Journal of Materials Processing Technology 175 (2006) 133–148

Journal of Materials Processing Technology

www.elsevier.com/locate/jmatprotec

Significance of materials science for the future development of societies

Leszek A. Dobrzański

Division of Materials Processing Technology and Computer Techniques in Materials Science, Institute of Engineering Materials and Biomaterials, Silesian University of Technology, 44-100 Gliwice, ul. Konarskiego 18A, Poland

PRESENTED BY: The paper was presented in Polish at the meeting of the Permanent Conference of the Deans of the Faculties of Mechanical Engineering of the Universities of Technology in Poland in the framework of the 12th International Scientific Conference on "Achievements in Mechanical and Materials Engineering AMME'2003 in Zakopane on 7–10 December 2003 and in English in the framework of the Eighth Cairo University International Conference on Mechanical Design And Production MDP-8 in Cairo, Egypt on 4–6 January 2004

Abstract

The paper emphasises the very significant role of materials selection for design and manufacturing processes of new needed products, having the highest attainable quality and performance at the optimum and possibly the lowest cost level. The engineering design processes cannot be set apart either from the material design, being more and more often computer aided, or the technological design of the most suitable manufacturing processes. The review of the multi-millennia long history of human civilisation indicates that the significant increase of the level of living and production is connected more often with the launching of new material groups with the properties better and better adjusted to real requirements of customers getting more sophisticated nearly each day, and also the launching of the technological processes which are relevant to them. The given reasons enable to forecast that the future of the market and products with the required properties, which appear on the market, are inseparably connected with the development of materials science and engineering. Two main priorities can be specified in that area, that is: the continuous improvement of existing materials, and technological processes and the development of materials and technological processes ensuring environment protection or/and improving conditions and extending of human life. The paper includes also the description of the world developmental trends in that area in the first decades of the 21st century. The fundamental aim of materials science and engineering is materials selection ensuring required functions and application properties of products, which are manufactured out of them. The tasks of that field of science in priority spheres of the world development are determined. Directions of activities of materials science and engineering ensuring the achievements of strategic aims of the developments of societies include materials design, computational materials science, advanced analytical methods, manufacturing and processing, nano-, smart and biomimetic materials are included. It is concluded that there is a humanistic mission which stands at the engineering circle, especially associated with materials and manufacturing engineering and its aim is to make products and consumer goods, deciding directly about the level and quality of human life, available to people and it is also mentioned that current financing of scientific researches especially in the mentioned fields of science gives a chance to achieve modern technological development and to ensure prosperity of societies in the future.

Keywords: Quality of life; Prosperity of societies; Development of human civilisation; Advanced products; Engineering design; Materials design; Manufacturing; Materials science and engineering

1. Introduction

Manufacturing processes feature the grounds for satisfying the needs of contemporary societies. Manufacturing is the process of transforming raw materials into products. Manufacturing consists in making products from the raw materials in various processes, using various machines and in operations organised according to the well-prepared plan. Therefore, the manufacturing process consists in a proper use of such resources as: materials, energy, capital, and people. Nowadays, manufacturing is a complex activity merging people working in various professions and carrying out miscellaneous jobs using diverse machines, equipment and tools, automated to a various extent, including computers and robots.

Manufacturing on a global scale involves many technologies and pertains to a wide range of products. That refers

E-mail address: ldobrzan@zmn.mt.polsl.gliwice.pl.

0924-0136/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.jmatprotec.2005.04.003

to the traditional mechanical products, consumer goods, including those made from leather, wood, textiles and polymer materials, and also to food, medicines, as well as to electronic goods and information technology products (Fig. 1). Value of that production reaches 4×10^{12} EUR in the European Union and its added value is 32%. Manufacturing provides jobs for about 40 million people directly and next 80 million others working in servicing of those products. About 25% of that production is mechanical products giving directly jobs to 5–6 million people. One can name the main segments of that production (look at Fig. 1) as the automobile industry (39%) employing 1.8 million people, aircraft industry (11%) employing 1.6 million people, and next, manufacturing of dies and moulds (11%), machine tools and technological equipment (9%), as well as microelements and miniature parts (8%). Other elements and mechanical devices total to about 22%.

The goal of manufacturing is always to satisfy the market needs of customers, according to the strategy of a company or an organisation being engaged in manufacturing, employing available possibilities and equipment. The technical aspects of introducing a product to the market by its manufacturing organisation refer to industrial design, engineering design, manufacturing process planning, manufacturing, and service (Fig. 2). The first stage of product design refers to industrial design connected with the general description of product functions and with the development of its general idea, encompassing its shape only, colour and eventual general requirements referring to connections of its main elements. Further stages include engineering design and manufacturing process planning.

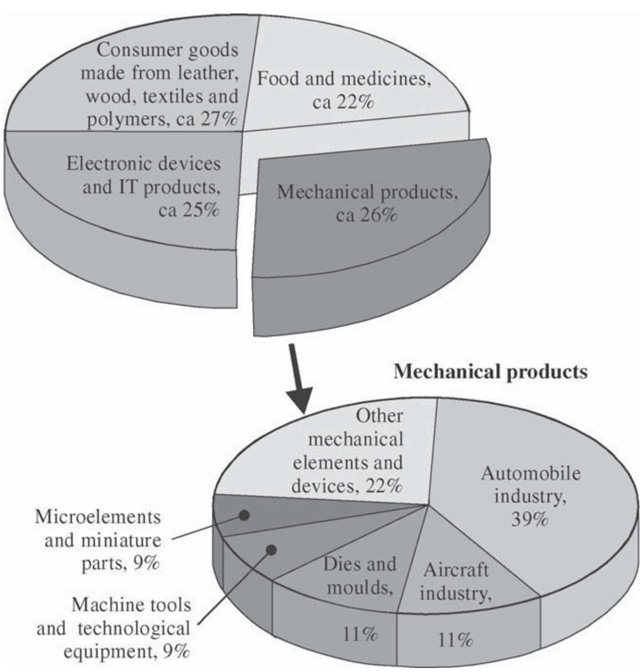

Fig. 1. Cost share of various technologies and products in the global manufacturing industry [14].

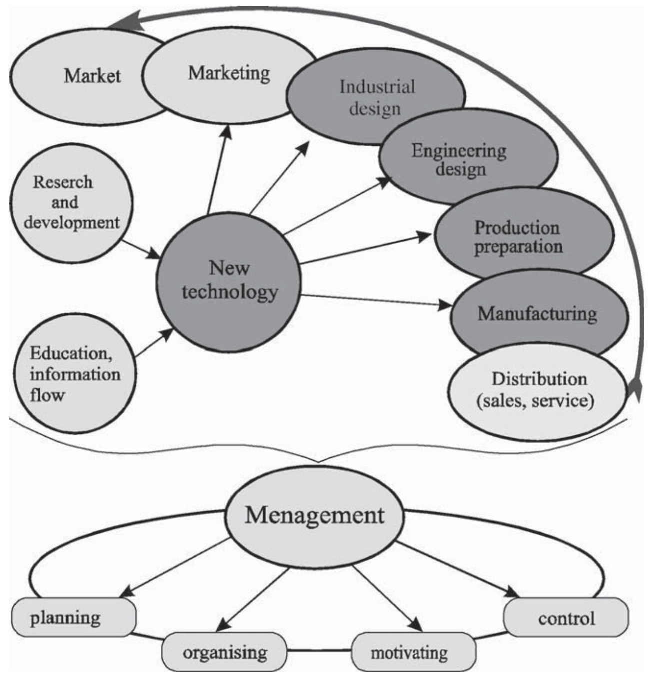

Fig. 2. Relations among factors connected with introducing a product to the market [2,3].

The goal of that paper is to explain the very important role of materials selection in the design and manufacturing processes of new, needed products, having the highest attainable quality and performance at the optimum and reasonably set, possibly lowest cost level. In that context the future development of materials science and engineering is, as a very significant element connected with advanced design and manufacturing processes of those new products.

2. Significance of materials design in the engineering design of products

Engineering design of a product is not a separated activity, as it influences all other phases of that process, on which it is simultaneously dependent. Engineering design of a product is to merge in itself three equally important and indivisible elements, i.e., Fig. 3:

- structural design, whose goal is to work out the shape and geometrical features of products satisfying human needs;
- material design for the selection of the required physical and chemical, as well as technological properties, ensuring the expected life of the product or its elements;
- technological design making it possible to impose the required geometrical features and properties to the particular product elements, and also to ensure their correct mating after assembly, accounting for the production volume, its automation level and computer assistance, and also with ensuring the lowest possible costs of the product.

