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Biomimetics — Biomimetic materials, structures and components

Biomimétisme — Matériaux, structures et composants biomimétiques

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Foreword

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The committee responsible for this document is ISO/TC 266, *Biomimetics*.

Introduction

The increasing complexity of technical solutions and products requires new approaches. Classic research and development methods and innovation approaches often reach their limits, especially in the development and optimization of materials, structures, and components. The identification of suitable biological principles and their transfer to technical applications in the sense of biomimetics, therefore, can make an important contribution to the development of functional, adaptive, efficient (in terms of resources), and safe (in terms of toxicity to humans and the environment) materials, structures, components and manufacturing techniques.

Biomimetics — Biomimetic materials, structures and components

1 Scope

This International Standard provides a framework of biomimetics for the development of materials, structures, surfaces, components, and manufacturing technologies.

This International Standard specifies the principles of biological systems, and especially the performance of biological materials, structures, surfaces, components, and manufacturing technologies that provide the motivation and reasons for biomimetic approaches. It specifies the methodology based on analysis of biological systems, which lead to analogies, and abstractions. The transfer process from biology to technology is described based on examples of biomimetic materials, structures, surfaces, components, and manufacturing technologies. This International Standard describes measurement methods and parameters for the characterization of properties of biomimetic materials. This International Standard provides information on the relevance of biomimetic materials, structures, surfaces, components, and manufacturing technologies for industry.

This International Standard also links to other subareas in biomimetics because fundamental developments in materials, structures, surfaces, components, and manufacturing technologies often form the basis for a wide variety of additional innovations. It provides guidance and support for all those who develop, design, process, or use biomimetic materials, structures, surfaces, components, and manufacturing technologies. This International Standard can also serve for those who want to learn about and investigate these topics.

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 18458, *Biomimetics — Terminology, concepts and methodology*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 18458 and the following apply.

3.1
adaptivity
ability to adapt to variable environmental conditions

3.2
efficiency
relationship between the useful outputs to all inputs of a system

3.3
generative manufacturing process
manufacturing process in which three-dimensional components are produced, for instance, by applying material layer-by-layer

Note 1 to entry: These technologies can be used in four different levels of manufacturing:

— Concept model (additive manufacturing): A mechanical load cannot be applied to these models and they only serve to provide a three-dimensional view.

— Functional models (additive manufacturing): These models have properties similar to those available in the components manufactured later on in mass-production.

— Tools (rapid tooling): Tools are created that can be combined with other manufacturing processes.

— Low volume production (rapid manufacturing): The properties of the geometries manufactured correspond to those desired in actual use.

3.4
gradient transition
gradual transition
direction-dependent, continuous change of a chemical, physical, or mechanical property

Note 1 to entry: Biological materials are often characterized by gradual transitions in terms of their physical and mechanical properties, which are achieved through structural changes at various hierarchical levels, among other things.

3.5
compatibility
recyclability and adaptability of a material flow or a technology in the environment

3.6
modularity
composition of an overall system from individual modules

3.7
multifunctionality
structure and properties of a material and component allowing several functions necessary for the organism or technically desired to be realized at a high level and in equilibrium

3.8
redundancy
existence of functionally comparable systems, whereby one system alone is sufficient to maintain the corresponding function (multiplicity in systems)

3.9
resilience
fault tolerance
tolerance of a system to malfunctions or capacity to recover functionality after stress

3.10
Self-X property
property and information existing in a material or on a surface proceed processes autonomously without requiring special control

Note 1 to entry: Self-X properties are widespread in biological materials and surfaces and are of great interest for transfer to technical products. Examples include self-organization, self-assembly, self-repair, self-healing, self-cleaning, and self-sharpening.

3.11
stereoregularity
tacticity
certain geometric regularity in the molecular structure of polymer chains

Note 1 to entry: Macromolecular materials with identical chemical compositions can have significantly different mechanical properties due to differences in the spatial arrangement of their atoms and groups of atoms. In chemical production techniques, the molecular geometry of polymer chains is determined during polymerization by the reaction temperature selected and the catalyst used.

