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ENGINEERING MATERIALS' DEVELOPMENT AS THE DETERMING FACTOR IN PROGRESS OF PRODUCT MANUFACTURING

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Abstract. *The significance of the materials selection in engineering design was presented in this paper. The relationships between materials selection and manufacturing process were taken into consideration. On the bases of observation of human civilisation development it was stated that civilisation development depends on materials development at a large extend. It should be foreseen that working out and introduction of new materials is necessary to make further progress in the future.*

Keywords: *engineering design, engineering materials, manufacturing process, materials selection, civilisation development.*

1. INTRODUCTION

Manufacturing consists in making products from the raw materials in various processes, using various machines and in operations organized according to the well-prepared plan.

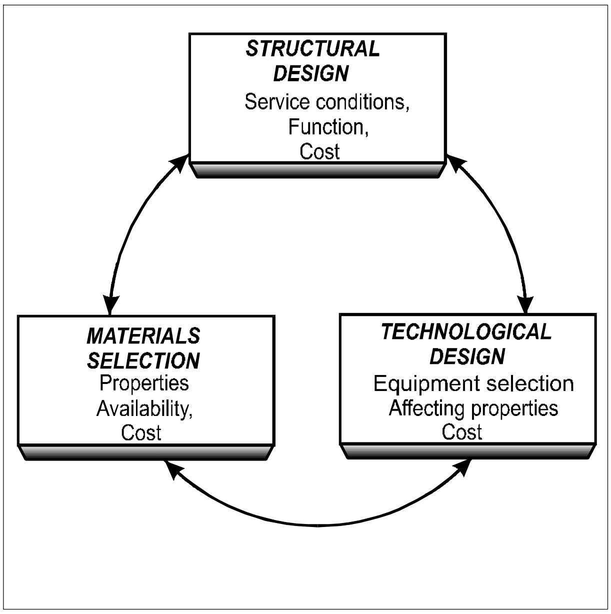

Figure 1 - Relationships between elements of engineering design i.e., structural design, material selection and technological design (prepared according to G.E.Dieter)

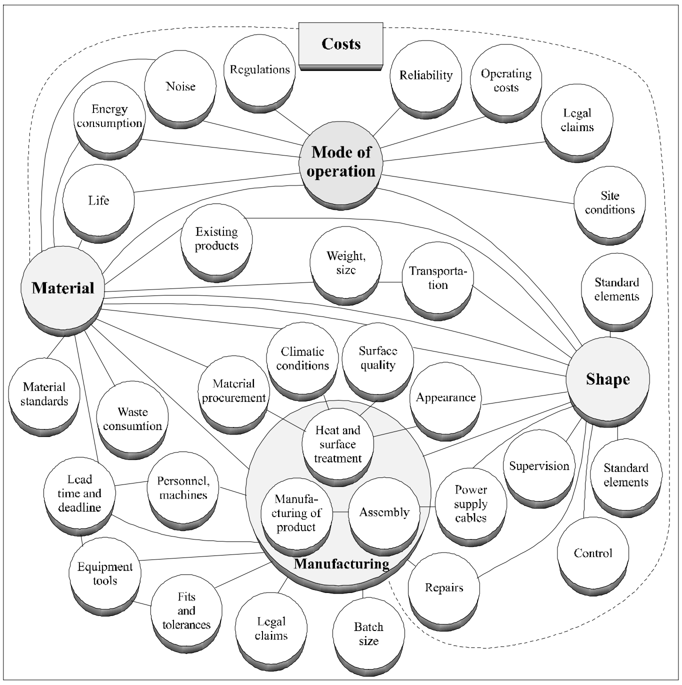

Figure 2 - Set up of tasks accounted for in engineering design and their interrelations

Therefore, the manufacturing process consists in a proper use of resources like: materials, energy, capital, and people. Nowadays, manufacturing is a complex activity uniting 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. The technical aspect of this effort pertains the engineering design of a product, merging in itself three equally important and indivisible elements, i.e., structural design, whose goal is to work out the shape and geometrical features of products satisfying human needs (fig. 1), materials' selection with the required physical and chemical, as well as technological properties, ensuring the expected life of the product or its elements, and the 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 support, and also with ensuring the lowest possible costs of the product.