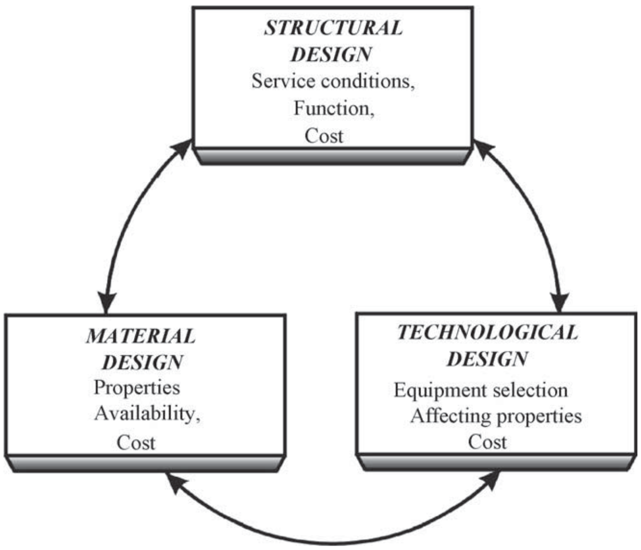

Fig. 3. Relationships between elements of engineering design, i.e., structural, material and technological designs [2,3,11].

Engineering design is connected with determining the shape of the product and its elements, the selection of materials from which they are to be made, and the selection of the relevant technological processes. The designed product has to meet the parameters pertaining fully to its functionality, and also requirements connected with its shape and dimensional tolerances; moreover, the design has to include the list of materials used, manufacturing methods and other necessary information. One has to account for, among other, consequences and risk of product failure, resulting from its foreseen, however probable misuse, or the imperfection of the manufacturing process. Possible consequences of product failure affect the evaluation of the significance of its assumed reliability. Economical aspects do not impose excessively demanding reliability requirements if there is no risk of injuries or incurring losses due to product failure in use. Each product shape version imposes some requirements pertaining to the material properties that can meet them, to which one may include the relationships between stresses resulting from the product shape and its load, and the material strength. A change of a manufacturing process may change material properties, and some product–material combinations may be infeasible using some technological processes. Each manufacturing process is connected with the product shape range that may be made using that process. Shape is closely connected with the manufactured product, and its complexity decides the feasible manufacturing process type. Increasing the product shape complexity limits the scope of processes that may be employed and increases costs.

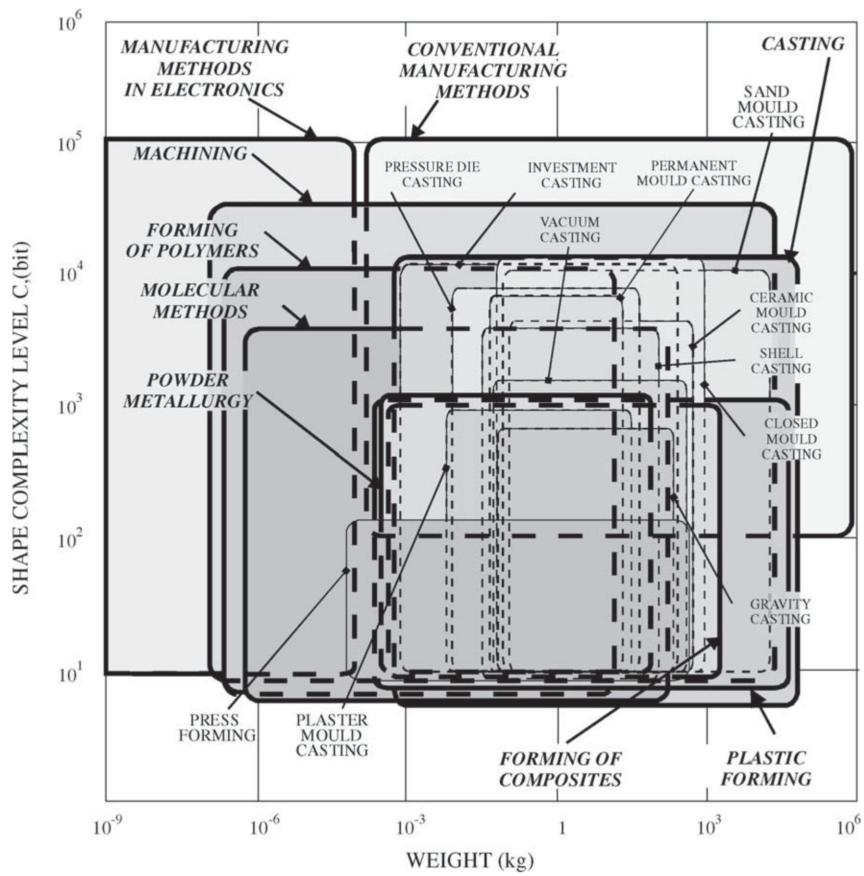

Fig. 4. Options of the product forming technological processes depending on its shape complexity level and weight [2,3,12,13].

The main design principle is to ensure the simplest shape possible. One can back out that principle if a more complex shape makes it possible to join several elements or if it lets us eliminate even one stage in the manufacturing process only. The general goal of the actually employed technological processes is to make the net-shaped products that make immediate assembly possible, or - in case it is not feasible - the near-net-shape products requiring limited finishing - usually by machining - before installing them into the final product. It is not possible to make any element exactly, according to the dimensions assumed. It is possible to select the manufacturing processes of the product elements basing on the analysis of the relationship among the employed technological process, a size of elements, and a complexity of their shapes (Fig. 4).

Dimensions and weight of the element influence selection of both its material and manufacturing process. Small sized elements are made from a bar stock even in large volume production, and the material cost may be then significantly lower than their manufacturing cost. It enables to use more expensive materials for small sized elements. However, due to difficulties or no possibility at all of carrying out heat treatment, making a full use of mechanical properties of materials used for large sized elements gets impossible. There are also limitations connected with sizes of elements that may be formed in particular technological processes. The examples include die-castings, investment castings or elements made using powder metallurgy whose weight is limited usually to a few kilograms. If the element weight is the critical factor, then it is often made from the material having the high strength to weight ratio.

The selection of the product manufacturing processes, closely related to the selection of materials for its parts, is a very important stage of the engineering design process. The main criterion for those selections is a maximisation of product quality with the simultaneous minimisation of costs of its elements. The selection of a material decides often selection of feasible manufacturing processes that may be used for producing elements from the particular material. The selection of the technological process is connected with the material's performance and limited by its hardness, brittleness or plasticity and melting temperature. Some materials are too brittle to be plastic formed; others are inapt to casting processes due to their excessive reactivity or low melting temperature. The possibility of using plastic forming is defined by loads required during forging or rolling, depending on plasticity. As cutting forces and temperatures of the machined material and tool during machining depend on hardness of the machined material, that feature decides the possibility of using machining in the manufacturing process. Functional properties of a product are obtained only when the right material is used, manufactured in the properly selected technological process, imparting both the required shape and other geometrical features, including dimensional tolerances of particular elements, making the final assembly of the product possible, and also forming the required material structure, ensuring the expected mechanical, physical and chemical properties of the product (Fig. 5).

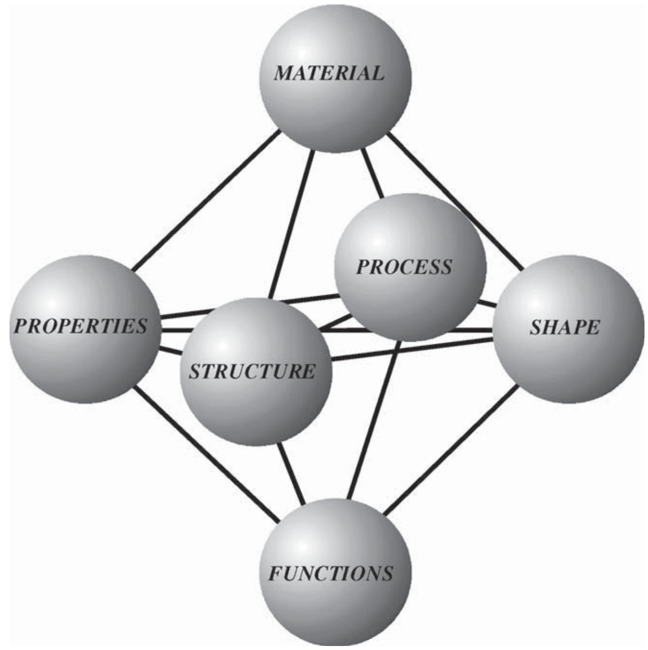

Fig. 5. Relationships among some factors connected with material, processes and functions of a product [1–9].

