TECHNICAL SPECIFICATION

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Nanotechnologies — Vocabulary —

Part 8:
Nanomanufacturing processes

Nanotechnologies — Vocabulaire —

Partie 8: Processus de nanofabrication

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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 documents 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).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared jointly by Technical Committee ISO/TC 229, *Nanotechnologies*, and Technical Committee IEC/TC 113, *Nanotechnology for electrotechnical products and systems*, in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 352, *Nanotechnologies*, in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement). The draft was circulated for voting to the national bodies of both ISO and IEC.

This second edition cancels and replaces the first edition (ISO/TS 80004-8:2013), which has been technically revised throughout.

A list of all parts in the ISO/TS 80004 series can be found on the ISO website.

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

Nanomanufacturing is the essential bridge between the discoveries of the nanosciences and real-world nanotechnology products.

Advancing nanotechnology from the laboratory into volume production ultimately requires careful study of manufacturing process issues including product design, reliability and quality, process design and control, shop floor operations, supply chain management, workplace safety and health practices during the production, use and handling of nanomaterials. Nanomanufacturing encompasses directed self-assembly and assembly techniques, synthetic methodologies, and fabrication processes such as lithography and biological processes. Nanomanufacturing also includes bottom-up directed assembly, top-down high-resolution processing, molecular systems engineering and hierarchical integration with larger scale systems. As dimensional scales of materials and molecular systems approach the nanoscale, the conventional rules governing their behaviour may change significantly. As such, the behaviour of a final product is enabled by the collective performance of its nanoscale building blocks.

Biological process terms are not included in this second edition of the nanomanufacturing vocabulary, but considering the rapid development of the field, it is expected that terms in this important area will be added in a future update to this document or in companion documents in the ISO/TS 80004 series. This could include both the processing of biological nanomaterials and the use of biological processes to manufacture materials at the nanoscale.

Similarly, additional terms from other developing areas of nanomanufacturing, including composite manufacturing, roll-to-roll manufacturing and others, will be included in future documents.

There is a distinction between the terms “nanomanufacturing” and “nanofabrication”. Nanomanufacturing encompasses a broader range of processes than does nanofabrication. Nanomanufacturing encompasses all nanofabrication techniques and also techniques associated with materials processing and chemical synthesis.

This document provides an introduction to processes used in the early stages of the nanomanufacturing value chain, namely the intentional synthesis, generation or control of nanomaterials, including fabrication steps in the nanoscale. The nanomaterials that result from these manufacturing processes are distributed in commerce where, for example, they may be further purified, be compatabilized to be dispersed in mixtures or composite matrices, or serve as integrated components of systems and devices. The nanomanufacturing value chain is, in actuality, a large and diverse group of commercial value chains that stretch across these sectors:

— the semiconductor industry (where the push to create smaller, faster, and more efficient microprocessors heralded the creation of circuitry less than 100 nm in size);

— electronics and telecommunications;

— aerospace, defence and national security;

— energy and automotive;

— plastics and ceramics;

— forest and paper products;

— food and food packaging;

— pharmaceuticals, biomedicine and biotechnology;

— environmental remediation;

— clothing and personal care.

There are thousands of tonnes of nanomaterials on the market with end-use applications in several of these sectors, such as carbon black and fumed silica. Nanomaterials that are rationally designed with specific purpose are expected to radically change the landscape in areas such as biotechnology, water purification and energy development.

The majority of clauses in this document are organized by process type. In Clause 6, the logic of placement is as follows: in the step before the particle is made, the material itself is in a gas/liquid/solid phase. The phase of the substrate or carrier in the process does not drive the categorization of the process. As an example, consider iron particles that are catalysts in a process by which you seed oil with iron particles, the oil vaporizes and condenses forming carbon particles on the iron particles. What vaporizes is the oil, and therefore it is a gas phase process. Nanotubes grow from the gas phase, starting with catalyst particles that react with the gas phase to grow the nanotubes, thus this is characterized as a gas process. Indication of whether synthesis processes are used to manufacture nano-objects, nanoparticles or both is provided in Annex A.

In addition, Annex A identifies the processes that are also applicable to macroscopic materials and are therefore not exclusively relevant to nanomanufacturing. A common understanding of the terminology used in practical applications will enable communities of practice in nanomanufacturing and will advance nanomanufacturing strength worldwide. Extending the understanding of terms across the existing manufacturing infrastructure will serve to bridge the transition between the innovations of the research laboratory and the economic viability of nanotechnologies.

For informative terms supportive of nanomanufacturing terminology, see BSI PAS 135[11].

This document belongs to a multi-part vocabulary covering the different aspects of nanotechnologies.

Nanotechnologies — Vocabulary —

Part 8:
Nanomanufacturing processes

1 Scope

This document defines terms related to nanomanufacturing processes in the field of nanotechnologies.

All the process terms in this document are relevant to nanomanufacturing, however, many of the listed processes are not exclusively relevant to the nanoscale. Terms that are not exclusive are noted within the definitions. Depending on controllable conditions, such processes can result in material features at the nanoscale or, alternatively, at larger scales.

There are many other terms that name tools, components, materials, systems control methods or metrology methods associated with nanomanufacturing that are beyond the scope of this document.

Terms and definitions from other parts of the ISO/TS 80004 series are reproduced in Clause 3 for context and better understanding.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

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

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

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

3.1
carbon nanotube
CNT
nanotube (3.9) composed of carbon

Note 1 to entry: Carbon nanotubes usually consist of curved graphene layers, including single-walled carbon nanotubes and multi-walled carbon nanotubes.

[SOURCE: ISO/TS 80004-3:2010, 4.3]

3.2
nanocomposite
solid comprising a mixture of two or more phase-separated materials, one or more being nanophase

Note 1 to entry: Gaseous nanophases are excluded (they are covered by nanoporous material).