Engineering design is a complex activity requiring taking into consideration many diversified elements. Interrelations between the tasks that have to be accounted for are shown schematically in fig. 2.

2. SELECTION OF MANUFACTURING PROCESSES FOR ELEMENTS MADE FROM VARIOUS MATERIAL GROUPS

Selection of the product manufacturing processes, closely related to selection of materials for its elements, is a very important stage of the engineering design process. The main criterion for these selections is maximization of product quality with the simultaneous minimization of costs of its elements. Manufacturing processes may be grouped in nine classes (fig. 3). The first row contains the initial forming processes, whereas the manufacturing processes put into the vertical column include the secondary forming processes and finishing.

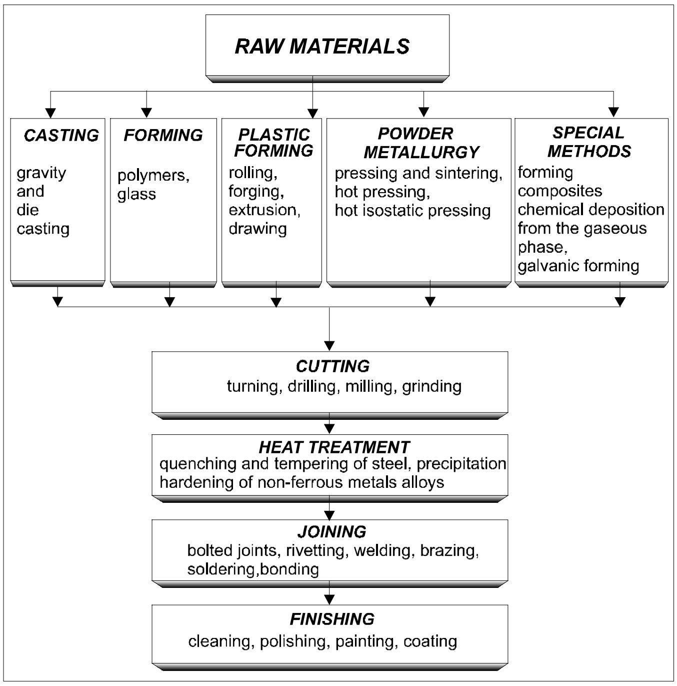

Figure 3 - Schematic diagram of manufacturing processes
(prepared according to M.F. Ashby)

Selection of a material decides often selection of feasible manufacturing processes that may be used to make elements from the particular material. Various technological processes are given in table 1, used most often for various product groups. Selection of the technological process is connected with the material's performance and limited by its hardness, brittleness

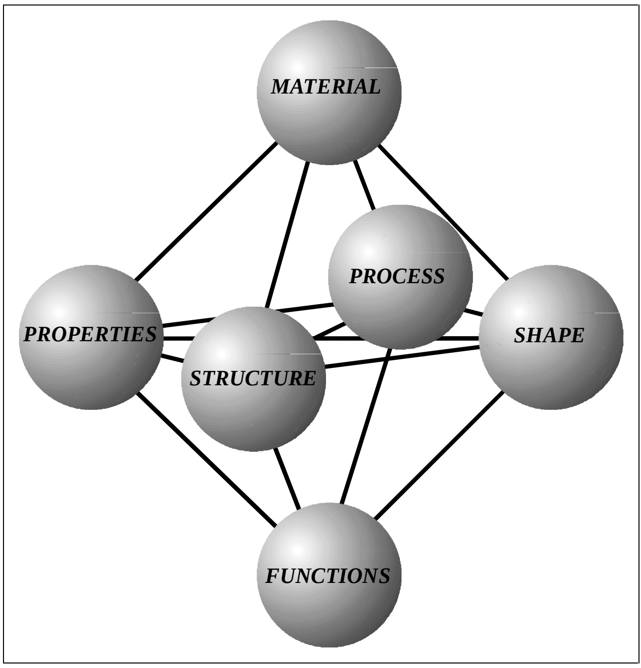

Figure 4 - Relationships among some factors connected with material, processes and functions of a product

