3. Materials and Their Characteristics: Overview

In its most general context, the term *materials measurements* denotes principles, techniques and operations to distinguish qualitatively and to determine quantitatively the characteristics of materials. As materials comprise all natural and synthetic substances and constitute the physical matter of products and systems, such as:

- machines, devices, commodities
- power plants and energy supplies
- means of habitation, transport, and communication

it is clear that materials characterization methods have a wide scope and impact for science, technology, the economy and society. Whereas in the preceding chapters the principles of metrology, the science of measurement, are outlined, in this chapter an overview on the basic features of materials is given as a basis for the classification of the various methods used to characterize materials by analysis, measurement, testing, modelling and simulation.

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Materials measurements are aimed at characterizing the features of materials quantitatively; this is often closely related to the analysis, modelling and simulation, and the qualitative characterization of materials through testing [3.1], see Fig. 3.1.

Generally speaking, measurement begins with a definition of the *measurand*, the quantity that is to be measured [3.2], and it always involves a comparison of the *measurand* with a known quantity of the same kind. Whereas the general metrological system is based on the

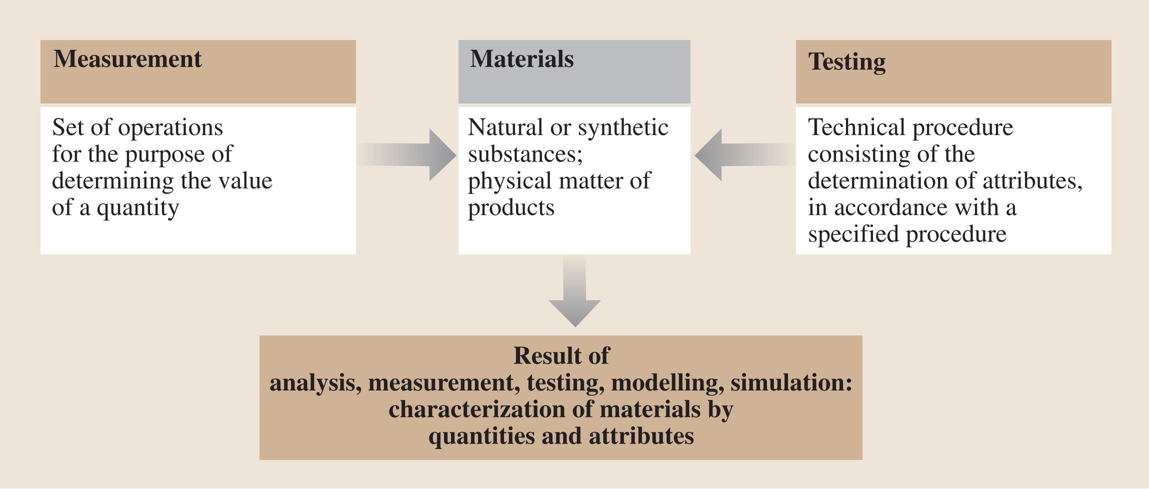

Fig. 3.1 Scheme for the characterization of materials

well-defined SI-Units (see Chapt. 1 of this handbook), for materials there is a broad spectrum of "material measurands". This is due to the variety of materials, their intrinsic chemical and physical nature, and the many attributes, which are related to materials with respect to composition, structure, scale, synthesis, properties and applications. Some of these attributes can be expressed – in a metrological sense – as numbers, like density or thermal conductivity; some are Boolean, such as the ability to be recycled; some, like resistance to corrosion, may be expressed as a ranking (poor, adequate, good, for instance) and some can only be captured with text and images [3.3]. As a background for the materials measurement system and the classification of materials characterization methods, in this chapter the basic features of materials are briefly reviewed.

3.1 Basic Features of Materials

Materials can be of natural origin or synthetically processed and manufactured. According to their chemical nature they are broadly grouped traditionally into inorganic and organic materials. Their physical structure can be crystalline, or amorphous. Composites are combinations of materials assembled together to obtain properties superior to those of their single constituents. Composites are classified according to the nature of their matrix: metal, ceramic or polymer composites, often designated MMCs, CMCs and PMCs, respectively. Figure 3.2 illustrates with characteristic examples the spectrum of materials between the categories natural, synthetic, inorganic, and organic.