Note 2 to entry: Materials with *nanoscale* (3.7) phases formed by precipitation alone are not considered to be nanocomposite materials.

[SOURCE: ISO/TS 80004-4:2011, 3.2]

3.3
nanofibre
nano-object (3.5) with two external dimensions in the *nanoscale* (3.7) and the third dimension significantly larger

Note 1 to entry: The largest external dimension is not necessarily in the nanoscale.

Note 2 to entry: The terms “nanofibril” and “nanofilament” can also be used.

Note 3 to entry: The largest external dimension is not necessarily in the nanoscale.

[SOURCE: ISO/TS 80004-2:2015, 4.5, modified — Note 3 to entry has been replaced.]

3.4
nanomaterial
material with any external dimension in the *nanoscale* (3.7) or having internal structure or surface structure in the nanoscale

Note 1 to entry: This generic term is inclusive of *nano-object* (3.5) and *nanostructured material* (3.8).

Note 2 to entry: See also engineered nanomaterial, manufactured nanomaterial and incidental nanomaterial.

[SOURCE: ISO/TS 80004-1:2015, 2.4]

3.5
nano-object
discrete piece of material with one, two or three external dimensions in the *nanoscale* (3.7)

Note 1 to entry: Generic term for all discrete nano-objects.

[SOURCE: ISO/TS 80004-1:2015, 2.5, modified — Note 1 to entry has been replaced.]

3.6
nanoparticle
nano-object (3.5) with all external dimensions in the *nanoscale* (3.7) where the lengths of the longest and the shortest axes of the nano-object do not differ significantly

Note 1 to entry: If the dimensions differ significantly (typically by more than three times), terms such as “nanofibre” or “nanoplate” may be preferred to the term “nanoparticle”.

[SOURCE: ISO/TS 80004-2:2015, 4.4]

3.7
nanoscale
length range from approximately from 1 nm to 100 nm

Note 1 to entry: Properties that are not extrapolations from a larger size are predominately exhibited in this length range.

[SOURCE: ISO/TS 80004-1:2015, 2.1]

3.8
nanostructured material
material having internal or surface structure in the *nanoscale* (3.7)

Note 1 to entry: If external dimensions are in the nanoscale, the term *nano-object* (3.5) is recommended.

Note 2 to entry: Adapted from ISO/TS 80004-1:2015, 2.7.

[SOURCE: ISO/TS 80004-4:2011, 2.11]

3.9
nanotube
hollow *nanofibre* (3.3)

[SOURCE: ISO/TS 80004-2:2015, 4.8]

4 Terms related to general aspects

4.1
bottom-up nanomanufacturing
processes that use small fundamental units in the *nanoscale* (3.7) to create larger, functionally rich structures or assemblies

4.2
co-deposition
simultaneous deposition of two or more source materials

Note 1 to entry: Common methods include vacuum, *thermal spray* (8.2.16), *electrodeposition* (8.2.7) and liquid suspension deposition techniques.

4.3
comminution
crushing or *grinding* (7.5.6) for particle size reduction

Note 1 to entry: The term is not exclusive to nanomanufacturing.

4.4
directed assembly
guided formation of a structure guided by external intervention using components at the *nanoscale* (3.7) that can, in principle, have any defined pattern

4.5
directed self-assembly
self-assembly (4.11) influenced by external intervention to produce a preferred structure, orientation or pattern

Note 1 to entry: Examples of external intervention include an applied field, a chemical or structural template, chemical gradient and fluidic flow.

4.6
lithography
reproducible creation of a pattern

Note 1 to entry: The pattern can be formed in a radiation sensitive material or by transfer of material onto a substrate by one of the following: transfer, printing or direct writing.

4.7
multilayer deposition
alternating deposition of two or more source materials to produce a composite layer structure

4.8
nanofabrication
ensemble of activities to intentionally create *nano-objects* (3.5) or *nanostructured materials* (3.8)

4.9
nanomanufacturing
intentional synthesis, generation or control of *nanomaterials* (3.4), or fabrication steps in the *nanoscale* (3.7), for commercial purposes

[SOURCE: ISO/TS 80004-1:2015, 2.11]

4.10
nanomanufacturing process
ensemble of activities to intentionally synthesize, generate or control *nanomaterials* (3.4), or fabrication steps in the *nanoscale* (3.7), for commercial purposes

[SOURCE: ISO/TS 80004-1:2015, 2.12]

4.11
self-assembly
autonomous action by which components organize themselves into patterns or structures

4.12
surface functionalization
chemical process that acts upon a surface to impart a selected chemical or physical functionality

4.13
top-down nanomanufacturing
processes that create structures at the *nanoscale* (3.7) from macroscopic objects

5 Terms related to directed assembly

5.1
electrostatic driven assembly
use of electrostatic force to orient or place *nanoscale* (3.7) elements in a device or material

5.2
fluidic alignment
use of fluid flow to orient *nanoscale* (3.7) elements in a device or material

5.3
hierarchical assembly
use of more than one type of *nanomanufacturing* (4.9) process to control a structure at multiple length scales

5.4
magnetic driven assembly
use of magnetic force to assemble elements/particles at the *nanoscale* (3.7) in a desired pattern or configuration

5.5
shape-based assembly
use of geometric shapes of *nanoparticles* (3.6) to achieve a desired pattern or configuration

5.6
supramolecular assembly
use of non-covalent chemical bonding to assemble molecules or *nanoparticles* (3.6) with surface ligands

5.7
surface-to-surface transfer
transfer of *nanoparticles* (3.6) or structures from the surface of one substrate, on which they have been deposited, grown or assembled, onto another substrate

6 Terms related to self-assembly processes

6.1
colloidal crystallization
sedimentation of *nanoparticles* (3.6) from a solution containing *nano-objects* (3.5) and their aggregates and agglomerates (NOAAs) to form a solid, which consists of an organization of particles to form an array of repeating units

Note 1 to entry: The term is not exclusive to nanomanufacturing but has been adapted to apply to nanomanufacturing processes.