Table 1. Manufacturing processes used for various materials

Process \ Material	**Cast iron**	**Carbon steel**	**Alloy steel**	**Corrosion resistant steel**	**Al and Al alloys**	**Cu and Cu alloys**	**Zn and Zn alloys**	**Mg and Mg alloys**	**Ti and Ti alloys**	**Ni and Ni alloys**	**Refractories**	**Thermoplastics**	**Hardening plastics**
Casting / shaping													
Sand casting	○	○	○	○	○	○	◑	○	◑	○	◑	●	●
Investment casting	◑	○	○	○	○	○	◑	◑	◑	○	◑	●	●
Pressure die casting	●	●	●	●	○	◑	○	○	●	●	●	●	●
Injection casting	●	●	●	●	●	●	●	●	●	●	●	○	◑
Engineering foams forming	●	●	●	●	●	●	●	●	●	●	●	○	●
Blow moulding	●	●	●	●	●	●	●	●	●	●	●	○	●
Injection moulding	●	●	●	●	●	●	●	●	●	●	●	○	●
Rotary swaging	●	●	●	●	●	●	●	●	●	●	●	○	●
Forging / forming of bars													
Blow extrusion	●	○	○	◑	○	○	○	◑	●	●	●	●	●
Cold upset forging	●	○	○	○	○	○	◑	◑	●	◑	●	●	●
Closed-die forging	●	○	○	○	○	○	●	○	○	◑	◑	●	●
Press moulding and sintering	●	○	○	○	○	○	●	○	◑	○	○	●	●
Hot extrusion	●	○	◑	◑	○	○	●	○	◑	◑	◑	●	●
Rotary swaging	●	○	○	○	○	◑	◑	○	●	○	○	●	●
Machining													
Machining from the semi-finished steel	○	○	○	○	○	○	○	○	◑	◑	◑	◑	◑
ECM – Electro-chemical machining	○	○	○	○	◑	◑	◑	◑	○	○	◑	●	●
Electromachining	●	○	○	○	○	○	◑	◑	◑	○	◑	●	●
Wire EDM – wire electrodischarge machining	●	○	○	○	○	○	◑	◑	◑	○	◑	○	●
Forming													
Sheet – metal forming	●	○	○	○	○	○	◑	◑	◑	◑	●	●	●
Thermoforming	●	●	●	●	●	●	●	●	●	●	●	○	●
Spinning	●	○	◑	○	○	○	○	◑	◑	◑	◑	●	●

Designation: ○ - standard practice ◑ - rarely used ● - N/A

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 loadings 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, this feature decides the possibility of using machining. Working 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

