.1 — Calculations of  $w$  and  $T_e$  average and standard deviations from three repeat runs of sample A**

| Parameter                                                     | Symbol    | Run 1 | Run 2 | Run 3 | Average | Standard deviation |
|---------------------------------------------------------------|-----------|-------|-------|-------|---------|--------------------|
| Extrapolated initial temperature (°C)                         | $T_e$     | 688,9 | 681,2 | 681,0 | 683,7   | 4,50               |
| Mass percentage content (%) of the sample at 300 °C           | $w_{300}$ | 99,70 | 99,70 | 99,50 | 99,63   | 0,12               |
| Mass percentage content (%) of the sample at $T_e$            | $w_e$     | 87,30 | 87,70 | 86,80 | 87,27   | 0,45               |
| Mass percentage (%) of the carbon impurities, $w_{300} - w_e$ | $w$       | 12,40 | 12,00 | 12,70 | 12,37   | 0,35               |

**A.5.2 Sample B**

TG and DTG curves of sample B are shown in [Figures A.4 to A.6](#).

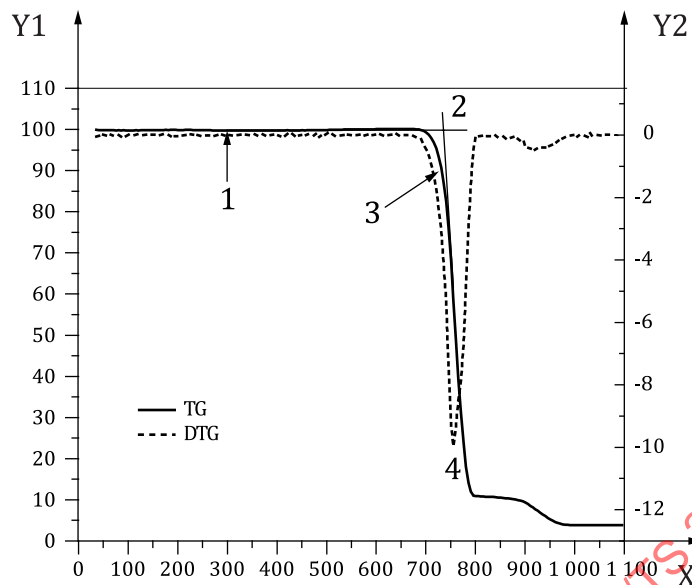


**Key**

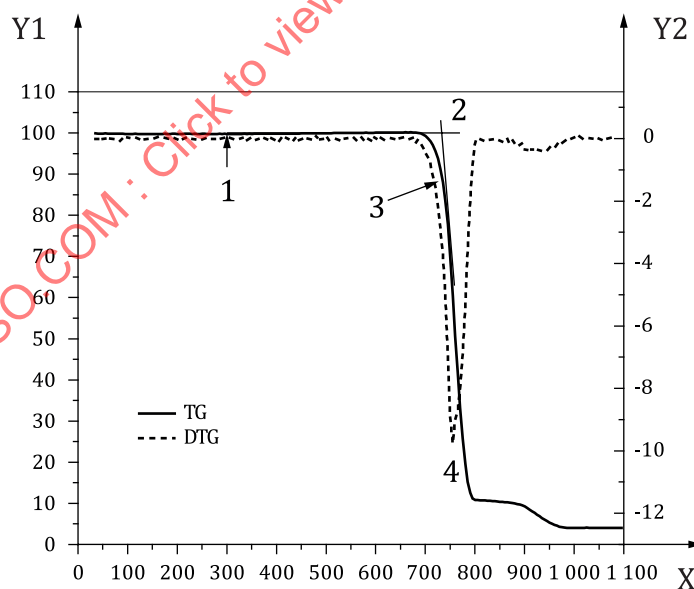
- |       |                                   |   |                  |
|-------|-----------------------------------|---|------------------|
| X     | temperature (°C)                  | 2 | $T_e = 736,5$ °C |
| $Y_1$ | mass percentage (%)               | 3 | $w_e = 89,24$ %  |
| $Y_2$ | derivative mass percentage (%/°C) | 4 | $T_o = 759,2$ °C |
| 1     | $w_{300} = 99,94$ %               |   |                  |