6.2
graphioepitaxy
directed self-assembly (4.5) using *nanoscale* (3.7) topographical features

Note 1 to entry: Includes the growth of a thin layer on the surface and growth of an additional layer on top of a substrate, which has the same or different structure as the underlying crystal.

Note 2 to entry: The term is not exclusive to nanomanufacturing but has been adapted to apply to nanomanufacturing processes.

6.3
ion beam surface reconstruction
use of an accelerated ion beam to cause surface modification, which can be at the *nanoscale* (3.7)

Note 1 to entry: The term is not exclusive to nanomanufacturing but has been adapted to apply to nanomanufacturing processes.

6.4
Langmuir-Blodgett film formation
creation of a film at an air-liquid interface

6.5
Langmuir-Blodgett film transfer
transfer of a Langmuir-Blodgett film formed at an air-liquid interface onto a solid surface by dipping a solid substrate into the supporting liquid

6.6
layer-by-layer deposition
LbL deposition
electrostatic process of depositing polyelectrolytes with opposite charges laid over or under another

6.7
modulated elemental reactant method
use of vapour deposited precursors with regions of controlled composition as a template for the formation of interleaved layers of two or more structures

Note 1 to entry: The term is not exclusive to nanomanufacturing.

6.8
self-assembled monolayer formation
SAM formation
spontaneous formation of an organized molecular layer on a solid surface from solution or the vapour phase, driven by molecule-to-surface bonding and weak intermolecular interaction

6.9
Stranski-Krastanow growth
mode of thin film growth which starts as a two-dimensional *Frank-van der Merve growth* (6.10), and then continues as a three-dimensional *Volmer-Weber growth* (6.11)

6.10
Frank-van der Merve growth
layer-by-layer film growth

Note 1 to entry: Frank-van der Merve growth corresponds to the situation when atoms of a film have a stronger connection with a substrate than with each other. As a result, the next layer growth could not begin until the previous is completed.

Note 2 to entry: Frank-van der Merve growth is strictly a two-dimensional growth mode.

6.11
Volmer-Weber growth
island film growth

Note 1 to entry: Volmer-Weber growth mode corresponds to the situation when atoms of a film have a stronger connection with each other than with a substrate.

Note 2 to entry: *Frank-van der Merve growth* (6.10) is a three-dimensional growth mode.

7 Terms related to synthesis

7.1 Gas process phase — Physical methods

7.1.1
cold gas dynamic spraying
process in which either *nanoscale* (3.7) crystalline powders or conventional powders are fluidized and then consolidated onto a surface coating in a high velocity inert gas

Note 1 to entry: The term is not exclusive to nanomanufacturing but has been adapted to apply to nanomanufacturing processes.

7.1.2
electro-spark deposition
pulsed-arc micro-welding process using short-duration, high-current electrical pulses to deposit an electrode material onto a substrate

7.1.3
electron-beam evaporation
process in which a material is vaporized by incidence of high energy electrons in high or ultra-high vacuum conditions for subsequent deposition onto a substrate

7.1.4
wire electric explosion
formation of *nanoparticles* (3.6) by applying an electrical pulse of high current density through a wire causing it to volatilize with subsequent recondensation

7.1.5
freeze drying
dehydration or solvent removal by rapid cooling immediately followed by vacuum sublimation

Note 1 to entry: The term is not exclusive to nanomanufacturing.

7.1.6
spray drying
method in which a dry powder is produced from a liquid or slurry by rapid *evaporation* (8.2.10) of the liquid from droplets formed by nebulization, via contact with a hot gas or equivalent

Note 1 to entry: The term is not exclusive to nanomanufacturing.

7.1.7
supercritical expansion
precipitation of *nano-objects* (3.5) resulting from an expansion of a solution above its critical temperature and critical pressure through a spray device

Note 1 to entry: The term is not exclusive to nanomanufacturing but has been adapted to apply to nanomanufacturing processes.

7.1.8
suspension combustion thermal spray
thermal spray (8.2.16) in which the precursor is introduced to a plasma jet in the form of a liquid suspension

7.1.9
vaporization
process of assisted change of phase from solid or liquid to gas or plasma phases

Note 1 to entry: The vaporization process is often used to consequently deposit the vaporized material on a target substrate. The whole process is known as *physical vapour deposition (PVD)* (8.2.14).

Note 2 to entry: High vacuum PVD is usually performed at pressures in the range of 10^{-6} to 10^{-9} Torr. Ultra-high vacuum (UHV) PVD is the deposition performed at pressures below 10^{-9} Torr.

Note 3 to entry: The term is not exclusive to nanomanufacturing.

7.2 Gas process phase — Chemical methods

7.2.1 Flame synthesis processes

7.2.1.1
liquid precursor combustion
creation of solid product, typically a *nanomaterial* (3.4) in aggregate form, via exothermic reaction of a feedstock solution with an oxidizer

Note 1 to entry: The term is not exclusive to nanomanufacturing but has been adapted to apply to nanomanufacturing processes.

7.2.1.2
plasma spray
creation of a jet of solid product, typically a *nanomaterial* (3.4) in aggregate form, from an ionized gaseous source

Note 1 to entry: The term is not exclusive to nanomanufacturing but has been adapted to apply to nanomanufacturing processes.

7.2.1.3
pyrogenesis
process using combustion or another heat source to produce solid product, typically a *nanomaterial* (3.4) in aggregate form, facilitated by an aerosolized spray

Note 1 to entry: The term is not exclusive to nanomanufacturing but has been adapted to apply to nanomanufacturing processes.

7.2.1.4
solution precursor plasma spray
gas phase process in which a thermal (equilibrium) plasma is formed into which a solution containing precursors is introduced resulting in gaseous species that during cooling form a solid product, typically a *nanomaterial* (3.4) in aggregate form

Note 1 to entry: The term is not exclusive to nanomanufacturing but has been adapted to apply to nanomanufacturing processes.