Table 2. Main properties of the selected manufacturing processes

Process \ Property	Surface roughness	Dimensional accuracy	Shape complexity	Production throughput	Production volume	Relative cost	Dimensions projection area
Pressure die casting	●	○	○	◑	○	○	◑ / ●
Spinning	◑	◑	◑	●	◑ / ●	○/ ◑	○/ ◑ / ●
Drawing	●	○	◑	○/ ◑	○/ ◑	○/ ◑	○/ ◑ / ●
Spray forming	●	○	○	○/ ◑	○/ ◑	○/ ◑ / ●	◑ / ●
Sand mould casting	○	◑	◑	●	○/ ◑ / ●	○/ ◑ / ●	○/ ◑ / ●
Shell casting	●	○	○	○/ ◑	○/ ◑ / ●	○/ ◑	◑ / ●
Investment casting	●	○	○	●	○/ ◑ / ●	○/ ◑	◑ / ●
Single-point machining	●	○	◑	○/ ◑ / ●	○/ ◑ / ●	○/ ◑ / ●	○/ ◑ / ●
Milling	●	○	○	◑ / ●	○/ ◑ / ●	○/ ◑ / ●	○/ ◑ / ●
Grinding	●	○		●	◑ / ●	○/ ◑	◑ / ●
Electromachining	●	○	○	●	●	○	◑ / ●
Blow moulding	◑	◑	◑	○/ ◑	○/ ◑	○/ ◑ / ●	◑ / ●
Sheet-metal forming	●	○	○	○/ ◑	○/ ◑	○/ ◑ / ●	●
Forging	◑	◑	◑	○/ ◑	○/ ◑	○/ ◑	○/ ◑ / ●
Rolling	●	◑	○	○	○	○/ ◑	○/ ◑
Extrusion	●	○	○	○/ ◑	○/ ◑	○/ ◑	◑ / ●
Powder metallurgy	●	○	○	○/ ◑	○	○/ ◑	●

Level	Designation	Surface roughness	Dimensional accuracy	Shape complexity	Production throughput	Production volume	Relative cost	Dimensions projection area
High	○	>6.3	<0.13	High	>100	>5000	High	>0.5
Medium	◑	>1.6 and <6.3	>0.13 and <1.3	Medium	>10 and <100	>100 and <5000	Medium	>0.02 and <0.5
Low	●	<1.6	>1.3	Low	<10	<100	Low	<0.02
Units		mm	mm	-	pc/h	pc	-	m^2

mechanical, physical and chemical properties of the product (fig. 4). In table 2 the basic features of the main manufacturing processes of products and their elements are given.

3. MAIN FACTORS DECIDING SELECTION OF MATERIALS FOR TECHNICAL APPLICATIONS

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. This selection should be carried out basing on the multi-criterial optimization. In table 3 exemplary information is given, necessary for various industrial applications.

Table 3. Necessary information about materials depending on their industrial application type

Properties \ Industrial Application	Housing	Transport	Power industry	Space technology	Armaments industry	Chemical industry	Petroleum production	Electronic and telecommunication industry	Material manufacturing	Manufacturing of consumer goods	Other industry bronches
Mechanical	●	●	●	●	●	●	●		●	●	●
Thermal	●	●	●	●	●	●	●		●	●	●
Electrical and electronical			●	●	●			●	●	●	●
Magnetic			●	●	●			●	●	●	●
Other physical properties				●	●			●	●		
Corrosion	●	●	●	●	●	●	●		●	●	
Oxidation	●	●	●	●	●	●	●		●	●	
Machinability	●	●	●	●	●			●	●	●	●

From the technical point of view, solids with properties that enable people to use them in order to manufacture products are called materials.

Generally, among the materials of technical significance one may distinguish the following:

- natural materials, requiring some shaping only for their technical use; examples of the natural materials are: wood, some stones, rocks, and minerals,
- engineering materials, not found in nature but requiring complex manufacturing processes to adjust them for the technical needs after using raw materials found in nature;

the main groups of engineering materials traditionally include: metals and their alloys, polymers and ceramic materials; this classification is based on the nature of bonding among the atoms forming the material, holding them in spatially coordinated arrangements, and determining the basic material properties (fig. 5).

In addition, it is possible to name composite materials created by integrating any two of