3.1.1 Nature of Materials

From the view of materials science [3.4], the fundamental features of a solid material are described as follows.

Materials Atomic Nature. The atomic elements of the periodic table which constitute the chemical composition of a material.

Materials Atomic Bonding. The type of cohesive electronic interactions between the atoms (or molecules) in a material, empirically categorised into the following basic classes:

- Ionic bonds form between chemical elements with very different electron-negativity (tendency to gain electrons), resulting in electron transfer and the formation of anions and cations. Bonding occurs through electrostatic forces between the ions.
- Covalent bonds form between elements that have similar electron-negativities, the electrons are localised and shared equally between the atoms, leading to spatially directed angular bonds.
- Metallic bonds occur between elements with low electron-negativities, so that the electrons are only loosely attracted to the ionic nuclei. A metal is thought of as a set of positively charged ions embedded in an electron sea.
- Van der Waals bonds are due to the different internal electronic polarities between adjacent atoms or molecules leading to weak (secondary) electrostatic dipole bonding forces.

Materials Spatial Atomic Structure. The amorphous or crystalline arrangement of atoms (or molecules) in crystalline structures is characterized by unit cells which are the fundamental building blocks or modules repeated many times in space within a crystal.

Grains. Crystallites made up of identical unit cells repeated in space, separated by grain boundaries.

Phases. Homogeneous aggregations of matter with respect to chemical composition and uniform crystal

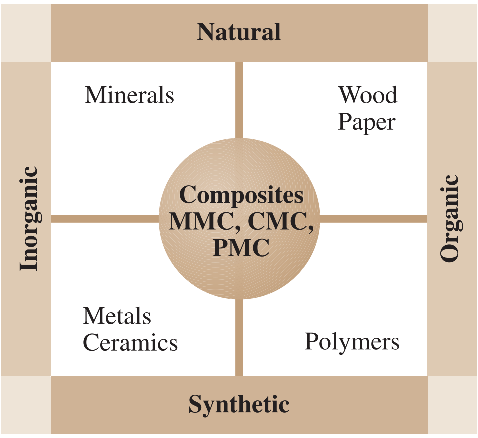

Fig. 3.2 Classification of materials

structure: grains composed of the same unit cells are the same phase.

Lattice Defects. Deviations of an ideal crystal structure:

- Point defects or missing atoms: vacancies
- Line defects or rows of missing atoms: dislocations
- Area defects: grain boundaries
- Volume defects: cavities

Microstructure. The microscopic collection of grains, phases, lattice defects and grain boundaries.

Together with bulk material characteristics, surface and interface phenomena have to considered.

3.1.2 Types of Materials

It has been estimated that there are between 40 000 and 80 000 materials which are used or can be used in today's technology [3.3]. Figure 3.3 lists the main conventional families of materials together with examples of classes, members, and attributes. For the examples of attributes, sufficient characterization methods are named.

From a technological point of view, the materials categorized in Fig. 3.3 as families have different characteristics relevant for engineering applications [3.5]:

Metallic Materials; Alloys. In metals, the grains as the buildings blocks are held together by the electron gas. The free valence electrons of the electron gas account for the high electrical and thermal conductivity and the optical gloss of metals. The metallic bonding – seen as an interaction between the sum total of atomic nuclei and the electron gas – is not significantly influenced by a displacement of atoms. This is the reason for the good ductility and formability of metals. Metals and metallic alloys are the most important group of the so-called structural materials (see below) whose special features for engineering applications are their mechanical properties, e.g. strength and toughness.

Semiconductors. Semiconductors have an intermediate position between metals and inorganic non-metallic materials. Their most important representatives are the elements silicon and germanium, possessing covalent bonding and diamond structure and the similarly structured III–V-compounds, like gallium arsenide (GaAs). Being electric non-conductors at absolute zero, semiconductors can be made conductive through thermal energy input or atomic doping which leads to the creation of free electrons contributing to electrical conductivity. Semiconductors are important *functional materials* (see below) for electronic components and applications.