7.2.1.5
thermal spray pyrolysis
creation of solid product, typically a *nanomaterial* (3.4) in aggregate form, from liquid precursors through liquid atomization and reaction using a thermal source

Note 1 to entry: The term is not exclusive to nanomanufacturing but has been adapted to apply to nanomanufacturing processes.

7.2.2 Other terms

7.2.2.1
hot wall tubular reaction
chemical vapour deposition (8.2.4) performed in a tubular furnace in which the reaction surface is maintained at a controlled elevated temperature

Note 1 to entry: The term is not exclusive to nanomanufacturing.

7.2.2.2
photothermal synthesis
gas phase process where a precursor or other gaseous species is heated by absorption of infrared radiation resulting in heating of the gas and thermal decomposition of the precursor producing a solid product, typically a *nanoparticle* (3.6)

Note 1 to entry: The term is not exclusive to nanomanufacturing but has been adapted to apply to nanomanufacturing processes.

7.2.2.3
vapour-liquid-solid nanofibre synthesis
VLS
growth of *nanofibres* (3.3) onto a substrate with feed material in gaseous form in the presence of a liquid catalyst

Note 1 to entry: The VLS method for fibres exploits a liquid phase on the end of a fibre, which can rapidly adsorb a vapour to supersaturation levels, and from which crystal growth subsequently occurs.

7.3 Liquid process phase — Physical methods

7.3.1
electrospinning
use of electrical potential to induce drawing of fine fibres from a liquid phase

Note 1 to entry: The term is not exclusive to nanomanufacturing.

7.3.2
in situ intercalative polymerization
insertion of monomers into layered inorganic materials followed by polymerization, which results in *nanocomposites* (3.2)

Note 1 to entry: The term is not exclusive to nanomanufacturing but has been adapted to apply to nanomanufacturing processes.

7.3.3
nanoparticle dispersion
creation of a suspension of *nanoparticles* (3.6) in a liquid through the use of added molecular ligands, surface charges or other interactions to prevent or slow sedimentation

7.3.4
tape casting
deposition of a macroscopic layer by spreading a slurry of ceramic paste onto a flat surface

Note 1 to entry: *Nanoparticles* (3.6) may be part of the composition of the layer.

Note 2 to entry: The term is not exclusive to nanomanufacturing but has been adapted to apply to nanomanufacturing processes.

7.3.5
wet ball milling
grinding (7.5.6) process in liquid via rolling feedstock material with crushing balls of greater hardness to create a force of impact in order to reduce the size of target components

Note 1 to entry: The product of the process is known as "slurry".

Note 2 to entry: The term is not exclusive to nanomanufacturing but has been adapted to apply to nanomanufacturing processes.

7.4 Liquid process phase — Chemical methods

7.4.1
acid hydrolysis of cellulose biomass
process in which strong mineral acids are used under controlled reaction conditions to digest amorphous cellulosic regions and release cellulose nanocrystals from appropriately pretreated cellulosic biomass (e.g. lignin or protein removal)

Note 1 to entry: As described in ISO/TR 19716:2016, cellulose nanocrystals can be released from a variety of naturally occurring (or "native") cellulose sources such as wood, annual plants, algae, bacteria and tunicates. These sources are collectively termed "cellulosic biomass".

Note 2 to entry: It should be noted that microcrystalline cellulose (also called "cellulose microcrystals", see ISO/TS 20477:2017, Annex A can also be released from cellulosic biomass by using mineral acids. The acids and reaction conditions generally used to produce cellulose microcrystals differ from those used to produce cellulose nanocrystals.

7.4.2
nanoparticle precipitation
formation of *nanoparticles* (3.6) from solution reactions where particle size may be controlled by kinetic factors

7.4.3
prompt inorganic condensation
formation of atomically smooth and dense films by *spin coating* (8.2.17) and low-temperature curing of organic free aqueous solutions based on organometallic molecular precursors

Note 1 to entry: The term is not exclusive to nanomanufacturing.

7.4.4
sol-gel processing
conversion of a chemical solution or colloidal suspension (sol) to an integrated network (gel), which can then be further densified

Note 1 to entry: The term is not exclusive to nanomanufacturing.

7.4.5
Stober process
generation of particles of silica by using a tetra-alkyl orthosilicate and a combination of low molecular weight alcohol and ammonia, used with or without water

Note 1 to entry: This is a *sol-gel processing* (7.4.4) method for synthesizing silica.

Note 2 to entry: The term is not exclusive to nanomanufacturing.

7.4.6
surfactant templating
use of surfactants to self-assemble molecular species such that they can be subsequently solidified in a structured configuration at the *nanoscale* (3.7)

EXAMPLE Mobil Composition of Matter No. 41.

7.5 Solid process phase — Physical methods

7.5.1
block copolymer phase segregation
formation of repeatable 2D and 3D structures from the segregation of immiscible polymer chain segments

Note 1 to entry: The term is not exclusive to nanomanufacturing.

7.5.2
block copolymer templating
incorporation of a material into the phase of a block copolymer to achieve a *nanoscale* (3.7) structure

Note 1 to entry: The term is not exclusive to nanomanufacturing but has been adapted to apply to nanomanufacturing processes.

Note 2 to entry: The term is not exclusive to nanomanufacturing.

7.5.3
cold pressing
compaction of *nanoscale* (3.7) particles, typically at room temperatures, to fuse them together and to increase the density

Note 1 to entry: The term is not exclusive to nanomanufacturing.

7.5.4
conshearing continuous confined strip shearing
C2S2
use of very large plastic strain to produce grains in a bulk metal without any significant change in the overall dimensions

Note 1 to entry: The main objective is to produce lightweight parts with greatly improved mechanical properties.