Variety of materials available nowadays, makes it necessary to select them properly for the constructional or functional elements, tools and eventually other products or their elements. That selection should be carried out basing on the multi-criterion optimisation. Functional properties of engineering materials are usually defined by their physical, mechanical, thermal, electrical, magnetic, and optical properties. Various properties can be obtained in composite materials, sometimes opposite of that characteristic for materials used as matrix or reinforcement of composite materials. Those properties depend on structure and chemical composition of the material and on service conditions of the element. Cyclic loading, service in high or low temperature, as well as the presence of media causing the general corrosion or cracks resulting from stress corrosion, all feature specific hazards that have to be considered in the material selection process. The reasons of some 90% failures caused by material fatigue in service are connected with the faulty design and manufacturing faults, and only 10% result from material faults, its improper chemical composition or heat treatment errors. Even the seemingly insignificant reasons may result in serious consequences. In one case, for instance, the fatigue damage of the aircraft in flight was caused by the inspection stamp that was imprinted too heavily on one of its elements. One has to take into consideration the possibility of failures and their consequences in analyses of the allowable product failure. The failure modes that might directly endanger life or limb or else damage or destroy products or their elements should not be allowed. However, the standard practice is to design a piece of equipment so that when it fails then they do not harm its environment and protects the product from consequences of more serious failures. The common example of that attitude, and connected requirements pertaining to the material, are fuses, in which the fuse-link melts because of the excessive electric current strength. Another example features the blowout plugs that are ejected when the hydraulic pressure in the circuit exceeds the allowed value. An example may be also the overload protection of an earth-moving machine that stalls when an attempt is made to load it above the allowable value.

The selection of the proper material along with the appropriate technological process is vital, as it ensures the longest product life with the lowest costs, considering that one has to account for more than 100,000 engineering materials possible and available on the market, and yet, the average engineer has a detailed knowledge about the practical applications of 50–100 engineering materials. Because of the significantly diversified conditions of a use of various products, and also their diversified design features, collecting many-detailed information is required for proper material selection.

The vast majority of engineering materials are derived from raw materials obtained from the crust of the earth, raised in mines such as ores and then enriched to make possible their extraction or synthesis. Fig. 6 illustrates the relation of strength and the specific energy consumption of materials (defined as the product of energy required to make the material, i.e., obtaining the raw materials, their refining, and shaping of the produced material, related to 1 kg of material, and its density). That coefficient expresses indirectly the influence of the material manufacturing process on degradation of the environment. The specific energy consumption shows linear dependence on material strength. The present situation and current forecasts require from engineers the coordinated activities aimed at saving the available raw materials, consisting in:

- designing with the economical use of materials, mostly those hardly available and close to be depleted, with minimisation of their energy consumption;
- using easier to acquire alternatives with the large margin of the half-life of their raw materials depletion and with lower energy consumption, instead of those hardly available and close to be depleted;
- making a full use of energy saving recycling for their reuse and full recovery of materials in all possible and economically justified cases.

The character of ductility and fracture toughness changes for various groups of engineering materials (measured by the stress intensity factor) differ from changes of their strength Fig. 7. That value is in a broad range from 0.01 to 100 MPa $m^{1/2}$. The highest ductility is demonstrated by metals and their alloys. It seems that their common use is owed to the compromising merging of the highest possible ductility with the very high strength. Composite materials demonstrate similar properties. However, the definite brittleness of the engineering ceramics features a serious limitation for its use. Wood and polymers demonstrate the comparable brittleness. Ductility of the porous ceramics is up to 10 times lower.

All engineering materials are equivalent from the engineering design point of view, all that can guarantee the required products' properties and the multi-criterion optimisation features the basis for the materials selection with the best functional and technological properties, and with the lowest possible manufacturing, processing, and operation costs of the material and product. So, the problem posed is: "what can the product of interest to the customer on the market be made from?" and not: "what can be made from the material we have at hand or which we know?"

3. Materials science and engineering and their historical evolution

The aim of materials science is to investigate the effect of the structure in various scales (electron, crystalline, micro, and macro) on materials properties. The numerous grades of the actually available materials yield new innovative potential in implementation of products. Determining the relationships among structure, technological process, and functional properties, and also the selection of materials and technological processes forming their structure and properties for a use in complex manufacturing systems, feature the main focus of materials engineering. Therefore, the development of materials engineering features an important determinant of the quality of life of the contemporary societies.

Materials science appeared as an independent branch of science at the end of the 1950s, continuing mainly the physical metallurgy traditions, which was created at the beginning of industrial revolution, converted next smoothly to materials technology and in consequence to the materials science. Links were developed simultaneously between materials technology and materials engineering, and applied sciences, which can be demonstrated by many examples. Investigations of semiconductors have provided the opportunity for co-operation with solid-state physics. The development of polymer materials demonstrated the effectiveness of co-operation with polymer chemistry. There are many examples of implementing numerous models discovered by physics and chemistry for the development of materials. Many mathematical models were used, among others, for describing phase transformations, conception of J integral in fracture mechanics, fractal geometry for describing growth of clusters and colloidal systems, for solving the non-linear grain boundary migration problem or Laplacian growth processes in description of the morphological phase transformations. The end of the 20th century has demonstrated that achievements of materials engineering are usually an outcome of the significant integration among various branches of science, which resulted in consequence in making the 21st century materials science an interdisciplinary area developed on the crossroad of many pure science disciplines, mostly of the solid-state physics, chemistry, mathematics, and process engineering, but also mechanics and mechanical engineering, ecology, economy, management and applied computer science, and even biology and medicine, taking advantage of achievements of those scientific disciplines to propose materials with the most advantageous set of properties and suiting higher and higher requirements posed to products and goods used by people in the best way, in conditions of the fierce market competition and with high requirements concerning quality, reliability, life, and price.

The target of materials science is an investigation of the effect of their structure in various scales (electron, crystalline, micro, and macro) on properties of materials. A great number of material brands available nowadays offer new innovative possibilities in design, manufacturing, and implementing of products. The determination of dependencies among the structure, technological process, and functional properties, as well as materials selection and technological properties forming their structure and properties for employment in complex manufacturing systems feature the core interest of materials engineering.

Since the dawn of history people employed, and sometimes processed, materials to acquire their meals, increase their safety, and assure a suitable standard of living. Following the history of human civilisation we may come to the conviction that its progress is governed notably by the development of materials and the accompanying growth of the productive forces. It is attested undoubtedly, among others, by naming various epochs in the history of humankind by materials deciding the conditions of living at that time, e.g., Stone Age, Bronze Age, Iron Age (Fig. 8).

The pre-historic man might use only the natural raw organic and inorganic materials, including, e.g., leather, wood, rock, flint, that he processed into the useful articles making it possible for him to get food, improving his safety and living conditions. Up to now it is hard to decide which metal was processed by humans first. It is sure that metals occurring in their raw native states, like gold (Near East, Caucasus, Egypt–Nubian desert, the Eastern desert), silver (north-east Asia Minor, the district associated with Hittites), copper (Asia Minor, Armenia, Elam, from which the Sumerians received it as early as 3500 B.C., Eastern Alps, Egypt up to c. 2000 B.C., Cyprus) and iron obtained from meteorites (Greenland, utilized by Eskimos for more than a century). The significant progress was made only after mastering the methods of obtaining metals from their ores. This has happened – most probably by chance – c. 4000 B.C., in pottery manufacturing, during glazing with the hot flame and pulverized minerals. Since that time, apart from the attempts to find the metals in their raw native forms, utilization of ores is carried out in-