**Figure A.4 — TG and DTG curves of sample B in the first run of measurement**



**Key**

|       |                                   |   |                                       |
|-------|-----------------------------------|---|---------------------------------------|
| X     | temperature (°C)                  | 2 | $T_e = 734,2 \text{ } ^\circ\text{C}$ |
| $Y_1$ | mass percentage (%)               | 3 | $w_e = 88,42 \text{ } \%$             |
| $Y_2$ | derivative mass percentage (%/°C) | 4 | $T_o = 756,1 \text{ } ^\circ\text{C}$ |
| 1     | $w_{300} = 99,73 \text{ } \%$     |   |                                       |

**Figure A.5 — TG and DTG curves of sample B in the second run of measurement****Key**

|       |                                   |   |                                       |
|-------|-----------------------------------|---|---------------------------------------|
| X     | temperature (°C)                  | 2 | $T_e = 734,1 \text{ } ^\circ\text{C}$ |
| $Y_1$ | mass percentage (%)               | 3 | $w_e = 88,87 \text{ } \%$             |
| $Y_2$ | derivative mass percentage (%/°C) | 4 | $T_o = 755,8 \text{ } ^\circ\text{C}$ |
| 1     | $w_{300} = 99,75 \text{ } \%$     |   |                                       |

**Figure A.6 — TG and DTG curves of sample B in the third run of measurement**

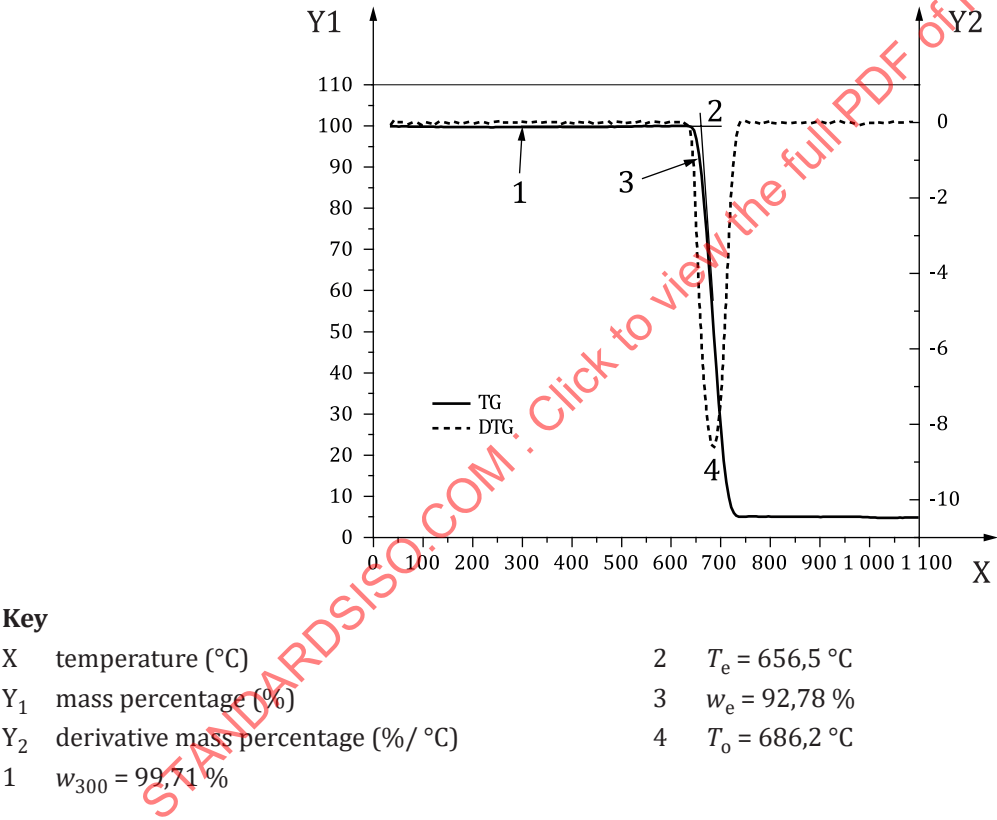
The average value of  $w$  and the standard deviation from multiple runs were calculated as shown in [Table A.2](#).