Note 2 to entry: The term is not exclusive to nanomanufacturing.

7.5.5
devitrification
structural transformation from a glassy state to a crystalline state that introduces *nanoscale* (3.7) voids or structure

7.5.6
grinding
creation of *nanoparticles* (3.6) via mechanical shearing in contact with a material of greater hardness

Note 1 to entry: The term is not exclusive to nanomanufacturing but has been adapted to apply to nanomanufacturing processes.

7.5.7
high-speed micromachining
creating precise two- and three-dimensional workpieces from the bulk or on the surface of an object or material by cutting using defined geometry cutting tools

Note 1 to entry: Precision is achieved through high cutting spindle speeds usually between 30 000 r/min and 100 000 r/min.

Note 2 to entry: Laser, e-beam, ion beam, ultrasound, milling and computer numerical controlled machining can be used.

Note 3 to entry: The definition of high speed varies with each specific technology.

Note 4 to entry: The term is not exclusive to nanomanufacturing.

7.5.8
ion implantation
use of incident flux high energy ions to modify the surface material by damage and recrystallization

Note 1 to entry: The term is not exclusive to nanomanufacturing.

7.5.9
cryogenic milling
grinding (7.5.6) at or below cryogenic temperatures (below −150 °C, −238 °F or 123 K)

Note 1 to entry: The term is not exclusive to nanomanufacturing.

7.5.10
dry ball milling
creation of *nanoparticles* (3.6) via rolling feedstock material with crushing balls of greater hardness to mix two or more immiscible nanoparticles, which are then heated to sinter them

Note 1 to entry: The term is not exclusive to nanomanufacturing but has been adapted to apply to nanomanufacturing processes.

7.5.11
multi-pass coin forging
production of *nanoscale* (3.7) grain structures using severe plastic deformation by mechanical pressing of a sheet of material between two sine-shaped dies with successive rotation of the workpiece followed by flat forging or rolling

Note 1 to entry: The term is not exclusive to nanomanufacturing but has been adapted to apply to nanomanufacturing processes.

7.5.12
nanotemplated growth
deposition from the solution or vapour phase of material into *nanoscale* (3.7) confined spaces to form *nanoparticles* (3.6) or *nanostructured materials* (3.8)

7.5.13
polymer nanoparticle dispersion
mixing of *nanoparticles* (3.6) into a liquid polymer matrix, which is solidified to produce a polymer matrix nanoparticle composite

7.5.14
hot pressing
high-pressure powder metallurgy process for forming hard and brittle materials at high temperatures

Note 1 to entry: Pressures of up to 50 MPa (7 300 psi) and temperatures of typically 2 400 °C (4 350 °F) may be used.

Note 2 to entry: The term is not exclusive to nanomanufacturing.

7.5.15
nanoparticle sintering
joining of *nanoparticles* (3.6) and increasing their contact interfaces by atom movement within and between the particles due to the application of heat

[SOURCE: ISO 836:2001, 120, modified — “nanoparticle” has been added to the term and “nanoparticles” has replaced “particles” in the definition.]

7.5.16
spark plasma sintering
densifying powders under mechanical pressure by applying DC pulsed currents to conducting powders at a very high heating or cooling rate (up to 1 000 K/min), avoiding coarsening the internal structure

7.6 Solid process phase — Chemical methods

7.6.1
block copolymer chemical derivatization
modification of block copolymer solid through the addition of atoms or molecules that selectively bind or segregate to only one phase

Note 1 to entry: The term is not exclusive to nanomanufacturing.

7.6.2
electrochemical anodization
process in which the anode is simultaneously oxidized and etched, resulting in *nanoscale* (3.7) pores usually with a high degree of regularity and controllability

Note 1 to entry: This process may also be referred to as "anodic etching".

7.6.3
intercalation
process by which a heterogeneous material (atoms, small molecules) is inserted into a host structure (crystal lattice or other macromolecular structure)

7.6.4
two-phase method
method in which a binary mixture of materials is heated and then rapidly cooled to produce a solid composite with *nanoscale* (3.7) features

8 Terms related to fabrication

8.1 Nanopatterning lithography

8.1.1
3D lithography
process in which patterns or structuring can be achieved with *nanoscale* (3.7) dimensions in all three dimensions

Note 1 to entry: The term is not exclusive to nanomanufacturing but has been adapted to apply to nanomanufacturing processes.

8.1.2
additive processing
process in which the addition of a layer of new material is used to create a pattern of deposited material on the substrate

Note 1 to entry: Two terms are used to describe additive processing using resist: "lift-off" and "stencil". In lift-off, the layer of new material is applied to the whole surface, and the pattern is revealed after the removal of the unexposed resist with the overlaid material. With a stencil, the new material is only added where the surface is not protected by resist [as with *electrodeposition* (8.2.7) with a resist layer in place].

Note 2 to entry: The term is not exclusive to nanomanufacturing.

8.1.3
block copolymer lithography
process in which microphase separation in diblock copolymers is used to create polymer templates with *nanoscale* (3.7) patterns

Note 1 to entry: The term is not exclusive to nanomanufacturing but has been adapted to apply to nanomanufacturing processes.

8.1.4
colloidal crystal template lithography
process in which crystallized colloidal particles are used to create a 2D or 3D framework for subsequent deposition or etching

Note 1 to entry: The term is not exclusive to nanomanufacturing.

8.1.5
deep ultraviolet lithography
DUV
patterned exposure of a photoactive polymer using ultraviolet light in the wavelength range 100 nm to 280 nm

Note 1 to entry: The term is not exclusive to nanomanufacturing.

8.1.6
dip-pen nanolithography
method in which a scanning tip is used to transfer specific material onto a substrate surface, via a solvent meniscus, for patterning a substrate at length scales below 100 nm

Note 1 to entry: Often the tip is an atomic-force microscopy (AFM) tip coated with specific molecules that are to be deposited on the surface in a layer that can be a monolayer. In other cases, the material to be deposited could be *nanoparticles* (3.6).