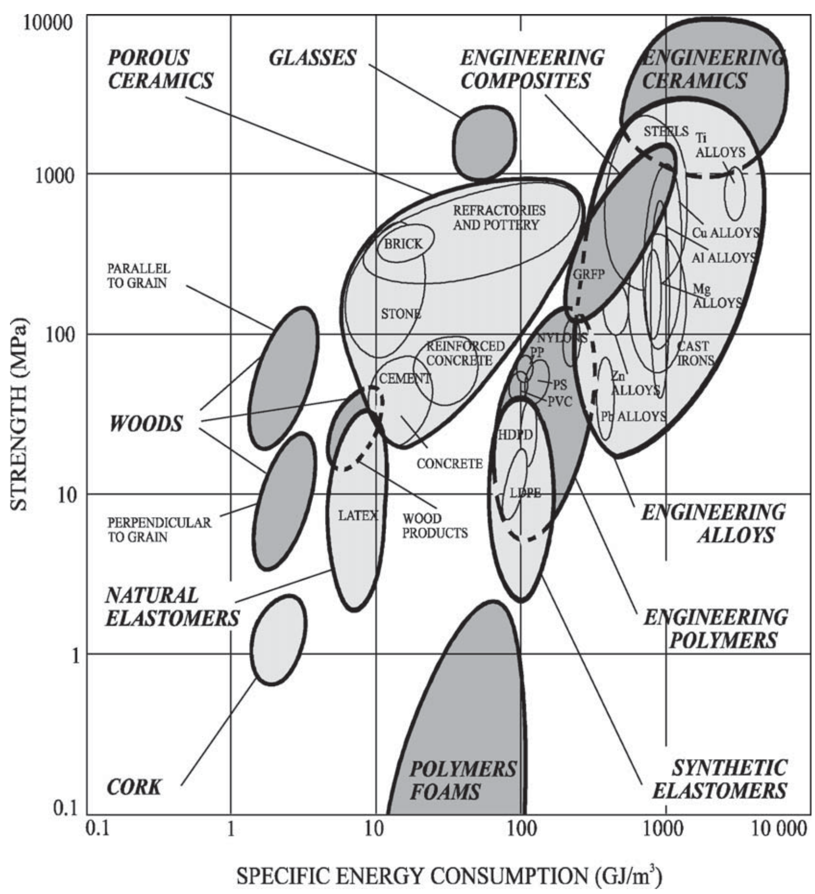

Fig. 6. Strength and specific energy consumption of various materials [2,3,12,13].

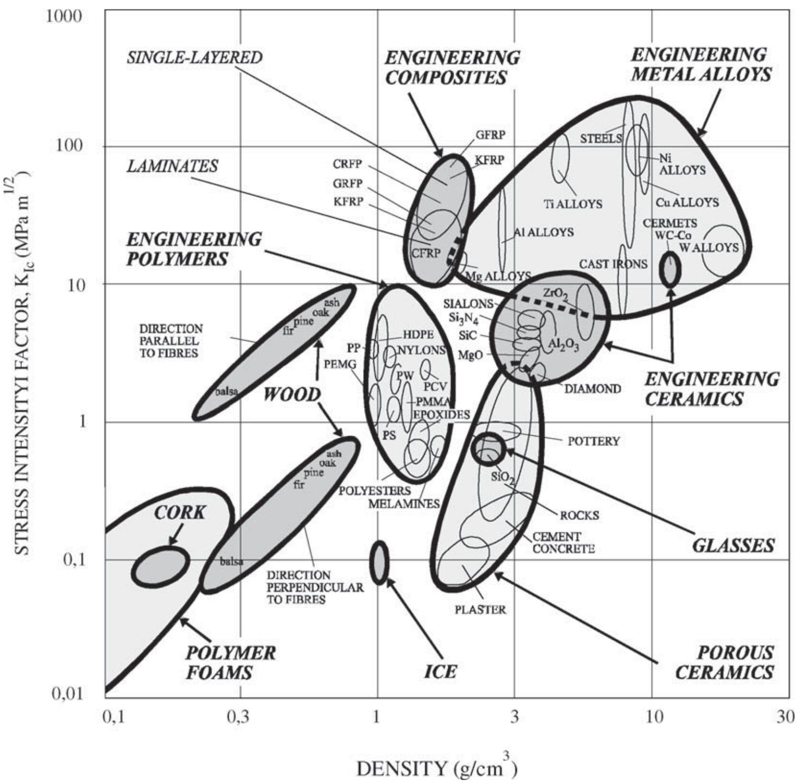

Fig. 7. Stress intensity factor and density of various materials [2,3,12,13].

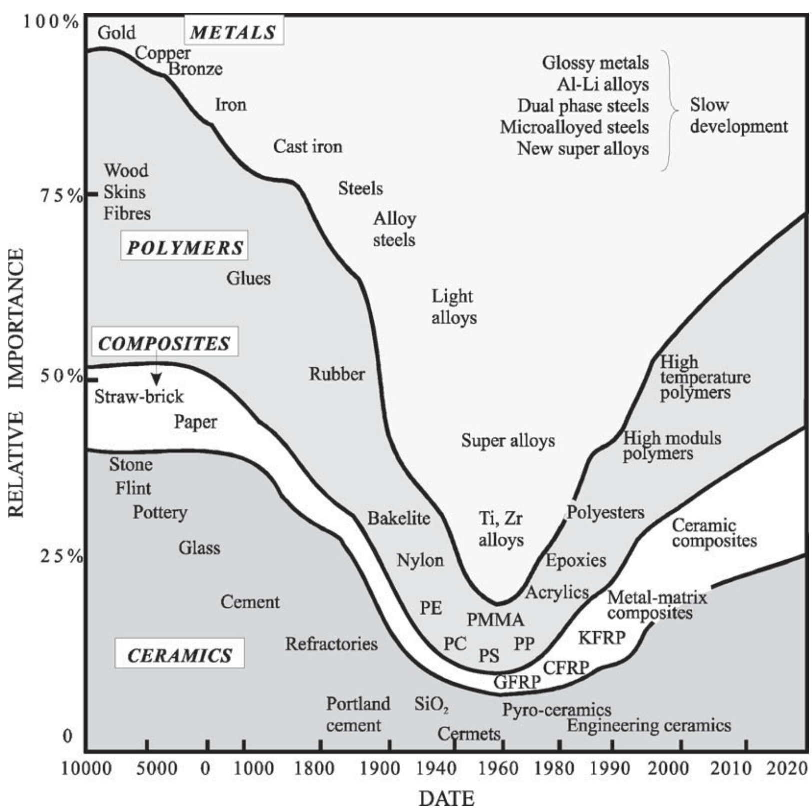

Fig. 8. Diagram presenting the significance of various epochs of the human civilisation development, with dates of introduction of new materials [2,3,12,13].

Fig. 9. Fragment of a picture on the western wall of the Redmere tomb in Thebes (c. 1450 B.C.) showing metal processing scenes in ancient Egypt (charge preparation, melting, casting, finishing) [7].

cluding two independent processes, i.e., separation of metals from other chemical elements with which they are chemically bounded and working-up of metals into useful articles. The working properties of articles made from metals were inferior to those of stone tools and a landmark was manufacturing of copper alloys–bronzes, with arsenic at first, and next with tin. Traces of getting of copper ores and its processing were found in settlements of farmers and herdsmen in valleys of Kura and Araxes rivers in Transcaucasia, in the eastern Anatolia, Assyria and Mesopotamia, as early as in 4000 and 5000 B.C. In 4000 B.C. the Cu–As bronze was used quite consciously, not by chance, that was later – at the turn of 3000 and 2000 B.C. replaced by the Cu–Sn bronze. At the cemetery of the Sumerian kings of the Ur state that reined at c. 2600 B.C. decorative articles were get out made from bronze containing both As and Sn. Also in Central Asia by Indus river and in Europe, as was used earlier than Sn as a bronze addition. The civilisation of the Bronze Age initiated in the middle of the third millennium B.C. in Asia Minor and Egypt (Fig. 9), embraced the entire Mediterranean basin and Southern Europe by c. 2000 B.C. (Figs. 10 and 11), and at about three centuries later also Central Europe. Metal blooms became the objects of commercial exchange, took over the role of money, and became the objects of accumulation (Fig. 12). Works of art and craft, weapons, ornamentations, and cult objects, remaining from the Bronze Age attest to the good knowledge of properties of

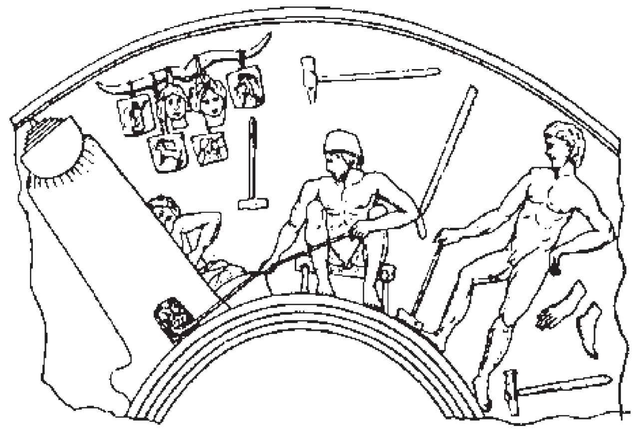

Fig. 11. Picture on a bowl from Troia (V century B.C.) showing a Troian forging [7].