Inorganic Non-Metallic Materials, Ceramics. Atoms in these materials are held together by covalent and ionic bonding. As covalent and ionic bonding energies are much higher than metallic bonds, inorganic non-metallic materials, like ceramics have high hardness and high melting temperatures. These materials are basically brittle and not ductile: In contrast to the metallic bond model, a displacement of atomistic dimensions theoretically already breaks localised covalent bonds or transforms anion–cation attractions into anion–anion or cation–cation repulsions. Because of missing free valence electrons, inorganic non-metallic materials are poor conductors for electricity and heat, this qualifies them as good insulators in engineering applications.

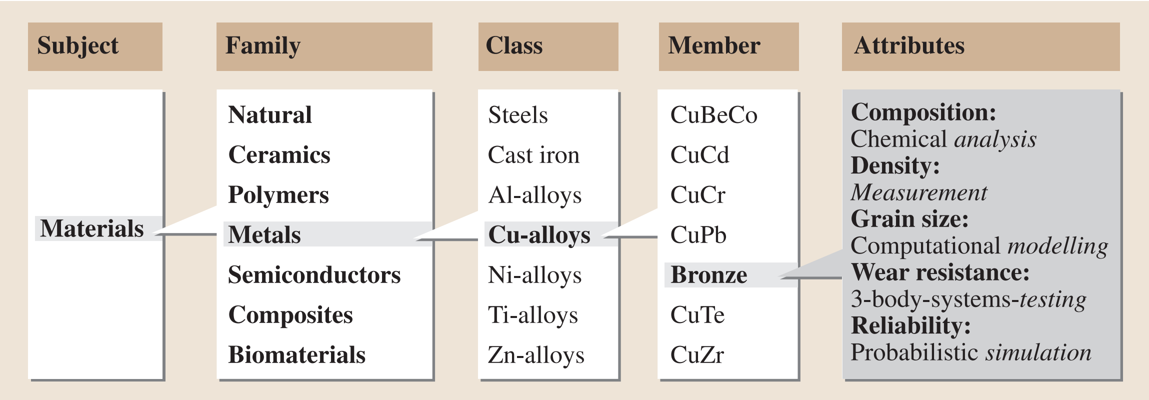

Fig. 3.3 Materials types with examples of materials attributes and characterization methods (after [3.3])

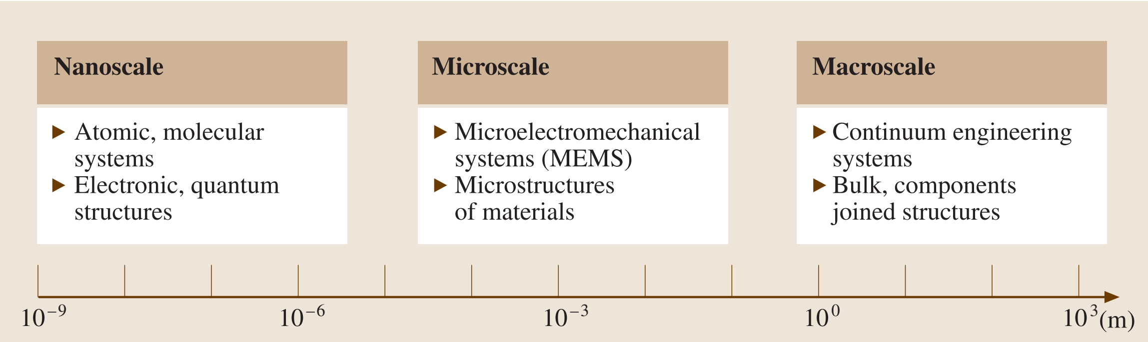

Fig. 3.4 Scale of materials: systems and structures

Organic Materials; Polymers, Blends. Organic materials whose technologically most important representatives are the polymers, consist of macromolecules containing carbon covalently bonded with itself and with elements of low atomic number (e.g. H, N, O, S). Intimate mechanical mixtures of several polymers are called blends. In thermoplastic materials, the molecular chains have long linear structures and are held together through (weak) intermolecular (van der Waals) bonds, leading to low melting temperatures. In thermosetting materials the chains are connected in a network structure and do not melt. Amorphous polymer structures (e.g. polystyrene) are transparent, whereas the crystalline polymers are translucent to opaque. The low density of polymers gives them a good strength-to-weight ratio and makes them competitive with metals in structural engineering applications.