Note 2 to entry: “Dip Pen Nanolithography” was the trade name of a product supplied by NanoInk, Inc. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of the product named. Equivalent products may be used if they can be shown to lead to the same results.

[SOURCE: ISO 18115-2:2013, 5.40]

8.1.7
electron-beam lithography
direct write patterning process that uses a focused, concentrated stream of electrons to modify the solubility of a resist layer

8.1.8
extreme ultraviolet lithography
EUV
exposure of a resist material using electromagnetic radiation of approximately 10 nm to 20 nm wavelength

Note 1 to entry: Usually reflective optics are used to focus the radiation.

8.1.9
focused ion-beam lithography
FIB lithography
direct write patterning process that uses a focused ion beam to modify the solubility of a resist layer

8.1.10
immersion optics
photolithography (8.1.21) process that immerses the objective lens and resist in a liquid to provide refractive index matching

8.1.11
interference lithography
use of diffraction gratings to create an interference pattern of radiation to create *nanoscale* (3.7) exposure patterns in resist

8.1.12
ion-induced deposition
use of a focused, concentrated stream of ions to bring about or give rise to the localized reaction of an adsorbed molecule to deposit material

8.1.13
ion-induced etching
use of a focused ion beam to induce the localized reaction of an adsorbed molecule to etch the substrate material

8.1.14
ion projection lithography
use of accelerated ions in conjunction with a mask to create *nanoscale* (3.7) exposure patterns in resist

8.1.15
micro-contact printing
form of *soft lithography* (8.1.25) in which a soft mould is dipped into an ink and the pattern transferred to a substate by pressing

Note 1 to entry: The fidelity of the transfer is strongly dependent on the local surface characteristics of the substrate for the particular material used as an ink.

8.1.16
microfluidic deposition
use of micrometre scale or *nanoscale* (3.7) channels in a solid manifold to facilitate the transfer of material from a liquid or solution state into a solid state onto a substrate surface

Note 1 to entry: The term is not exclusive to nanomanufacturing but has been adapted to apply to nanomanufacturing processes.

8.1.17
nano-embossing
transfer of a pattern using a template into bulk material rather than into a thin film

Note 1 to entry: This definition also includes 3D patterning.

Note 2 to entry: In *embossing* (8.4.1), the flow of material displaced by the template is not constrained. The embossed artefact is normally the end product, while in imprinting, the patterned resist is used in subsequent processing.

8.1.18
nano-imprint lithography
NIL
process in which a pattern is transferred by pressing a *nanoscale* (3.7) template (usually called a die, stamp, mask or mould) of the desired pattern in relief into a deformable resist, which is then cured thermally or with light

Note 1 to entry: As the pattern is defined by the topography of the template, it is a printing process and not a primary *lithography* (4.6).

Note 2 to entry: Types of nano-imprint lithography are conveniently divided by the use of a particular type of resist for imprinting. With thermoplastic polymeric materials, the resist is heated so that it can flow when the pressure is applied to the template. With thermosetting resists, heat is applied after the initially liquid resist has been displaced by the template. Negative photosensitive resists can be set by the application of light though the (transparent in this case) template. Processes using photosensitive resist are called by different workers, optical imprinting, optical nano-imprinting or step and flash.

8.1.19
natural lithography
process in which the primary pattern is defined by the replication of a pattern that occurs in nature

EXAMPLE The stripes that occur on collagen fibres or the pattern formed by strands of RNA. The term refers to the use of a mask or template that does not require the use of a focused beam of radiation to define the pattern[12].

Note 1 to entry: The term is not exclusive to nanomanufacturing.

8.1.20
phase-contrast photolithography
exposure of a resist material through phase-shifting reticles to increase resolution of *nanoscale* (3.7) patterns

8.1.21
photolithography
optical lithography
process in which electromagnetic radiation is used to transfer a mask through a reticle to create a pattern

Note 1 to entry: Usually a resist material is used to make the mask.

Note 2 to entry: The term is not exclusive to nanomanufacturing.

8.1.22
plasmonic lithography
use of *nanoscale* (3.7) metallic patterns to guide near-field optical radiation to create nanoscale photolithographic exposure patterns in resist

8.1.23
scanning force probe writing
use of a scanning probe microscope (SPM) tip to mark, ink or otherwise locally modify the surface of a substrate

8.1.24
scanning tunnelling microscope chemical vapour deposition
STM CVD
application of a voltage to an STM tip to facilitate *nanoscale* (3.7) *CVD* (8.2.4) in the proximity of the tip onto a substrate

8.1.25
soft lithography
mechanical printing processes in which an elastomeric (or soft) template is used to transfer the pattern

8.1.26
subtractive processing
removal of material except where the surface is protected by the patterned resist

Note 1 to entry: The term is not exclusive to nanomanufacturing.

8.1.27
X-ray lithography
process that uses X-ray radiation to expose a mask to create a lithographic pattern

Note 1 to entry: As X-rays are difficult to focus on a *nanoscale*-sized (3.7) beam [(but see *extreme ultraviolet lithography (EUV)* (8.1.8)], X-ray lithography is used to refer to a printing process, using a mask that has a pattern that consists of regions opaque and transparent to X-rays. The mask typically consists of a membrane of a material that has low X-ray absorption, with a pattern of highly absorbing material (e.g. a metal). Usually, a resist material is used to make the mask.

8.2 Deposition processes

8.2.1
adsorption
retention, by physical or chemical forces, of gas molecules, dissolved substances or liquids by the surfaces of solids or liquids with which they are in contact

Note 1 to entry: The term is not exclusive to nanomanufacturing.

[SOURCE: ISO 14532:2014, 2.2.2.7, modified — Note 1 to entry has been replaced.]