Fig. 10. Picture on the vase from Attica found in Orvieto (VII–V century B.C.) showing a Greek blacksmith [7].

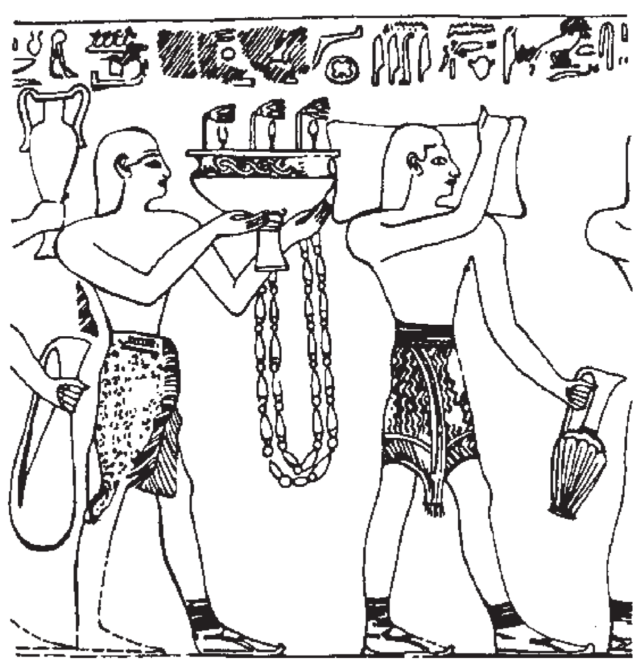

Fig. 12. Fragment of a picture in the temple no. 100 in Thebes erected during the reign of Tuthmosis III (1490–1436 B.C.) showing gifts in the form of the copper ingots from Crete submitted to the Egyptian Pharaoh [7].

Fig. 13. Dirk with an iron blade found in the Tutenkhamon's tomb in Egypt (c. 1350 B.C.) [7].

copper and bronze of their contemporary makers, from various – even located far away from each other - geographical regions. Many engineering works appeared also at that time, e.g., the 3 km long pressure water line erected at c. 180 B.C. by the King of Pergamum, Eumenes II, supplying water by the cast bronze pipes from the Hagios-Georgios mountain. As early as in the Bronze Age weapons and tools began to be made from iron, better suited for this purpose.

A sword with a golden grip made from the meteoritic iron dated from 3100 B.C. was found in the archeological excavations in the city of Ur in Mesopotamia, and also a dagger with the iron blade was found in the Tutankhamen tomb from 1350 B.C. (Fig. 13). The first steel was obtained–most probably in China c. 2220 B.C. by the long annealing of the iron pellets mixed with chunks of charcoal with no air access, which turned out to be just the first known case of employing cementation. This process was used a little bit later in India in manufacturing weapons. Obtaining iron from its ore by the direct reduction with the charcoal took place in the middle of the second millennium B.C. south of Caucasus, beginning of the Iron Age in the Middle East was c. 1200 B.C., in the countries of the Mediterranean basin c.1000 B.C., in Central Europe c. 750 B.C., and in IV–II century B.C. it was in common use already. Making of iron axes (7000 B.C.), saw and woodworking tools, as well as scissors used for shearing sheep fleece (500 B.C.), anvils and dies (200 B.C.) are among many achievements of the craftsmen's art. A method of refining of the drained cast iron purged repeatedly with oxygen in Huainan was described about 120 B.C. The newly introduced iron, first from meteorites, and then obtained by ore reduction, was processed in a similar way as copper and bronze, forming the products on the required shape by cold forging and applying soft annealing in fire. Manufacturing of iron tools with the satisfactory properties, e.g., with the edges sharp enough, required cementation to 0.15/1.5% and eliminating of slag.

Invention of cementation, apparently by the "Chalybes" of Asia Minor, a subject-tribe of the Hittite empire, at 1400 B.C. solved the problem only in part. Manufacturing of iron consisted in a process for steeling wrought-iron bars by repeated hammerings and heatings in direct contact with charcoal to diffuse carbon into the surface of the metal. If the smelting process is sufficiently elaborated, then some iron ores yield steel directly. This phenomenon was exploited c. 500 B.C. in the central European region of Styria and Carinthia. Nevertheless, it was still not known that steel required to be further hardened by quenching the hot article in cold water, which effect upon copper or bronze was to make it softer. The cementation process was followed some two centuries later by the tempering process. As late as in the last millennium B.C. the ancient iron metallurgy reached its height, and even then it could not provide cast iron that was virtually unobtainable with the small furnaces and low temperatures of that period. At the turn of VIII and VII century B.C. Homer described quenching of steel in water, which is recognized as the first literary description of this process. Just these discoveries gave rise to the contemporary heat treatment.

The unquestionable achievement of the craftsmen's art remains up to our time the Damascus steel, attesting to their high skill of the thermo-mechanical treatment. During the conquest of India by Alexander the Great in 327 B.C., swords made from this steel were used, with very good properties, which were later forgotten, albeit began to be widespread in Europe in III century B.C. This steel was first made by Hindu tribes by forging together the sintered bars from the steel containing 1.2/1.8%C at a temperature of about 750 °C, annealing and repeated forging, which ensured its high hardness and elasticity, although it was not quenched, with the corrugated lines visible on its surface, originating due to its natural etching throughout ages in natural conditions. Weapon made from this steel with good properties appeared in ancient Rome, samurai swords were also known in Japan at that time. This production was improved in IV–XI centuries A.D. by Arabs, mostly near Damascus, and then in Central Asia, Syria, and Persia, to appear again in Europe at the turn of XIV and XV centuries A.D., as the Damascus steel this time, that was most probably in addition quenched and tempered. Table 1 presents the historical development of the heat treatment technology.

The VI century A.D. in China and in X century A.D. in Hartz Mountains in Europe brings an invention of obtaining iron in its liquid state, which took place before developing the iron blast furnace. In Mediaeval times, in many regions, including also Europe, metals processing methods were developed, along with the necessary technological equipment, among others for minting (Fig. 14) and for armour making (Fig. 15). Inventions of Bessemer (1856), Siemens (1863), Martin brothers (1865), and Thomas (1877), created the fundamentals of the modern, mass production of steel with the engineering methods. In the second half of XIX century A.D. and in the first 50 years of XX century A.D. most of the steel groups known now were worked out as regards their chemical composition and technology, and the XX century A.D. witnessed emerging of the metal alloys theory from the hands-on practice. In 1722, Reaumur presented a schema of the internal structure of steel. For the first time in the world he investigated this structure using the light microscope. In 1799 Clouet and de Morreau found out that iron obtains its hardness due presence of carbon. The first systematic studies on fusibility and crystallisation of alloys were begun by Rodberg (1831). Sorby, in 1864, was the first one to carry out observations of the etched steel, and this work was continued by Martens (1878). The first alloy microscopic structures were obtained by Osmov and Werth (1885), and the metallographic investigations of the microstructure were begun by Le Chatelier in 1890–1905. In 1867 Matthiessen explained

Table 1
Historical development of the heat treatment technology [7]

Period	Type	Geographical region
c. 2220 B.C.	Cementation of iron in the presence of charcoal	China
VIII/VII Century B.C.	Quenching of steel by heating to the red heat and immersing in water	Mediterranean basin
c. 530 B.C.	Soft annealing with the subsequent forging of the steel bars welded together	India
III Century B.C.	Annealing of castings to obtain malleable cast iron	China
100 B.C.	Nitriding or carbonitriding of steel by burning of soya in the presence of the red hot steel	China
I Century A.D.	Employment of olive oil for quenching of steel	Rome
XI Century A.D.	Manufacturing of Damascus steel	Europe
XV Century A.D.	Annealing of castings	France
1924	Gas nitriding	Germany
1930	Bath and glow discharge quenching	Germany
1938	Heat treatment—heating with the electron beam	Germany
c. 1965	Laser heating in heat treatment	Europe, USA

presence of impurities and intermetallic compounds in metals, and Guthrie in 1884 gave the definition of the eutectic alloy.