Composites. Generally speaking, composites are hybrid creations made of two or more materials that maintain their identities when combined. The materials are chosen so that the properties of one constituent enhance the deficient properties of the other. Usually, a given property of a composite lies between the values for each constituent, but not always. Sometimes, the property of a composite is clearly superior to those of either of the constituents. The potential for such a synergy is one reason for the interest in composites for high-performance applications. However, because manufacturing of composites involves many steps and is labour intensive, composites may be too expensive to compete with metals and polymers, even if their properties are superior. In high-tech applications of advanced composites it should also be borne in mind that they are usually difficult to recycle.

Natural Materials. Natural materials used in engineering applications are classified into natural materials of mineral origin, e.g. marble, granite, sandstone, mica, sapphire, ruby, diamond, and those of organic origin, e.g. timber, India rubber, natural fibres, like cotton and wool. The properties of natural materials of mineral

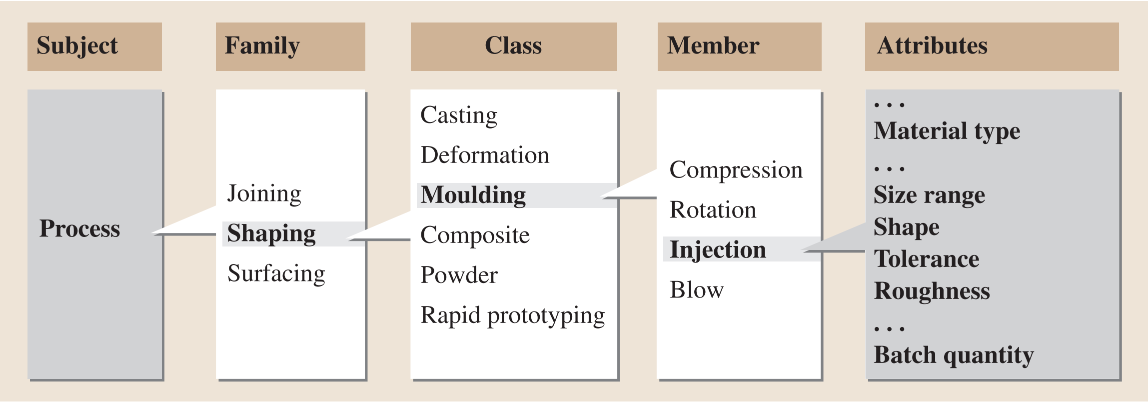

Fig. 3.5 Hierarchy of processing of materials

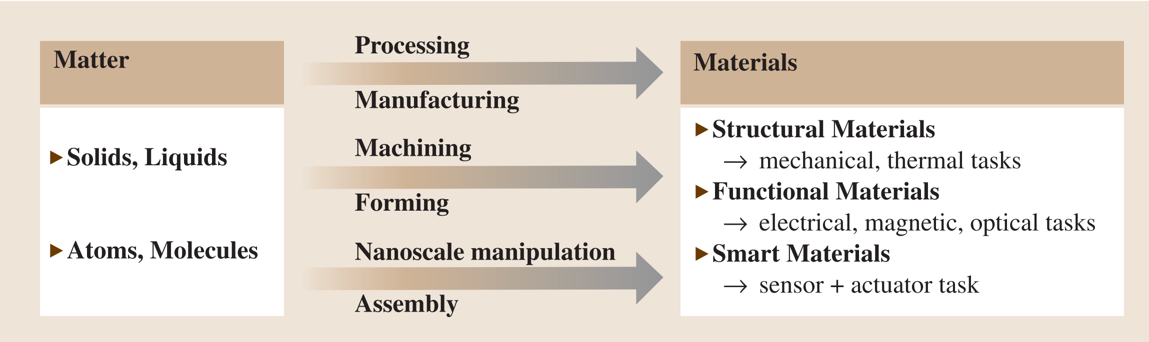

Fig. 3.6 Materials and their characteristics result from the processing of matter