Note 2 to entry: A classic example from nature is polyisoprene, which can be elastic (natural rubber), as well as hard (balata, gutta-percha).

4 Abbreviated terms

AES	Auger Electron Spectroscopy
AFM	Atomic Force Microscope
CT	Computed Tomography
DSC	Differential Scanning Calorimetry
DTA	Differential Thermal Analysis
GC	Gas Chromatography
GC-MS/MS	Gas Chromatography-tandem Mass Spectrometry
GPC	Gel Permeation Chromatography
HPLC	High performance liquid chromatography
IR	Infrared Spectroscopy
LC-MS/MS	Liquid Chromatography-tandem Mass Spectrometry
MALDI-MS	Matrix Assisted Laser Desorption/Ionization-Mass Spectrometry
NMR	Nuclear Magnetic Resonance
OM	Optical microscope
SEM	Scanning Electron Microscope
SEM-EDS	Scanning Electron Microscopy-Energy Dispersion Spectroscopy
SIM	Structured Illumination Microscopy
SIMS	Secondary Ion Mass Spectrometry
SPM	Scanning Probe Microscope
TEM	Transmission Electron Microscope
TOF-SIMS	Time-of-Flight Secondary Mass Spectrometry
UVVIS	Ultra Violet Visible
XPS	X-ray Photoelectron Spectroscopy
XRF	X-ray Fluorescence Analysis

5 Biological materials

5.1 Characteristics

5.1.1 General

The terms material and structure sometimes have different meanings in biology and in technology. Classic technical materials are often considered to be homogeneous, so that it is reasonable and permissible to assume in calculations and for manufacturing purposes that the model is isotropic.

Technical materials rely mostly on chemistry for their properties whereas biological materials rely on structure and are almost invariably composite.

Owing to their hierarchical structure from the molecular to the macroscopic level, it is not possible to clearly distinguish between the terms “material” and “structure” in the field of biology. For this reason, the term “material” is used in the following as a general term for all biological materials with their respective structures.

Some characteristics of biological materials that are relevant to biomimetic implementations are listed in Table 1.

Table 1 — Characteristics of biological materials

Characteristics	Biological Example	Explanations
Properties		
Multifunctionality	**Wood**: integration of water pipes, strength, damping, storage, among other things	Biological materials are often multicriteria-optimized and possess a high-function density, and they often combine supposedly conflicting functions.
Hierarchy	**Wood**: at least five structural levels, from the molecular structure of the cell wall to the structure of the tree trunk	A special feature of the hierarchical design of biological materials is that structural or (bio) chemical changes in one level lead to specific adaptations in the other hierarchy levels. This level spanning adaptability permits a wide variety of different functions.
Fault and failure tolerance (resilience and redundancy)	**Bones**: ample breaking strength, tolerance to micro-cracks, crack stoppers	Biological materials can handle a high level of faults and damage before they fail as a whole.
Self-X	**Rubber tree**: self-repair **Teeth of rodents**: self-sharpening **Surface of leaves**: self-cleaning	Biological materials are able to generate and maintain their complex functions autonomously, meaning, without external control.
Adaptivity	**Bones**: load adaptivity **Plant motion**: for example, nastic movements and tropism	Biological materials can react to changes in environmental conditions by changing their form or through growth and restructuring processes.
Compatibility	**Walls of plant cells**: consist almost exclusively of carbon, oxygen and hydrogen	Availability/biodegradability of the biological building blocks. The waste products produced are rarely pollutants. The waste products are in fact biodegradable and recyclable.
Modularity	Organization of **organs**: composition of several different tissues	Repetition of identical basic units at different hierarchical levels.
Lifespan according to needs	**Tree:** dropping of leaves	Important properties are maintained through renewal. The lifespans of individual components match, and the components are renewed.
Gradual transitions	Many biological materials, for example, plant stems (e.g. fibre/substrate tissue transitions), long bones (such as cortical/cancellous bone transitions), bone/ tendon/ muscle transitions	Prevention of sudden transitions between properties to increase the lifespan and tolerance to damage.