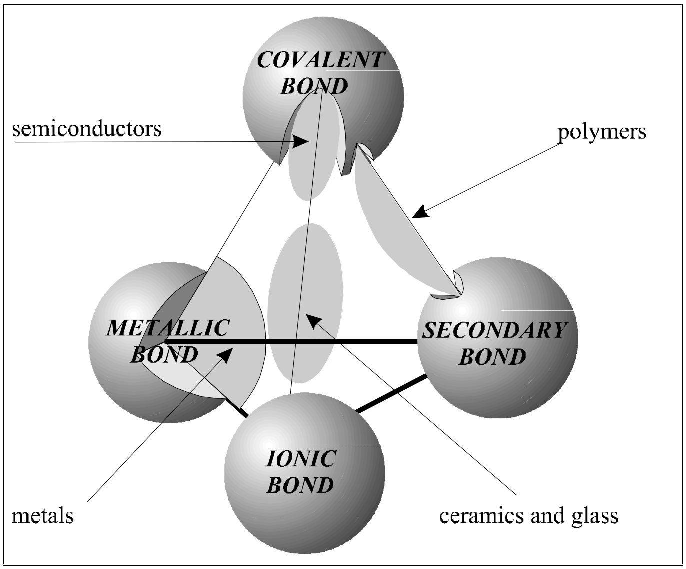

Figure 5 - Type of bondings among the atoms occurring in the main engineering materials groups (prepared according to J.F. Shackelford)

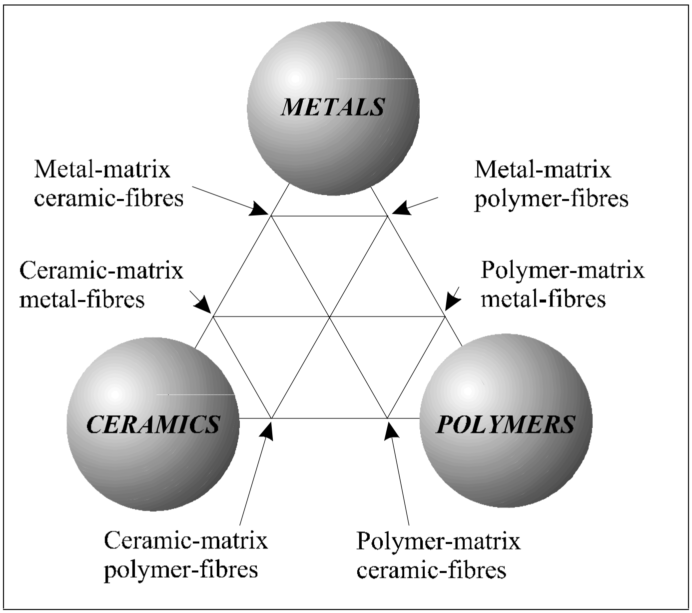

Figure 6 - Main composites‘ groups (prepared according to M.W. Grabski)

the engineering materials mentioned above into a monolithic aggregate, which yields other properties, different from the properties specific for each of the constituent materials.

The composite materials are splices of two, or more, separate phases, insoluble among themselves, each of which corresponds to another main engineering material, ensuring more advantageous set of properties and structural features, than are characteristic for each of the constituent materials individually (fig. 6).

The vast majority of engineering materials derive from raw materials obtained from the crust of the earth, raised in mines as ores and then enriched to make possible their extraction or synthesis. Some few engineering materials are synthesized from raw materials obtained from atmosphere or the oceans. Table 4 presents mass fractions of the chemical elements occurring on the Earth. Availability of the natural resources depends on their volume, location

Table 4. Mass fraction of chemical elements in the Earth (in %)

lithosphere		oceans		atmosphere	
oxygen	47	oxygen	85	nitrogen	79
silicon	27	hydrogen	10	oxygen	19
aluminium	8	chlorine	2	argon	2
iron	5	sodium	1	carbon dioxide	0.04
calcium	4	magnesium	0.1		
sodium	3	sulphur	0.1		
potassium	3	calcium	0.04		
magnesium	2	potassium	0.04		
titanium	0.4	bromine	0.007		
hydrogen	0.1	carbon	0.002		
phosphorus	0.1				
manganese	0.1				
fluorine	0.06	Total weight of the Earth’s crust up to the depth of 1 km is $3 \cdot 10^{21}$ kg, weight of the oceans - 10^{20} kg, and of the atmosphere - $5 \cdot 10^{18}$ kg.			
barium	0.04				
strontium	0.04				
sulphur	0.03				
carbon	0.02				