origin, such as for example high hardness and good chemical durability, are determined by strong covalent and ionic bonds between their atomic or molecular constituents and stable crystal structures. Natural materials of organic origin often possess complex structures with direction-dependent properties. Advantageous application aspects of natural materials are recycling and sustainability.

Biomaterials. Biomaterials can be broadly defined as the class of materials suitable for biomedical applications. They may be synthetically derived from non-biological or even inorganic materials or they may originate in living tissues. The products that incorporate biomaterials are extremely varied and include artificial organs; biochemical sensors; disposable materials and commodities; drug-delivery systems; dental, plastic surgery, ear and ophthalmological devices; orthopedic replacements; wound management aids; and packaging materials for biomedical and hygienic uses.

For the application of biomaterials the understanding of the interactions between synthetic substrates and biological tissues are of crucial importance to meet the needs of clinical requirements. However, medical and clinical aspects of biomaterials are not treated in this Handbook.

3.1.3 Scale of Materials

The geometric length scale of materials has more than twelve orders of magnitude. The scale ranges from the nanometer dimensions of quantum-well structures – with novel application potentials for advanced communications technologies – to the kilometer-long. structures of bridges for public transport, pipelines and oil-drilling platforms for the energy supply of society. Accordingly, materials measurement methods have to characterize materials with respect to the

1. Nanoscale, sizes of about 1 to 100 nanometers [3.6],
2. Microscale, relevant for micro-devices and microsystems having sizes of typically 1 to 1000 micrometers [3.7],
3. Macroscale materials have the dimensions of all customary products, devices and plants, ranging from the millimeter to the kilometer scale [3.8].

Figure 3.4 gives an overview on materials scales with some key words.

3.1.4 Processing of Materials

For their use, materials have to be engineered by processing and manufacture in order to fulfil their purpose as the physical basis of products designed for the needs of the economy and society. There are the following main technologies to transform matter into engineered materials [3.9]:

- *Machining*, i. e. shaping, cutting, drilling, etc. of solids,
- *Net forming* of suitable matter, e.g. liquids, moulds,
- *Nanotechnology assembly* of atoms or molecules.

In addition to these methods, there are also further technologies, like surfacing and joining, which are applied to process, shape and assemble materials and products. The design of materials may also be supported by computational methods [3.10]. It has been estimated that there are at least 1000 different ways to produce materials [3.3]. Figure 3.5 lists some of the families of processing materials together with examples of classes, members, and attributes.