8.2.2
atomic layer deposition
ALD
process of fabricating uniform conformal films through the cyclic deposition of material through self-terminating surface reactions that enable thickness control at the atomic scale

Note 1 to entry: This process often involves the use of at least two sequential reactions to complete a cycle that can be repeated several times to establish a desired thickness.

8.2.3
catalytic chemical vapour deposition
CCVD
chemical vapour deposition (8.2.4) based on the decomposition of gaseous molecules in the presence of a catalyst

Note 1 to entry: CCVD is used in the synthesis of *carbon nanotubes* (3.1) on a substrate from source materials such as hydrocarbons (e.g. methane) with catalysts such as Fe, Ni or Co.

Note 2 to entry: The term "CCVD" is redundant with the process of catalysis.

8.2.4
chemical vapour deposition
CVD
deposition of a solid material onto a substrate by chemical reaction of a gaseous precursor or mixture of precursors, commonly initiated by heat

8.2.5
cluster beam coating
deposition of *nanoparticles* (3.6) to form a solid-structured film using a source beam

8.2.6
dip coating
creation of a thin film by dipping a substrate into a solution containing the material of interest

Note 1 to entry: The term is not exclusive to nanomanufacturing.

8.2.7
electrodeposition
electroplating
deposition of material onto an electrode surface from ions in solution by electrochemical reduction

Note 1 to entry: The term is not exclusive to nanomanufacturing.

8.2.8
electroless deposition
autocatalytic deposition of material onto a solid surface from ions in solution in the presence of a soluble reducing agent

Note 1 to entry: The term is not exclusive to nanomanufacturing.

8.2.9
electro-spray
deposition of material onto a surface by pressurization through a nozzle held at an applied voltage

Note 1 to entry: The term is not exclusive to nanomanufacturing.

8.2.10
evaporation
process in which a material is vaporized by heating in high or ultra-high vacuum conditions for subsequent deposition onto a substrate

Note 1 to entry: The term is not exclusive to nanomanufacturing.

8.2.11
focused electron-beam deposition
chemical vapour deposition (8.2.4) using a focused, concentrated stream of electrons to induce localized reactions of molecules from a precursor gas onto a surface

8.2.12
focused ion-beam deposition
FIB deposition
ion induced formation and transfer of a material onto the surface of a substrate

Note 1 to entry: FIB-assisted *chemical vapour deposition* (8.2.4) occurs when a gas, such as tungsten hexacarbonyl ($W(CO)_6$), is introduced to the vacuum chamber and allowed to chemisorb onto the sample. By scanning an area with the beam, the precursor gas will be decomposed into volatile and non-volatile components; the non-volatile component, such as tungsten, remains on the surface as a deposit. This is useful, as the deposited metal can be used as a sacrificial layer, to protect the underlying sample from the destructive sputtering of the beam. Other materials such as platinum can also be deposited.

8.2.13
molecular beam epitaxy
MBE
process of growing single crystals in which beams of atoms or molecules are deposited on a single-crystal substrate in vacuum, giving rise to crystals whose crystallographic orientation is in registry with that of the substrate

Note 1 to entry: The beam is defined by allowing the vapour to escape from the *evaporation* (8.2.10) zone to a high vacuum zone through a small orifice.

Note 2 to entry: Structures with *nanoscale* (3.7) features can be grown in this method by exploiting strain, e.g. InAs dots on GaAs substrate.

Note 3 to entry: Adapted from Reference [13].

8.2.14
physical vapour deposition
PVD
process of depositing a coating by vaporizing and subsequently condensing an element or compound, usually in a high vacuum

[SOURCE: ISO 2080:2008, 2.12]

8.2.15
polyelectrolyte layer-by-layer
LbL
repeated alternate deposition of oppositely charged polymers onto a surface

8.2.16
thermal spray
deposition of *nanoparticles* (3.6) to form a solid film from a plasma-based or combustion-based nanoparticle source

Note 1 to entry: The term is not exclusive to nanomanufacturing but has been adapted to apply to nanomanufacturing processes.

8.2.17
spin coating
creation of a thin film by deposition of a material in solution onto a rotating substrate by utilizing centrifugal force

Note 1 to entry: The term is not exclusive to nanomanufacturing.

8.2.18
spray deposition
process to deposit material onto the outside or uppermost layer of substrate by pressurization of a liquid through a nozzle to create droplets or aerosols

Note 1 to entry: The term is not exclusive to nanomanufacturing.

8.2.19
sputter deposition
physical *vapour deposition* (8.2.14) process employing energetic particles to transfer atoms from a target material to a substrate

8.2.20
surface polymerization
creation of a polymer film on a surface from a vapour phase or liquid phase monomer

Note 1 to entry: The term is not exclusive to nanomanufacturing.

8.3 Etching processes

8.3.1
anisotropic etching
process in which the etch rate in the direction normal to the surface is much higher than in direction parallel to the surface

Note 1 to entry: The term is not exclusive to nanomanufacturing.

8.3.2
Bosch etching
process that alternates repeatedly between an etching mode and a passivation mode to achieve the etching of nearly vertical structures

Note 1 to entry: The term is not exclusive to nanomanufacturing.

8.3.3
chemical etching
process of using acids, bases or other chemicals to dissolve away unwanted materials from a substrate

Note 1 to entry: The products of a chemical etch are either soluble in the etch solution [as in *wet etching* (8.3.22) or volatile at low pressures [as in *dry-etching* (8.3.9)].

Note 2 to entry: The term is not exclusive to nanomanufacturing.

8.3.4
chemically assisted ion beam etching
reactive gases are introduced during etching via needles or gas rings above the substrate

8.3.5
cryogenic etching
process in which the substrate is cooled to approximately 163 K to produce nearly vertical etched sidewall structures

Note 1 to entry: The low temperature slows down the chemical reaction that produces *isotropic etching* (8.3.14). Ions continue to bombard upward-facing surfaces and etch them away producing steep side walls.