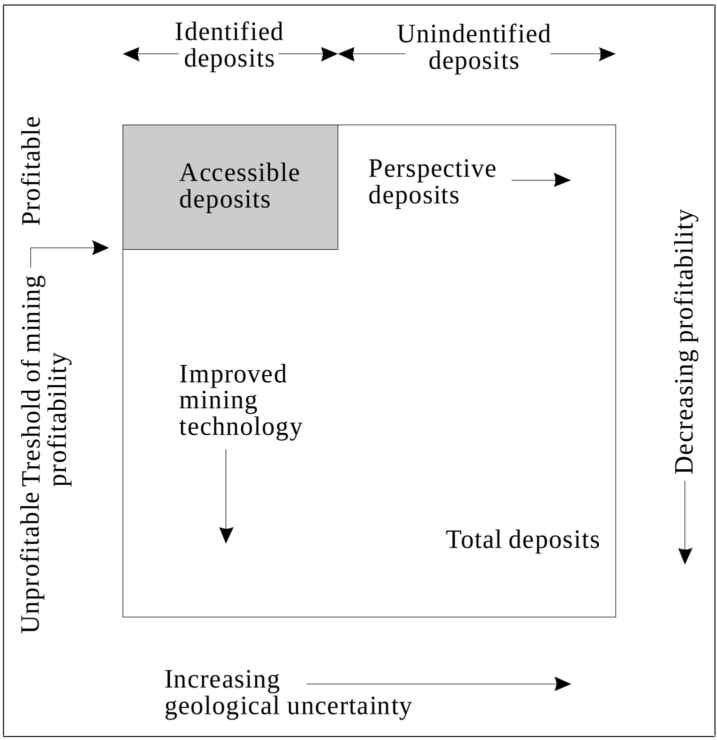

Figure 7 - Rough estimate of natural resources (schematic diagram according to A. McElvey)

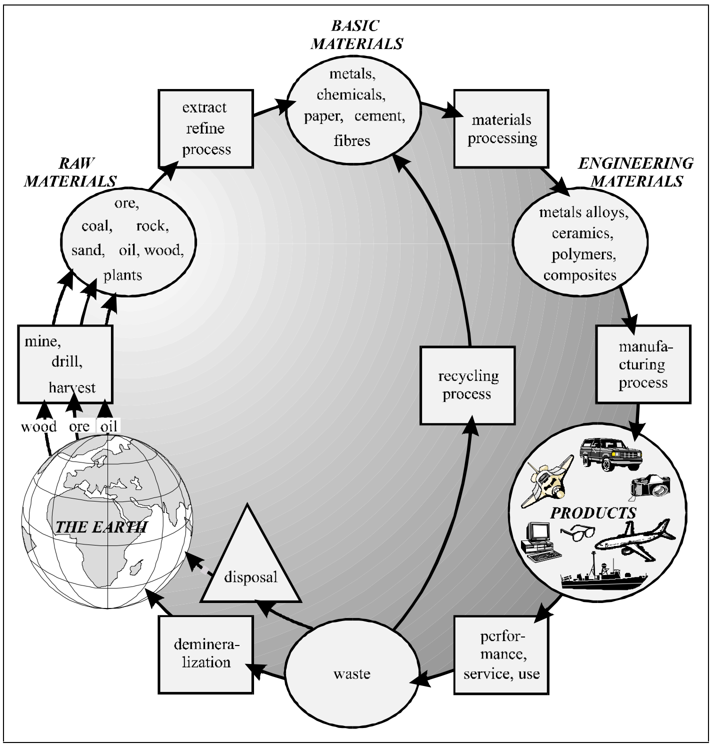

Figure 8 - Diagram of a technical life-cycle of the engineering materials (prepared according to C. Newey and E. Weaver)