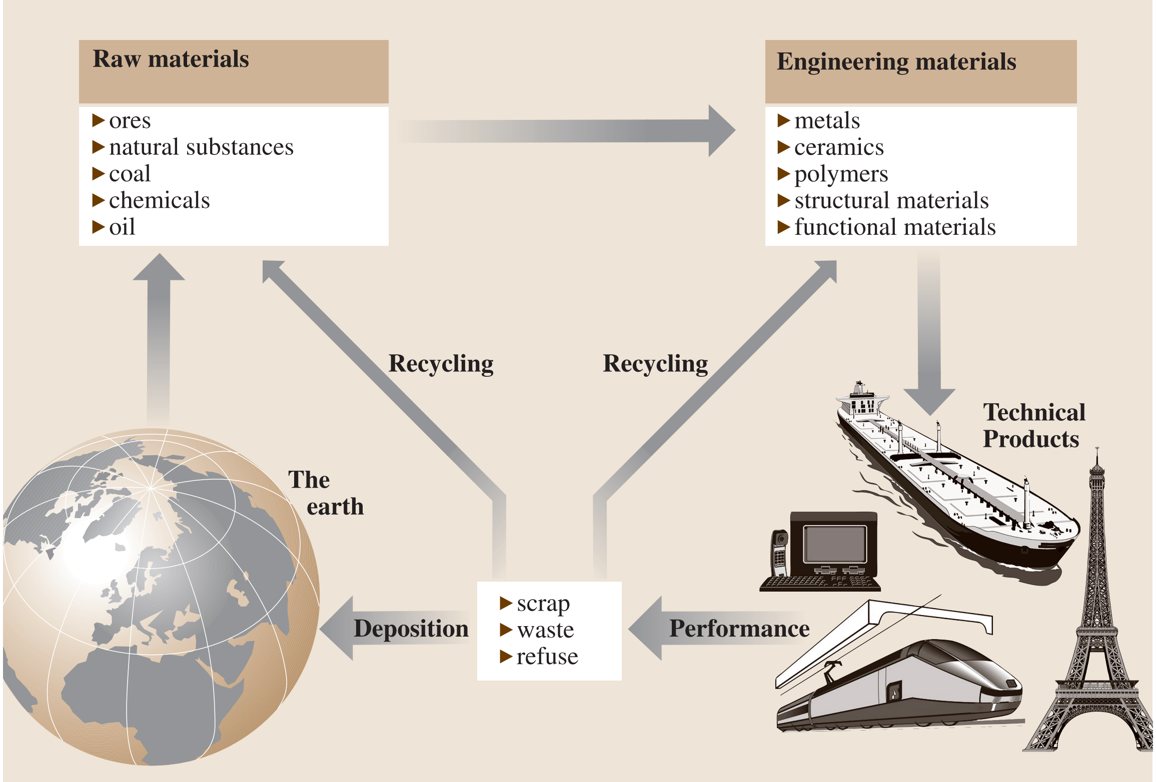

Fig. 3.7 The materials cycle

3.1.5 Properties of Materials

According to their properties, materials can be broadly classified into the following groups [3.11]:

- *Structural materials*: engineered materials with specific mechanical or thermal properties
- *Functional materials*: engineered materials with specific electrical, magnetic or optical properties
- *Smart materials*: engineered materials with intrinsic or embedded "sensors" and "actuators" which are able to react in response to external loading, aiming at optimising the materials' behaviour according to given requirements for the materials performance [3.12].

It must be emphasized that the characteristics of engineered structural, functional, and smart materials depend essentially on their processing and manufacture, as illustrated in a highly simplified manner in Fig. 3.6.

3.1.6 Application of Materials

For the application of materials, their quality, safety and reliability as constituents of products and engineered components and systems are of special importance. This adds performance attributes to the characteristics to be determined by materials measurement and testing. In this context the materials cycle must be considered.

Figure 3.7 illustrates that all materials (accompanied by the necessary flow of energy and information) move in cycles through the techno-economic system: from raw materials to engineering materials and technical products, and finally, after the termination of their task and performance, to deposition or recycling. From the materials cycle, which applies to all branches of technology, it is obvious that materials and their properties – to be determined through measurement and testing – are of crucial importance for the performance of technical products. This is illustrated in Table 3.1 for some examples of products and technical systems from the energy sector [3.13].

Table 3.1 Application examples of materials in energy systems and relevant materials properties [3.13]

Application	Materials properties				
	Mechanical	Thermal	Electrical	Magnetic	Optical
Heat engine	High-temperature strength				
Electricity generator	High-temperature strength				
Nuclear pressure vessel	Resistance to crack growth				
Solar energy		Heat absorption	Photoelectricity		Reflectance
Superconductor	Ductility; strength		High current capacity	Magnetic quenching	
Conservation	Light weight; strength	Thermal insulation; high-temperature resistance	Semiconductivity	Magnetic efficiency	Low transmission loss

3.2 Classification of Materials Characterization Methods

From a realization concerning the application of all material, a classification of materials characterization methods can be outlined in a simplified manner:

Whenever a material is being created, developed, or produced the properties or phenomena the material exhibits are of central concern. Experience shows that the properties and performance associated with a material are intimately related to its composition and structure at all levels, including which atoms are present and how the atoms are arranged in the material, and that this structure is the result of synthesis, processing and manufacture. The final material must perform a given task and must do so in an economical and socially acceptable manner. These main elements:

- composition and structure,
- properties,
- performance

and the interrelationship among them define the main categories of materials characterization methods to be applied to these elements, see Fig. 3.8.