Fundamentals of the knowledge about the phase transformations in iron alloys were created by Chernov (1868) working on the carbon-iron phase equilibrium diagram, Abel, who in 1888 has found out occurrence of the F_3C cementite in iron alloys, as well as Osmov (1895–1900) who discovered martensite as a separate phase in the quenched steel. Later results of works of Bain and Davenport (1929) concerned kinetics and mechanism of transformations of the super-cooled austenite, creating fundamentals of the theory of heat treatment of iron-base alloys. The exceptional significance had discoveries of Wilm (1906), as well as of Guinier and Preston (1935) concerning processes of supersaturation and ageing. Development of the physical chemistry, physics and chemistry of the solid body, as well as of physics of metals, electron theory of metals and quantum mechanics, theory of defects of the crystal structure, physics of plastic deformation and cracking, as well as of grain boundaries, developed in XX century A.D., have provided the comprehensive cognitive basis for development of the contemporary heat treatment theory of metal alloys. Research methods introduced in parallel turned out to be very useful, mostly discovery made by von Laue (1912) and employed by Bragg brothers (1913) of the X-ray diffraction, designing by Knoll and Ruska (1931) of the electron microscope, and also development of spectral methods, mostly WDS and EDS, which – equipment and research methods alike – were improved and modified in the next decades and their use for the contemporary materials science and engineering has been invaluable. The historical review presented above indicates that only after three millennia of the practical use of iron and its alloys and 5000 years of using copper and its alloys, and also of other metals, the

Fig. 14. Striking coins from XII century A.D. – Norman carving (currently a symbol of *Journal of Materials Processing Technology* published by Elsevier B.V., The Netherlands) [7].

Fig. 15. Armourer's workshop of the XVI century A.D. Showing some of its products and the tools used in making them [7,15].

roles were learned of the chemical composition and phase transformations occurring during heat treatment, in forming of the structure and properties of these alloys. Science and technology developed in time as different and separate activities. The science used to be a field of speculation practiced mostly by philosophers, while the technology was a matter of practical concern to craftsmen of many types. The fields of interest of scientists and technologists remained different in the ancient cultures. This situation began to change as late as during the medieval period of development in the West when both technical innovation and scientific understanding began to interact being stimulated by the commercial expansion and a growing rapidly urban culture. Looking at this process from the contemporary perspective we can see that it was not just a one-way influence of science on technology. It was a synergy of these two activities as technology created new tools and machines with which the scientists were able to achieve better insight and understanding of phenomena.

The practical application of many inventions was made possible only since proper materials had become available. As an example we may mention the draft sketch of a helicopter that was found in works of Leonardo da Vinci from the 15th century [16], however, the first helicopter was made in the 1940s. Space ships were described in the literary works long time ago, and the necessary calculations were made already in the first decade of the 20th century, nevertheless, the first artificial satellite of the Earth was launched only in the end of the 1950s, and the first space shuttle orbiter was launched in the 1970s.

Modern products could not be often designed and manufactured without employing many materials, just as that they could not operate in required service conditions and with the required very high reliability. One has to realise that the contemporary product is composed of a host of elements made from materials varying a great deal. As an example, the average car is composed of about 15,000 elements, whereas the passenger aircraft consists of more than 4,000,000 elements. As modern materials are worked out and deployed, they also become the substitutes for the ones being employed until now. As an example, materials developed and introduced for the space or aerospace technology may be mentioned, that are very often employed in other areas, including sport. Among many reasons for that attitude one may name the simplification of the design, extending the life and increasing reliability, making assembly and engineering easier, along with decreasing the material, manufacturing and operation costs.

Analysing the contemporary development trends of various material groups one can find out, which is evident, that the mass portion of the ultramodern products (like the aircraft and space technology products or even biomedical materials) in the total volume of products manufactured by people, albeit growing, is not big. Gaining widespread presence by polymers in our environment (which only seem to be ubiquitous) is neither possible so far, because of their relatively low abrasion resistance and other types of wear, and also because of their limited operation temperature range, which does not exceed 300/400 °C. Porous ceramics belongs to the building industry domain, albeit glass finds numerous applications in household and also in car production. Some brands of ceramics, especially of the glass type, are used even in machine design. Metals and their alloys are the main materials in machine design, automobile industry and shipbuilding, in machine-building, household consumer goods industry, tool industry and in many other ones, but they are also important in building industry, albeit in many cases engineering ceramics and also some composites compete with those materials.

Nobel Prizes awarded in the area of physics and chemistry in the last decades for the outstanding achievements, which have changed the technical reality in the world may attest to the dynamics of materials engineering development. May it be enough to mention transistors, integrated circuits, fullerens, superconducting materials, electric current conducting polymers, semiconductors, and other materials.

One might attempt to present a vision of the future and evaluate the development trends of various fields of activity and manufacturing processes basing on visions proposed by eminent bodies consisting of scientists and futurologists. Certainly, they are connected with forecasts pertaining the development of various engineering materials. Many people, even today, do their work at home, without leaving it. Houses will have to be organised and furnished in a totally other way within several years' time span. Towns, transportation, and telecom systems will be organised differently than nowadays. Towns and transport system will be organised in another way, including novel urban transportation systems connecting the sky high buildings, electrically powered cars, robotised safety systems and municipal wastes' utilization systems. Health care system will be based on diagnoses made at home, non-allergic nutrition, an early detection of serious illnesses and their prevention, and also on implanting of artificial organs - heart, and of a new generation of biomaterials. Future agriculture, forestry, and fish industry will be based on genetic engineering achievements, mastering farming new plants, employing other processes than photosynthesis, and also comprehensive robotisation. Mining and manufacturing industries will be based on a total robotisation of processes of industrial recycling of water and air, on the development of the ultra-microprocessor technology, and also on the high throughput power transmission systems employing organic materials substituting copper. Earth protection systems fighting climatic effects, implementing recovery from damages caused by torrential rains, fighting droughts, and exploitation of the tropical forests, as well as decreasing the ozone layer discontinuity effects, will undergo significant changes. Systems for surveillance of oceans and seas and monitoring their contamination, and for observations of earthquakes will be developed, moreover, robots will be introduced to underwater service. Space technique employing solar energy will make space flights more common and will give rise to novel technologies and the setting up of space factories for market production, the setting up of lunar observation bases and to space journeys to Mars.

Table 2
Area of interest of materials science and materials engineering [1–10]

Range of topic	Goals to pursue and methods of action
Synthesis and processing of materials	The arrangement of atoms and constituents in a bigger scale in materials into systems with the required configuration
Chemical composition and microstructure of materials	The assessment of the chemical composition effect and microstructure on materials' behaviour
Phenomena and properties of materials	The investigation of mechanisms active in materials during the technological processes and operation for explaining the phenomena and their effect on materials' properties
Behaviour of materials in operating conditions	The assessment of the usefulness of materials for various applications
Materials design and prediction their durability and/or life	Predictionthe chemical composition, properties, and durability of materials in their working conditions using the theoretical methods and with computer assistance, including the artificial intelligence methods

Even if not everything, according to those forecasts, will come true or be slightly delayed, one has to take into account that nearly all of the forecasted projects will require the relevant manufacturing technologies and above all - relevant materials. Many of those materials are already available nowadays; some of them should be developed soon according to the outlined requirements. It is good to realise that many venturous projects will be made possible if those new materials are made. The future successes connected with the introduction of better and better products into the market, satisfying the needs of the steadily growing requirements of the societies, are connected closely with development and the implementation of new generations of the engineering materials, which can be used for manufacturing those new expected products. The process of implementing the new materials is connected with improving the existing materials or with taking into account the contemporary achievements connected with the outworking of the new compounds, structure, and ensuring the new properties.