**Table A.2 — Calculations of  $w$  and  $T_e$  average and standard deviations from three repeat runs of sample B**

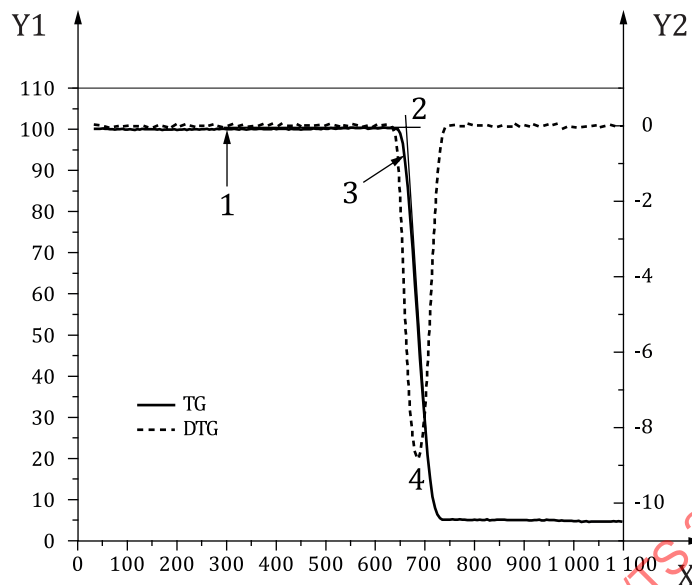
| Parameter                                                     | Symbol    | Run 1 | Run 2 | Run 3 | Average | Standard deviation |
|---------------------------------------------------------------|-----------|-------|-------|-------|---------|--------------------|
| Extrapolated initial temperature (°C)                         | $T_e$     | 736,5 | 734,2 | 734,1 | 734,9   | 1,36               |
| Mass percentage content (%) of the sample at 300 °C           | $w_{300}$ | 99,94 | 99,73 | 99,75 | 99,81   | 0,12               |
| Mass percentage content (%) of the sample at $T_e$            | $w_e$     | 89,24 | 88,42 | 88,87 | 88,84   | 0,41               |
| Mass percentage (%) of the carbon impurities, $w_{300} - w_e$ | $w$       | 10,70 | 11,31 | 10,88 | 10,96   | 0,31               |

**A.5.3 Sample C**

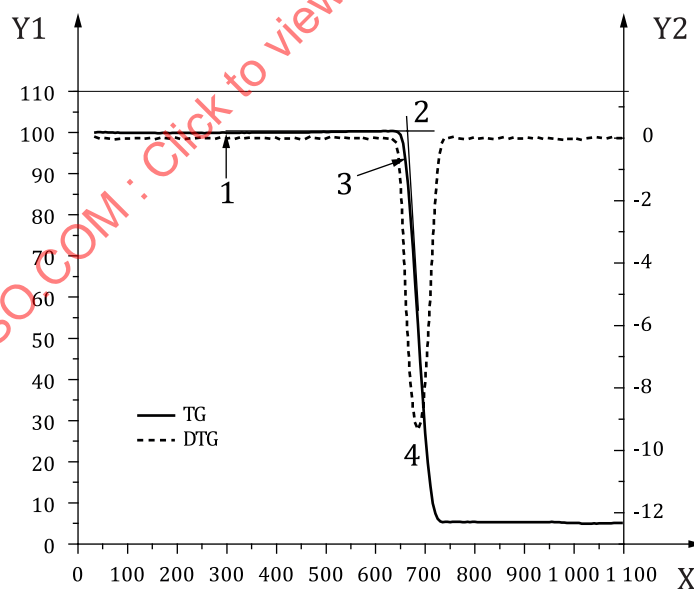
TG and DTG curves of sample C are shown in [Figures A.7](#) to [A.9](#).