Figure 3.8 illustrates that the materials characterization methods comprise analysis, measurement, testing, modelling, and simulation. These methods are described in detail in the following parts of this book:

- Methods to analyze the composition and structure of materials with respect to chemical composition, nanoscopic architecture and microstructure, surfaces and interfaces are compiled in Part B .
- Methods to measure the mechanical, thermal, electrical, magnetic and optical material properties are described in Part C .
- Methods of testing material performance through the determination of mechanisms which are detrimental to materials integrity, like corrosion, wear, biodeterioration, materials-environment interactions, are outlined in Part D , which also contains the description of methods for performance control and condition monitoring.
- Methods of modelling and simulation by mathematical and computational approaches – ranging from Molecular Dynamics Modelling to Monte Carlo simulation – are described in Part E .

Supporting the presentation of the materials characterization methods, in the Appendix relevant International Standards of Materials Measurement Methods are compiled.

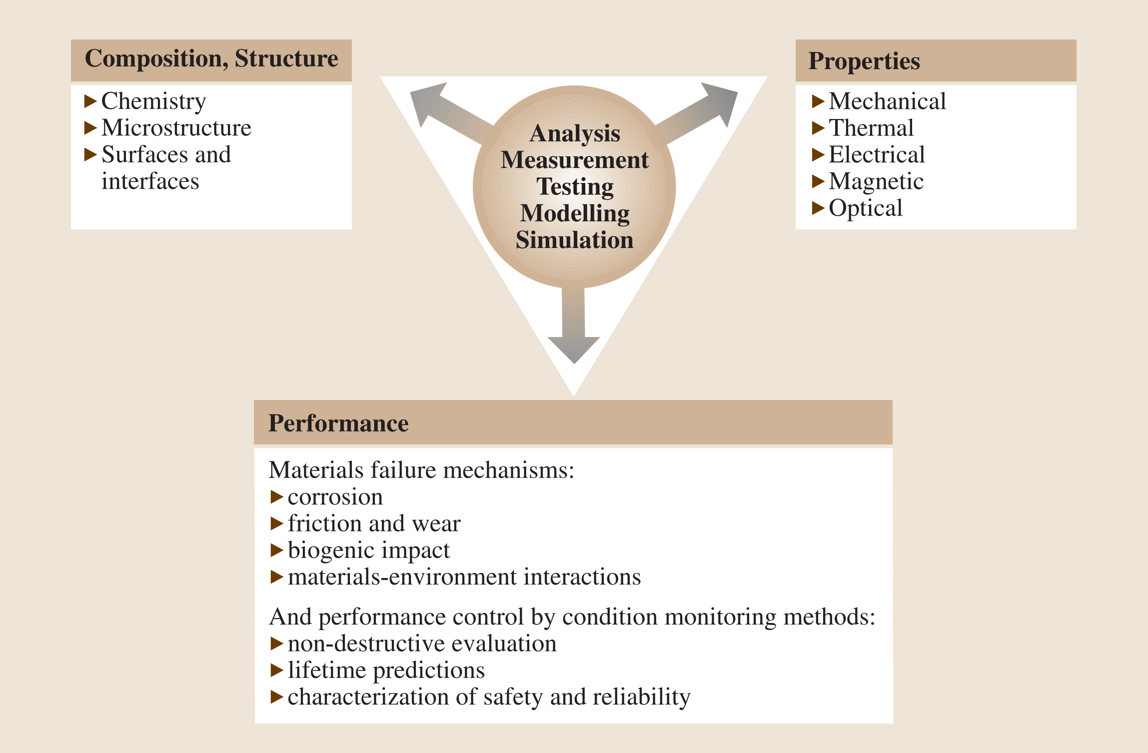

Fig. 3.8 Categories of materials characterization methods

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