Table 1 *(continued)*

Characteristics	Biological Example	Explanations
Manufacture		
Growth	Many biological materials, as well as, for example, **self-cleaning leaf surfaces:** self-assembly of the genetically coded wax molecules	Biological materials and organisms are created through genetically controlled self-organization. Living organisms are formed using molecules, organelles, cells, tissues and organs, i.e. by growing from small to large.
Opportunism (use of readily available resources)	**Photosynthesis**: utilization of solar energy	In biology, a few predominantly light elements that are available locally and in large quantities are used (C, H, O, N, S, Ca, P, Si).
Mild environmental conditions	**Enzymes**: catalysis at ambient temperatures	Adequate conversion of material at low ambient temperatures.

5.1.2 Biological materials: multifunctional, fault-tolerant, modular, and adaptive

The characteristics of biological materials listed in Table 1 can be divided into properties and manufacturing characteristics. The properties of biological materials include multifunctionality, fault and failure tolerance, the Self-X properties, adaptivity, and modularity, only to name a few. Manufacturing characteristics such as biological growth, meaning, genetically controlled self-organization from the level of molecules to the level of the living organism itself, and resource-oriented construction under mild environmental conditions are further examples of the abilities of biological materials. Furthermore, biological materials have a limited lifespan. After the organism dies, they are generally completely broken down and return into the natural material cycle. When applied to the "lifespans" of technical applications, this property is also of interest and is studied in biomimetic research and development projects.

Tree trunks are a biological example of multicriteria optimization in nature in which numerous and sometimes conflicting functions are executed simultaneously with high reliability. They combine mechanical stability against working loads (such as the weight of its own tree trunk and crown, as well as wind and snow loads) with transport functions for water and metabolic products, storage functions, and photosynthesis[1].

Another characteristic of living organisms is their ability to adapt to variable environmental conditions (adaptivity), which enables them to survive. The high tolerance of biological materials to damage shall also be mentioned in this context, as well as the ability of many living organisms to quickly and efficiently repair damage. The capability for self-repair and adaptivity are characteristics of living organisms that are particularly interesting for biomimetic developments[2].

5.1.3 Technical components: monofunctional, durable, with a limited ability to adapt

Technical components are generally developed and optimized with the focus on a single dominant function. In technical systems such as vehicles, though, they often fulfil many other boundary conditions and constraints such as a limited design space, multiple mechanical loads, connection of additional components, manufacturing and component joining restrictions, but also limited development times. This often results in compromised solutions or oversized components that are not ideal. Components are often manufactured based on the material, meaning, they are manufactured from the large (work piece blank) to the small (product), and are not adaptive or self-repairing as a rule. The durability of a component can be problematic once it has passed its normal lifespan, and it is often difficult to return it to geo-ecological material cycles.

While living organisms shall function continuously in order to ensure their survival and successful reproduction, machines can be taken out of operation for maintenance, modification, and reconstruction. It is therefore possible to optimize machine components quickly and for a specific function, and all resources, materials, and technologies available (e.g. high temperature processes in metal processing and silicon technologies) can be used for this purpose. In comparison to evolutionary processes, these conditions allow very short development stages, and sometimes old technologies are even completely replaced by new technologies (for example, the replacement of analog technologies by digital technologies).

These differences cause biological evolution and human technology to reach very different solutions to comparable "problems" in some cases even though they are subject to the same physical laws and share the same physical environment[3].

5.2 Performances

Performances of biological systems are rich in variety. Examples of 151 biological systems are shown in Table 2[4]. Performances of biological systems are classified into eight categories:

a) materials;

b) process;

c) Self-X;

d) sensors;

e) hydrodynamics;

f) saving energy/saving resources;

g) adaptability to the environment;

h) behaviour/ecology.

The categories contain 56 kinds of specific examples. 43 expected fields of applications are summarized in Table 2 to see the overview of performance of biological systems. Especially, the interfaces of biological systems demonstrate particularly interesting properties that have a high potential to lead to new technological developments; examples are optics, anti-reflection, wettability, adhesion, fluid dynamics, surface tension, self-organization, self-cleaning, lift, fluid resistance, friction control.