and energy necessary to obtain and process them. Total volume of resources includes also resources that may be opened out in future (also unknown today) due to progress of the geologic prospecting, increase of the sales price of raw materials, and modification of technology of their obtaining and processing, and also due to rationalization of transport. Figure 7 presents rough estimates of natural resources at a given time. It is expected that the levels of economical profitability for employment of particular raw materials are determined by their half-periods of depleting of their respective stocks. After that time a rapid price advance is expected of the raw material that will render material procurement significantly difficult. It is estimated that only 20 years are left to complete the half-period for petroleum for example, whereas zinc, tin, lead, mercury, silver, and tungsten - some 50 to 80 years are left, and several hundred years will pass until the half-period is reached for aluminium, iron, and majority of raw materials used to make ceramics and glass.

The present situation and 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 minimization of their energy consumption,
- using easier available 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 full use of the energy saving recycling for their reuse and full recovery of materials in all possible and economically justified cases.

Fig. 8 presents a general perspective on the life-cycle of engineering materials: a short manufacturing cycle links into a very long geological one within the Earth. Notice that the recycling of waste products offers a shortcut in the cycle.

4. HISTORICAL DEVELOPMENT OF ENGINEERING MATERIALS AND THEIR DEVELOPMENT TRENDS

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.

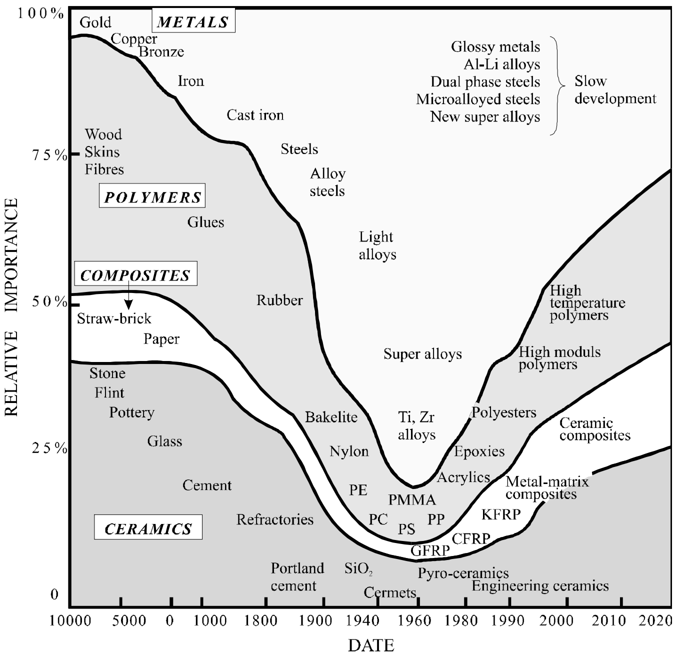

Figure 9 - Diagram presenting the significance of various epochs of the human civilisation development, with dates of introduction of new materials (prepared according to M.F. Ashby)

Table 5. Common industrial applications of several material groups

Industrial applications / Groups of materials	World consumption per year, Mt	Building industry	Transportation	Maritime economy	Power industry	Space technology	Armaments industry	Defense and aviation	Chemical industry	Petroleum production	Household	Electronic industry and telecommunication	Materials production	Health protection	Packings	Consumer goods production	Communication electro-technology	Other industry branches
Steel and other iron alloys	750	●	●	●	●	●	●	●	●	●	●		●		●	●		●
Nonferrous metals	x	●	●		●	●	●		●			●	●			●		●
Aluminium	17	●	●					●			●				●		●	
Nickel	0.9				●			●										
Titanium	0.1							●										●
Copper	x	●									●							
Zinc	x														●			
Lead	x	●	●															
Tin	x														●			
Heat-resistant alloys and super alloys	x		●		●	●	●			●			●					
Ceramic materials and glasses	x	●	●		●	●	●	●	●			●	●			●	●	●
Concrete	10^3	●	●															
Composites	x		●			●	●									●		
Polymer-matrix composites	x		●	●				●									●	
Inorganic compounds	x						●		●									
Polymer materials	80	●	●								●		●		●	●	●	●
Semiconductors	x					●						●				●		
Biomaterials	x													●				
Wood	x	●											●					

Following the history of human civilization we may come to the conviction that its progress is governed notably by the development of materials and accompanying growth of the productive forces. This is attested undoubtedly, among others, by naming of the various epochs in the history of humankind by materials deciding the conditions of living at that time, eg.,- Stone Age, Bronze Age, Iron Age (fig. 9). Practical application of many inventions was made possible only since proper materials had become available.