**Figure A.7 — TG and DTG curves of sample C in the first run of measurement**

**Key**

|       |                                   |   |                                       |
|-------|-----------------------------------|---|---------------------------------------|
| X     | temperature (°C)                  | 2 | $T_e = 658,5 \text{ } ^\circ\text{C}$ |
| $Y_1$ | mass percentage (%)               | 3 | $w_e = 93,68 \%$                      |
| $Y_2$ | derivative mass percentage (%/°C) | 4 | $T_o = 684,9 \text{ } ^\circ\text{C}$ |
| 1     | $w_{300} = 100,01 \%$             |   |                                       |

**Figure A.8 — TG and DTG curves of sample C in the second run of measurement****Key**

|       |                                   |   |                                       |
|-------|-----------------------------------|---|---------------------------------------|
| X     | temperature (°C)                  | 2 | $T_e = 660,0 \text{ } ^\circ\text{C}$ |
| $Y_1$ | mass percentage (%)               | 3 | $w_e = 93,20 \%$                      |
| $Y_2$ | derivative mass percentage (%/°C) | 4 | $T_o = 685,5 \text{ } ^\circ\text{C}$ |
| 1     | $w_{300} = 99,95 \%$              |   |                                       |

**Figure A.9 — TG and DTG curves of sample C in the third run of measurement**

The average value of the  $w$  and the standard deviation from multiple runs were calculated as shown in [Table A.3](#).

**Table A.3 — Calculations of  $w$  and  $T_e$  average and standard deviations from three repeat runs of sample C**

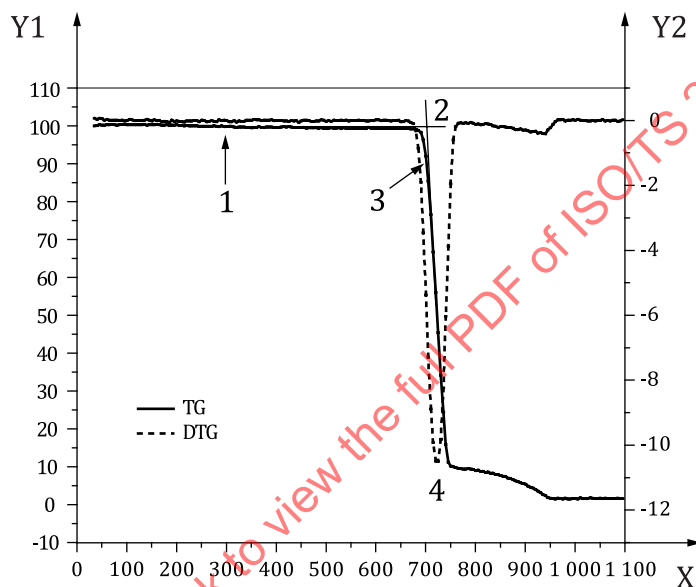
| Parameter                                                     | Symbol    | Run 1 | Run 2  | Run 3 | Average | Standard deviation |
|---------------------------------------------------------------|-----------|-------|--------|-------|---------|--------------------|
| Extrapolated initial temperature (°C)                         | $T_e$     | 656,5 | 658,5  | 660,0 | 658,3   | 1,76               |
| Mass percentage content (%) of the sample at 300 °C           | $w_{300}$ | 99,71 | 100,01 | 99,95 | 99,89   | 0,16               |
| Mass percentage content (%) of the sample at $T_e$            | $w_e$     | 92,78 | 93,68  | 93,20 | 93,22   | 0,45               |
| Mass percentage (%) of the carbon impurities, $w_{300} - w_e$ | $w$       | 6,93  | 6,33   | 6,75  | 6,67    | 0,31               |