Some examples of biomimetic products are introduced in Annex A.

Table 2 — Performances of biological systems and possible applications in different categories

No.	Performances	Biological example	Possible application areas
a) Materials			
1	Anti-reflection, structural colour, photonics	Morpho butterfly (see A.9), moth eyes (see A.10), blue damselfish, maranta, fish scales (see A.4)	Liquid crystal, decoration, electronics, functional film, cosmetics
2	Luminescence	Fire fly, squid, jellyfish	Automobile, household electric appliances, decoration
3	Lightweight structure	Bamboo, plant stem, winter horsetail (see A.6), boxfish, diatom, bone	Architecture, automobile, structural material
4	Wettability	Lotus (see A.12), land snail, wings of butterfly, wings of cicadas, rose, Namibian desert beetle, pitcher plant	Texture, coating material, architecture, automobile, glass, water harvesting, (marine industry)
5	Mechanical properties	Abalone(see A.3), bone, tree, bamboo, spider silk	Texture, architecture, medicine, sports industry
6a	Dynamics of a bistable system	Venus flytrap	Switching structures
6b	Torsional buckling	Strelitzia	Architecture

Table 2 *(continued)*

No.	Performances	Biological example	Possible application areas
7	Adhesion and attachment	Blue mussel, gecko (see A.11), leaf beetle, land snail, burdock seeds, octopus suckers, sea urchin, slime mould	Architecture, medicine, manufacture
8	Fluid dynamics	Shark skin, dolphin, bluefin tuna, penguin, bird, dragonfly, maple seeds	Aircraft, ship, household electric appliances, coating materials, sports industry
9	Electrical properties/ isolator, electricity generation	Electric eel, dried shells, dried trees	Ceramic industry, electric industry
10	Impact absorption	Pomelo, cashew, joint, rhinoceros beetle	Automobile, medicine, defence industry
11	Bio-template	Tobacco mosaic virus, DNA, wings of butterflies, spirulina	Electronics, semiconductor industry
12	Tube structure	Mosquito, butterfly, wharf roach	Medicine
13	Surface tension	Whirligig beetle, backswimmer	Coating materials
14	Unidirectional	Mouth of snake, earthworm, bee, pitcher plant	Machine parts
b) Process			
15	Bio-mineral	Shells, teeth, bone, diatom	Medicine, decoration, ceramic industry
16	Photosynthesis	Plant	Energy industry, agriculture, food industry
17	Organic synthesis	Spider silk, blue mussel, plant wax, pine resin, Para rubber tree, ligaments of grasshopper (see A.2)	Medicine, chemical industry
18	Processing	Shipworm	Civil engineering
19	Metabolism	Cellulose degradation, silk, amino-acid fermentation, alcohol fermentation, entomophagy, stockbreeding	Food industry, energy industry, plastics industry
20	Micro-mist	Bombardier beetle	Machine parts, internal-combustion engine, coating materials
21	Abscission	Leaf fall	Manufacture
22	Scattering	Poppy	Household electric appliances
c) Self-X			
23	Self-organization	Organisms	Medicine, electronics, films
24	Self-healing, self-repair	Skin, bone, teeth, lizard, plant leaves, shark teeth, planarian	Medicine, coating materials, automobile, electronics, household electric appliances
25	Self-assembly	Cell membrane	Medicine, coating
26	Self-cleaning	Lotus leaf, land snail, wings of butterflies, wings of cicadas	Architecture, automobile, coating materials
27	Self-sharpening	Teeth of rodents (see A.5)	Tools
d) Sensor			
28	Ocular vision/visible light, infrared, specific wavelength	Eyes, compound eyes, photoreceptors in crown-of-thorn starfish, tube feet urchin, *Melanophila* beetle, cabbage white butterfly	Sensor, architecture, household electric appliances, automobile, aircraft
29	Olfaction	Ant, dog, insect, deep-sea fish	Sensor, household electric appliances, automobile