4. Contemporary development trends of materials science and engineering and their significance for development of societies

Contemporary interests of materials science and engineering may be reduced to issues presented in Table 2, taking into account lots of interdisciplinary factors. Knowledge and further investigation of many phenomena, among others, electrical, magnetic, optical, mechanical, thermal, taking into account the mutual interactions among the external factors, material structure, and theory pertaining to the fundamentals of those phenomena, after using modern mathematical modelling methods, and also with using the artificial intelligence tools and other computer assistance methods along with the advanced analytical techniques and testing methods explaining materials' behaviour, especially in their nanometric and atomic scales, and in the exceptionally short time periods of femtoseconds (10^{-15} s) make it possible to adjust properties of materials, including nanomaterials, biomaterials and biomimetic materials to requirements posed by their practical use.

The introduction of the new generations of materials and the propagation of products with the expected properties that can be made from those materials, calls for coming to know the materials behaviour, as substances for manufacturing the new products, from their atomic/nanostructure scale, through their microstructure, up to the macroscopic one, using the advanced analytical methods and computer modelling. That strategy calls for the improvement of the conventional materials manufactured and used on a large scale, like steel or the non-ferrous metals alloys, and also of the new functional materials used in smaller and smaller smart devices.

Employing the fundamental principles of physics and chemistry pertaining to the state and properties of the condensed matter, the theory of materials is used for modelling the structure and properties of the functional real materials, and for designing and forecasting the new materials and devices with the improved practical usability. The modern theory of materials science and modelling specific for the computational materials science, are used for the development of new materials. The introduction of new materials and the improvement of the properties of materials manufactured to date call also for working out and implementing the new synthesis and processing methods.

The fundamental feature is the possibility of designing the new materials focused on their small scale, inclusive the nanometric one, the optimisation of their applications, and also the optimisation of their manufacturing, including modelling of properties and processes.

Therefore, materials science and engineering play a key role in establishing and upgrading the economical conditions of quality of living, especially in the spheres chosen as priority ones in the world development for the forthcoming decades of the 21st century (Table 3).

The main directions of activities assumed or continued in the area of materials science and engineering, which results, as it is judged now, will have the most important effect on reaching the goals connected with the development of societies in the coming decades of the 21st century are given in Table 4. One should estimate, in particular, that the further progress of civilisation connected with introducing new products with the required high functional properties, will be to a great extent dependent on the development of

Table 3
Tasks of materials science and engineering in priority spheres of the world development in the next decades [1–10]

Priority development sphere	Strategic goal	Role of materials science and engineering
Improvement of conditions of living	More efficient use of materials and energy sources is required urgently because of hazards to the environment.	The participation in the development of new energy generation technologies, more energy-efficient devices and less toxic materials and better suited to recycling
Health care system	The development of novel diagnostic and therapeutic methods, as well as new devices, apparatus and drugs is required, because of the need to overcome and prevent diseases, to limit the scope and consequences of disability and because of the concern for the improvement of the health state in the whole world.	The development and the introduction of novel materials, including those for the development of artificial bones, implants, and artificial organs, safe administration of drugs, water filtration systems, as well as of the therapeutic and diagnostic equipment
Communication and information transmission	The development of new generations of telecommunication and IT devices, as well as fully miniaturised computers along with all peripheral devices, due to the need of increasing the speed and reliability of connection network in the world.	Determining the progress in the IT and computer revolution, as well as introducing the new electronic, optic, and magnetic materials
Consumer goods	Intensive efforts to obtain the expected state are required because of the customers' expectation for the fast delivery of consumer goods with the very high quality and reliability, at the possibly lowest, justified, and acceptable prices, delivered regardless of the manufacturing location in the world, and also of the high quality and effective services.	The development and the introduction of materials that will make it possible to improve the quality and usefulness of products, as well as ways of their delivery (e.g., packing) which will result in speeding and facilitating of their manufacturing, and cutting short delivery of consumer goods with the best properties
Transport	Co-ordinated actions are needed, connected with increasing the speed, safety, and comfort of transport means, because of the need to improve travel conditions in connection with business projects, rest, and the Earth and the space exploration.	The development and the introduction, among others, of the lightweight car bodies and accessories made from, e.g., aluminium and magnesium alloys, as well as from composite materials, brake systems for the high-speed trains, airplanes emitting much less noise, insulation coatings for space shuttles, and many other technical solutions guaranteeing reaching the assumed goals

the engineering materials, making it possible to use them in engineering design of many new products expected on the market, encompassing, among others:

- the development of modelling the relationships among chemical composition, structure, parameters of the technological processes, and service conditions of the engineering materials, using the modern IT tools, including the Artificial Intelligence methods, to improve the methodology of the engineering design processes, including the improvement of the engineering materials selection and the most suitable technological processes;
- the development of the pro-ecological manufacturing technologies with the possible lowest harmful environmental impact and/or the influence of the environment and atmosphere, as well as the decrease of the degradation of the environment to date and the deployment of the relevant materials and technologies;
- the development of surface engineering and related technologies in order to increase significantly the competitiveness of products and technological processes, to reduce the hazard to the environment, as well as the deployment of fast and inexpensive welding technologies making it possible to introduce the competitive products and manufacturing processes;
- the development and the deployment of the industrial applications of the smart materials and automatically supervised technological processes;
- the development of manufacturing technologies making it possible employing the existing high-temperature superconductors in market products, and the development of materials for the cellular telephony and telecom industry needs, including materials for opto-electronics;
- the introduction of new heat resistant and high-temperature creep resisting materials for service at elevated and high temperatures, especially for the space, aviation, automotive, power generation, and electronic industries,
- the development of the nanocrystalline and amorphous materials along with the development of the nanotechnology;
- the development of composite materials and others obtained using other non-conventional technologies;
- the introduction of new generations of biomaterials and biomimetic materials that will render it possible to extend the range of possible medical interventions and implanting the artificial organs and limbs to improve the level of treatment of diseases and injuries.

Table 4
Main directions of activities in materials science and engineering for achieving the strategic aims of the development of societies [1–10]

Main directions of activity	Evaluation of the current situation and plans for future
Materials design	The subject of the contemporary materials science and engineering is adjustment of materials, beginning from their chemical composition, constituent phases and microstructure, up to the set of properties required for the particular application. The traditional empirical methods of introducing the new materials will be supplemented to a growing extent by the theoretical predictions in the not so distant future. Computer simulation is employed in certain cases in the commercial scale, and the development of computer tools is expected for the evaluation of materials properties in their virtual environment. It will make it possible to improve those properties, as well as their prediction—even before manufacturing of materials, with the significant reduction of expenditures and time required for their investigation and implementation
Computational materials science	A significant progress has been made in the last decade in the area of simulation of properties and the processing of engineering materials; however, computer modelling will become the indispensable tool in materials science and engineering soon. The computer strategy provides the description of materials from the chemical and physical points of view in a broad scale of both dimension and time, and the multi-scale modelling makes using the consistent simulation structure possible within the entire range of those scales or in their prevailing parts
Advanced analytical techniques	The development of new engineering materials in future and thediscovery of new phenomena deciding their properties call for the development, the introduction, and the dissemination of the new and more efficient research techniques making examination of materials possible in the atomic scale, like the high resolution transmission electron microscopy, scanning probe microscopy, X-ray and neutron diffraction, as well as various types of spectroscopy, integrated with the more powerful computers, making the fast visualisation possible and the comparison with computer models, including also their use in the manufacturing (synthesis) processes, where they can be employed for control and manipulating the materials in the atomic and nanocrystalline scales, as well as in the atomic force microscopy
Synthesis and processing	The goal of the manufacturing and processing techniques of the future is to design the engineering materials from the complex arrangements of atoms and particles, with the same accuracy and control as is currently used to the semiconductor materials, and including, e.g., the chemical conversion from the simple precursor units, fast prototyping of the ceramic and metal components using the streaming technique, microwave sintering, deposition methods from gas phases (CVD, PVD) to form the thin films, infiltration of composites, to the most promising techniques
Nanomaterials	The capacity to control, synthesise and design materials in the nanometric scale (10^{-9} m) features one of the main progress directions to use those materials for the development of their new applications, scrap and waste reduction, as well as for optimisation of properties in all main engineering material groups, including, e.g., high-precision drug administration systems, nanorobots, in micro-manufacturing, nanoelectronics, ultra-selective molecular screens, and nanocomposites for employment in airplanes and other vehicles
Smart materials	Smart materials, different from other materials are designed in such a way that they react to the external stimuli and improve their properties, adapting themselves to the environmental conditions, increasing their life, saving energy, or modifying the conditions to improve human comfort, and also autonomously multiplicating themselves, repairing or damaging - as needed, reducing waste and increasing efficiency; all work in that area is considered especially vanguard in its character
Biomimetic materials	Thanks to a better understanding of the development of minerals and composites by the live organisms, biomimetic materials become the fast developing area of materials engineering, enabling to copy the biological processes and materials, both organic and inorganic ones (e.g., synthetic spider's thread, DNA chips, crystal growth within the virus crates) and are manufactured more and more accurately and efficiently, due to which their usefulness improves and new possibilities of their use become apparent (e.g., self-repair feature, ultra-hard and ultra-light composites for airplanes), which calls for the new chemical strategy Bering the self-organisation with their capability to from the hierarchically built materials

Moreover, taking into account the current needs of economy and the universal tendency to increase the competitiveness of products, and taking into consideration forecasts pertaining to the future development of civilisation and connected demand for engineering materials, one should consistently and in a coordinated way act for saving the raw materials, which is of course reflected in the engineering design practice and in the succeeding manufacturing and operation processes of products.