As an example we may mention that the draft sketch of a helicopter was found in works of Leonardo da Vinci from the fifteenth century, however, the first helicopter was made in the forties. Space ships were described in the literary works long ago, and the necessary calculations were made already in the first decade of the twentieth century, nevertheless, the first artificial satellite of the Earth was launched only in the end of fifties, and the first space shuttle orbiter was launched in the seventies. Analyzing the contemporary development trends

Table 6. Forms in which some materials available on the market are supplied

Form / Process	Sheet	Foil	Bars	Tubes	Wire	Constru-ctional sections	Ingots
Steels	○	●	○	○	○	○	○
Aluminium and its alloys	○	○	○	○	○	○	○
Copper and its alloys	○	◑	○	○	○	◑	○
Magnesium and its alloys	○	●	○	○	◑	○	○
Noble metals	○	○	○	◑	○	●	○
Zinc	○	○	○	●	○	●	○
Polymers	○	◑	○	○	◑	●	●
Elastomers	○	●	◑	●	○	●	●
Ceramic materials	◑	●	○	○	●	◑	●
Glass	○	●	○	○	○	◑	●
Graphite	○	●	○	○	○	◑	●
Designation: ○ - common application ◑ - limited usability ● - not used							

of various material groups, it is realized - which is evident - that the mass share of the ultramodern products (like space technology products or even biomedical materials) in all products manufactured by people, is not large, albeit it is continuously growing. So far it is not possible that polymers would conquer the surrounding reality (they only seem to be ubiquitous), because of their relatively low wear resistance and other types of wear, low corrosion resistance, and also because of their service temperature range that does not exceed 300÷400°C. Porous ceramics belongs to the construction domain, although glass has also many household applications, but additionally it is used in car manufacturing, moreover, some grades -especially glass ceramics - are used even in machines. The main materials in machine technology, car, ship, household, and tool industries, as well as in many others, but important also in construction, are still metals and their alloys, albeit in many cases engineering ceramics, and also some composites, compete successfully with these materials. Main industrial applications of some engineering materials groups are given in table 5. Moreover, in table 6 forms are given in which the most often used engineering materials are supplied.

One might attempt to present a vision of the future and evaluate the development trends of various engineering materials. Certainly, they are connected with forecasts pertaining development of various fields of activity and manufacturing processes. Even if not everything, according to these 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 these materials are already available nowadays, some of them should be developed soon according to the outlined requirements. It is good to realize that many venturous projects will be made possible if these new materials are made.

5. FINAL REMARKS

Materials' selection plays a very significant role in the design and manufacturing processes of new, demanded products, having the highest attainable quality and performance at the optimal and reasonably set possibly lowest costs level. The engineering design processes cannot be set apart from the materials' selection, being more and more often computer-aided, nor from the technological design of the most suitable manufacturing processes. The review of the multi-millennia long history of human civilization indicates that the significant increase of the level of life and production is connected most often with introduction of new material groups, having properties better and better adjusted to the real customers' requirements that get more sophisticated nearly each day, and also relevant to them technological processes. The reasons given, make it possible to forecast that the future of the market and products on it with the required properties, are inseparably connected with the development of Materials Engineering and Materials Processing Technologies. One can specify two main priorities in this area:

- continuous improvement of the existing materials and technological processes,
- development of materials and technological processes ensuring environment protection or improving conditions of human life or extending its time span.

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