8.3.6
crystallographic etching
process in which the etch rates are different for different crystallographic directions

8.3.7
deep reactive ion etching
DRIE
highly *anisotropic etching* (8.3.1) process used to create high aspect ratio structures

EXAMPLE Steep sided holes and trenches.

Note 1 to entry: There are two main technologies for DRIE: *cryogenic etching* (8.3.5) and *Bosch etching* (8.3.2).

8.3.8
dry-ashing
form of *chemical etching* (8.3.3) in which surface material is spontaneously etched by a neutral or activated gas and forms volatile etch products

EXAMPLE Photoresist mask removal in an oxygen plasma ambient.

Note 1 to entry: The term is not exclusive to nanomanufacturing.

8.3.9
dry-etching
process that makes use of partially ionized gases to remove material from a substrate

8.3.10
focused ion-beam etching
FIB etching
FIB milling
beam of ions (usually gallium) focused through a set of electrostatic lenses to create a small spot on the substrate

Note 1 to entry: The beam removes material from the substrate through physical sputtering. The beam spot can be scanned across the surface to create a pattern. *Nanoscale* (3.7) resolution can be obtained in this process.

8.3.11
high-density plasma etching
plasma etching (8.3.18) that uses a high density (typically 10^{11} to 10^{12} ions per cubic centimetre) ion beam as created by electron cyclotron resonance, helicon, magnetron or inductive methods

Note 1 to entry: Plasma can be used for either etching or deposition depending on the location of the substrate.

8.3.12
inductively coupled plasma
ICP
method by which energy is magnetically coupled into the plasma by a current carrying loop around the chamber

Note 1 to entry: The term is not exclusive to nanomanufacturing.

8.3.13
ion beam etching
ion beam milling
use of a plasma source to produce an ion beam to remove material from a substrate

8.3.14
isotropic etching
process (usually wet) in which the etch rate in the horizontal and vertical directions are identical

Note 1 to entry: The term is not exclusive to nanomanufacturing.

8.3.15
laser ablation
process using the energy from a pulsed laser to erode material from the surface of a target

Note 1 to entry: It is a method of producing *nanoscale* (3.7) features on a surface.

8.3.16
light-assisted etching
photochemical etching
processes in which light is used to influence or control the etching process

Note 1 to entry: Light-assisted etching is based on the photosensitivity of *chemical etching* (8.3.3) under certain conditions. A desired lateral structure can be produced, depending on the illumination pattern, which is defined by optical imaging during the etching process. This process has been used to prepare laterally structured luminescent porous silicon, for example.

Note 2 to entry: The term is not exclusive to nanomanufacturing.

8.3.17
physical etching
sputter etching
process of etching through physical interactions (momentum transfer) between accelerated chemically inert ions (e.g. argon) and an etched solid

Note 1 to entry: The process is anisotropic and non-selective.

8.3.18
plasma etching
process that takes place in a gaseous system consisting of ions and electrons formed by an electrical discharge to remove material from a substrate

Note 1 to entry: The term “plasma etching machine” is usually restricted to a machine with two capacitive electrodes in which the material to be etched is immersed in the plasma.

Note 2 to entry: As the ionization of the gas is rarely complete, there are also neutral species, some in an excited state (radicals), that can participate in the etching.

8.3.19
radiation track etching
formation of a structure by etching along the pathways formed by radiation damage in a solid

EXAMPLE Porous polymer in which tracks are etched using a selective solvent that only dissolves short chains.

8.3.20
reactive ion etching
RIE
form of *plasma etching* (8.3.18) in which the wafer is placed on a radio-frequency-driven electrode and the counter electrode has a larger area than the driven electrode

Note 1 to entry: The plasma beam is generated under low pressure by an electromagnetic field. High energy ions, predominantly bombarding the surface, normally create a local abundance of radicals that react with the surface. RIE can produce very anisotropic profiles as compared with isotropic profiles produced with *wet etching* (8.3.22).

8.3.21
selective etching
process in which one surface material is removed rapidly while the other is removed very slowly or not removed at all

EXAMPLE HF water solution etches SiO_2 very rapidly while not etching silicon.

Note 1 to entry: The term is not exclusive to nanomanufacturing.

8.3.22
wet etching
chemical removal of a surface material with a liquid etchant

Note 1 to entry: The term is not exclusive to nanomanufacturing.

8.4 Printing and coating

8.4.1
embossing
imprinting
transfer of a pattern by pressing a rolling master template into a deformable bulk material

Note 1 to entry: The term is not exclusive to nanomanufacturing.

8.4.2
multilayer film process
creation of a multilayer by bonding individual films together in a rolling process

Note 1 to entry: The term is not exclusive to nanomanufacturing.

8.4.3
nanofibre precipitation
precipitation of *nanofibres* (3.3) from solution onto a substrate

8.4.4
nanoparticle spray coating
deposition of *nanoparticles* (3.6) from a solvent, a plasma, a cluster beam or from another nanoparticle source

Annex A
(informative)

Identification of output resulting from defined synthesis processes

Table A.1 — Identification of output resulting from defined synthesis processes

Process phase	Headings	Nanomanufacturing process term to be defined	Nano-object process	Nanostructured material process	Applicable to macroscopic materials
Gas physical methods		Cold gas dynamic spraying		√	√
		Electron-beam evaporation	√		
	Electro-spark deposition processes	Electro-spark deposition	√		
		Photothermal synthesis	√		√
		Solution precursor plasma spray		√	√
		Physical vapour deposition (PVD)	√		
	Spray drying (agglomeration) processes	Freeze drying	√		√
	Spray drying (agglomeration) processes	Spray drying	√		√
		Supercritical expansion	√		√
		Suspension combustion thermal spray	√		√
		Wire electric explosion	√		
		Vaporization	√		√