The introduction of new materials and the improvement of properties of materials manufactured so far call for the development and the implementation of the new synthesis and processing methods. The basic selection criterion for those processes is their quality maximisation with the simultaneous minimisation of costs. Continuously increasing quality requirements of customers force on manufacturers their pro-quality approach.

The appropriate selection of material for the particular application, based on the multi-criterion optimisation taking into account its chemical composition, manufacturing conditions, synthesis conditions, operating conditions, and the material waste disposal method in its after-service phase, as well as the price-dependant issues connected with obtaining the material, its transforming into a product, the product itself, and also costs of the disposal of the industrial waste and scrap, as well as the modelling of all processes and properties connected with materials, feature the fundamentals of the dynamically developing computational materials science.

Various models are employed in computational materials science, depending on scale and also possibilities of using the engineering materials modelling, their synthesis, structure, properties, and phenomena. The experimental verification enables to check the computer simulation in various scales and using the artificial intelligence methods, for employing the new materials and their manufacturing processes.

An essential determinant of the manufacturing processes' development, giving consideration to economical and ecological conditions, at the threshold of the 21st century, is an integration in the area of advanced design and manufacturing of the up-to-date products and consumer goods, deciding the improvement of the quality of life and welfare of societies, which encompasses the development of design methodology and connected with it newer and newer designs developed using the computer aided design methods (CAD), the development of new technologies and manufacturing processes, of technology design methodology, contemporary production organisation, operational management and quality driven management along with the computer aided manufacturing (CAM), and also the development of materials engineering methodology, the development of entirely new engineering materials with the required better and better functional properties, with the pro-ecological values and minimised energy consumption along with the development of the computer based materials science and methodology of computer aided materials design (CAMD).

As nearly in all cases, however not exclusively, material and its properties decide feasibility of manufacturing of the product and its functional properties, teaching materials engineering to the students and cadres of all engineering special fields is required. On the other hand, progress in the materials engineering is so big that in the most advanced and avant-garde areas the half-obsolescence period[1] of the detailed knowledge does not exceed 2/3 years. Somebody who is not up to date with that progress has–after some time–only the obsolete knowledge and is not able to carry out any reasonable engineering activity without the repeated thorough studies.

5. Résumé

The strategic importance of engineering materials for the future development of civilisation poses essential requirements in that area, and the short half-obsolescence period of knowledge in materials science, materials engineering, and materials processing technology areas call for methodical and dynamical studies as well as research and development activities, along with the coordinated and systematic efforts for upgrading the general knowledge level of the engineering cadres of various special fields for fast transfer of that knowledge to the product engineering design practice and their spheres of their manufacturing and use. One can indicate to the basic determinants connected with those areas of science and technology, indispensable for attaining the expected improvement of life quality of the contemporary societies:

- Giving people access to products and consumer goods deciding directly the level and the quality of living, the information interchange, the education level, the quality and the potential of health service and many other aspects of the environment in which we live, features the profoundly humanistic mission awaiting the engineers' circles, in which the materials issues play an important role and thus decide directly possibilities of the development of societies.
- The optimisation of the functional properties of materials used in products and consumer goods, improving quality of living of societies, decides main development trends of materials science and engineering in the next decades of the 21st century; one can name among them materials engineering connected with adjusting materials, beginning from their chemical composition, constituent phases and microstructure to the set of properties required in final products, computer based materials science as an indispensable tool for prediction of materials' properties and technological processes influencing them, advanced techniques for manufacturing engineering materials composed of patterns of atoms and particles, and the development of nanomaterials, as well as smart and biomimetic materials.
- Only the continuous financing of scientific research by contemporary societies, and especially in the area of materials science and engineering, as well as creating the advantageous conditions for minimising the time span between making the scientific discoveries and their practical applications, may give a chance for introducing the innovative products and consumer goods in future, ensuring the expected improvement of the quality of living and prosperity of societies, and only the permanent conviction of the societies of the links between the basic research currently carried out and future prosperity and high quality of living may guarantee attaining that goal.

[1] The half-obsolescence period of the detailed knowledge (concept introduced by analogy to the radio-active half-life period) denotes that after such period about 50% of the detailed information in the particular area will be replaced by new, up-to-date information, introduced in connection with new technological and scientific discoveries.

References

[1] L.A. Dobrzański, Materials design as an important element of advanced products' engineering design and manufacturing, in: Proceedings COBEM-2003, Sao Paulo CD-ROM, 2003.
[2] L.A. Dobrzański, Fundamentals of Materials Science and Physical Metallurgy. Engineering Materials with the Fundamentals of Materials Design, WNT, Warszawa, 2002 (in Polish).
[3] L.A. Dobrzański, Metallic Engineering Materials, WNT, Warszawa, 2004 (in Polish).
[4] L.A. Dobrzański, Contemporary development trends in materials science and materials engineering, Inżynieria Mater. (2003) 271–278 (in Polish).

[5] L.A. Dobrzański, Significance of materials science and engineering for advances in design and manufacturing processes, Computer Integrated Manufacturing, in: B. Skołud, D. Krenczyk (Eds.), Advanced Design and Management, WNT, Warszawa, 2003, pp. 128–140.
[6] L.A. Dobrzański, Significance of the development of materials science and engineering for improvement of quality of living of the contemporary societies, Podole University of Technology, Chmielnickij-Satanov, Ukraine, 2003, pp. 34–47 (in Polish).
[7] L.A. Dobrzański, Heat treatment as the fundamental technological process of formation of structure and properties of the metallic engineering materials, in: Proceedings of the Eighth Seminar of the International Federation for Heat Treatment and Surface Engineering IFHTSE 2001, Dubrovnik-Cavtat, Croatia, 2001, pp. 1–12.
[8] Dobrzański, L.A., Significance of materials science for advances in products design and manufacturing, Opening lecture on General Assembly of CIRP, Cracov, 2004, unpublished.
[9] Dobrzański, L.A., “Computational materials science as a method of design of contemporary engineering materials and products”, 10th Seminary of Research and Education Programmes in Materials Engineering, Myczkowce, 55–88, 2004 (in Polish).
[10] M. Ruehle, H. Dosch, E.J. Mittemeijer, M.H. Van de Voorde (Eds.), European White Book on Fundamental Research in Materials Science, Max-Planck-Institute fuer Metallforschung, Stuttgart, 2001.
[11] G.E. Dieter (Ed.), ASM Handbook—Materials Selection and Design, vol. 20, ASM International, Metals Park, 1997.
[12] M.F. Ashby, Materials Selection in Mechanical Design, Pergamon Press, Oxford/New York/Seoul/Tokyo, 1992.
[13] N.A. Waterman, M.F. Ashby, The Materials Selector, vol. 1–3, Chapman & Hall, London/Weinheim/New York/Tokyo/Melbourne/Madras, 1997.
[14] R. Wertheim, J. Harpaz, Collaboatin and globalisation of R&D in manufacturing engineering, in: Proceedings of Fourth International Conference on Industrial Tools ICIT’2003, Bled-Celje, 3–8, 2003.
[15] T.K. Derry, T.I. Williams, A Short History of Technology, Dover Publications Inc., New York, 1993.
[16] C.C. Bambach (Ed.), Leonardo da Vinci–Master Draftsman, The Metropolitan Museum of Art, New York, Yale University Press, New Haven and London, 2003.