## Annex B (informative)

### Reproducibility test: Case study

#### B.1 Data analysis between different laboratories

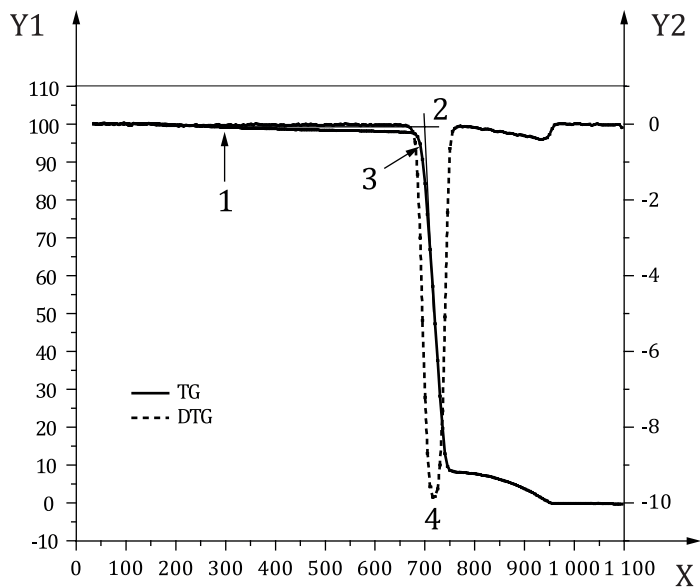
TG and DTG curves of sample D between lab I and lab II are shown in [Figures B.1](#) to [B.6](#)



#### Key

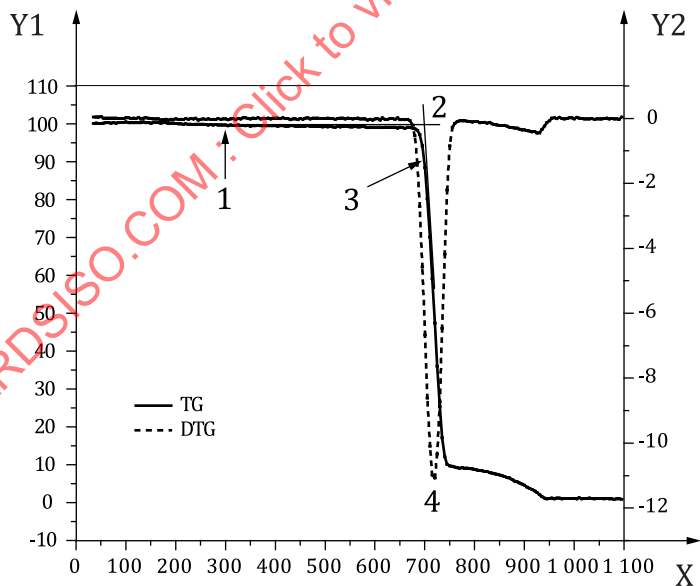
|                |                                   |   |                         |
|----------------|-----------------------------------|---|-------------------------|
| X              | temperature (°C)                  | 2 | $T_e = 694,9\text{ °C}$ |
| Y <sub>1</sub> | mass percentage (%)               | 3 | $w_e = 91,27\text{ %}$  |
| Y <sub>2</sub> | derivative mass percentage (%/°C) | 4 | $T_o = 724,0\text{ °C}$ |
| 1              | $w_{300} = 99,17\text{ %}$        |   |                         |

**Figure B.1** — TG and DTG curves of sample D in the first run of measurement in lab I



- |       |                                   |   |                         |
|-------|-----------------------------------|---|-------------------------|
| X     | temperature (°C)                  | 2 | $T_e = 699,7\text{ °C}$ |
| $Y_1$ | mass percentage (%)               | 3 | $w_e = 92,56\text{ %}$  |
| $Y_2$ | derivative mass percentage (%/°C) | 4 | $T_o = 719,0\text{ °C}$ |
| 1     | $w_{300} = 99,87\text{ %}$        |   |                         |

Figure B.2 — TG and DTG curves of sample D in the second run of measurement in lab I



- Key**
- |       |                                   |   |                         |
|-------|-----------------------------------|---|-------------------------|
| X     | temperature (°C)                  | 2 | $T_e = 698,0\text{ °C}$ |
| $Y_1$ | mass percentage (%)               | 3 | $w_e = 91,06\text{ %}$  |
| $Y_2$ | derivative mass percentage (%/°C) | 4 | $T_o = 718,0\text{ °C}$ |
| 1     | $w_{300} = 99,71\text{ %}$        |   |                         |

Figure B.3 — TG and DTG curves of sample D in the third run of measurement in lab I