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MATERIALS IN THE THIRD MILLENNIUM

PROBLEMS OF MATERIALS IN THE TWENTY-FIRST CENTURY (REVIEW)

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The second half of the twentieth century was characterized by rapid growth of the list of grades and the volume of production of structural and functional materials by classical metallurgical methods. At the present time, the machine-building industry uses about 2000 alloys. The whole set of machine-building materials can be divided into six classes, namely, metals, polymers, ceramics, glasses, and elastomers, which, when used in various combinations, form the sixth class – composite materials (CM). This classification is universal; though it has been accepted in recent years, its roots go back to the very beginning of man's activity, i.e. to 5000 – 10,000 B.C. The proportion and the quality of the materials changed with time. For example, in 5000 B.C., polymers + elastomers (wood, pelage, fiber) and ceramics + glass (stones, clay, glass, quartz) composed about 90% of the material used, while metals and composites were less than 10%. By the beginning of the twentieth century, the share of metals grew to 65 – 70%, that of polymers + elastomers diminished to 12 – 15%, that of ceramics + glass diminished to 8 – 10%, and that of composites to 2 – 5%. Metal predominated in the late 50s – early 60s, when their proportion amounted to about 85%, that of polymers + elastomers amounted to about 1 – 2%, and that of ceramics + glass to 4 – 5%. Then the proportion of the used classes of material changed markedly every 5 years in favor of polymers (elastomers), composites, and ceramics (glass) at the expense of metals. In 1990, the proportion of metals fell to 60 – 65%, i.e., became comparable with the figure typical for the beginning of the century, whereas the share of plastics and composites increased. These changes occurred differently in different countries. For example, if we compare the USA and Russia, the proportion of plastics + CM to steel in the USA was 27.9%, whereas in Russia it was only 3.6%. A comparison of the same materials with respect to their specific weight, i.e., in cubic meters (the actual proportion in the total consumption) shows that the use of plastic + CM in the USA at that time exceeded that of steel, whereas in Russia the amount of steel exceeded plastics + CM by a factor of 4.2. This gives grounds to assume that in 1990 the USA had passed to the "age of plastics and composite materials," whereas Russia still lived in the "age of steel" typical for the 1950s, which certainly had a negative effect on the technical level of products.

In 1995, the world's production of metals and plastics amounted to 215 and 365 mln m^3, respectively. The predicted proportion of metals in the world's production in 2020 will fall to 25% and that of polymers (elastomers), composites, and ceramics (glass) will increase about equally. The growth in the proportion of plastics, ceramics, and composite materials in the twenty-first century will be accompanied by the creation of qualitatively new types of them with properties much better than those of metallic materials, such as high-modulus and high-temperature polymers, composites with a metallic matrix, ceramic composites, Pyrocerams, viscous engineering ceramics, etc. The production of nanocrystalline ceramics markedly elevates their plasticity, which gives us grounds to speak of the possibility of obtaining superplastic ceramics on a commercial scale. Successful examples in this respect are chemically modified silicon nitride and zirconia reinforced by phase transformation ("ceramic steel"). The existing technological, economical, and organizational problems promise to be overcome in the twenty-first century, which will make it possible to create structures such as ceramic engines.

The decline of the fraction of metallic materials is accompanied by their qualitative change. Virtually every new material possesses high, superhigh, or ultrahigh properties. In the beginning of the third millennium, iron alloys, steels primarily, promise to remain the most popular metallic materials. In the last 50 years, the world's production of steel has increased from 200 to 740 mln tons a year. Predictions show that the volume of the production of steel will decrease considerably only if the infrastructure of the world economy changes radically. Therefore, it seems that the volume of the production of steel attained by the end of the twentieth century should be preserved for the whole of the twenty-first century.

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The modern level of technological and industrial development of basic engineering characterized by substantial intensification of the use of machines and other equipment has created fundamentally new stable trends in the choice of materials and technologies for their production, which will determine the approach to the creation of materials in the next millennium. The essential changes in this concept are based on the following facts:

– we have witnessed an intense transition to the use of materials in a metastable state;

– the role of synergism of mechanical properties and extreme technologies has acquired more and more importance; the technological processes should provide the creation of highly nonequilibrium structures and their self-organization under nonequilibrium conditions;

– we have witnessed the formation of a tendency toward the creation of "intellectual" materials and their technologies, i.e., the production processes should involve the principles self-recovery, self-control, and self-diagnostics, which will make it possible to eliminate the degradation of properties during the service of parts and sometimes even improve them substantially (materials with the shape-memory effect, functional and gradient materials, composite materials);

– materials have begun to be treated as integral objects that involve the substance itself, its structure, the technology of fabrication, and its treatment rather than as simply a substance with the specified chemical composition (this approach makes it possible to raise markedly the coefficient of utilization of materials in a structure, change, in principle, its production technology, and provide a substantial economic effect);

– a new approach has appeared and progressed in the estimation of the role of the material in the provision of structural strength; this approach acknowledges the leading role of the surface and its properties (and not only the volume properties, as is commonly done) in the provision of the strength and service properties of parts; this has given rise to a new direction of surface engineering that involves combined energy and physicochemical actions.

Realization of these features in the thinking used to choose the material should substantially decrease the consumption of materials for the production of parts, thus improving their service properties. Its existence involves the development of technological processes of a new level characterized by a limited number of basic operations in order to provide a full transition of the initial materials into the target project (nonwaste technology), which is characterized by a radical change in the structure and properties of the material. The methods of its production and hardening treatment, including the heat one, acquire a fundamental importance for structure formation. All of the types of heat treatment can be classified into two large groups: those providing a stable state or a metastable state. The first group includes all kinds of annealing, and the second group includes the other treatment methods that yield structures with various degrees of nonequilibrium. The second group can be divided into two subgroups, i.e., the treatment performed for providing the volume properties and the treatment for providing high surface properties. The end of the twentieth century was characterized by the appearance of a new direction in heat treatment, i.e., the specific weight of surface treatment has become substantially higher than that of volume treatment. In the new century, the methods of controlled surface treatment based on the use of concentrated energy fluxes will start to dominate; vacuum, ionic, laser, and other processes have progressed considerably. The plasma, high-frequency induction, and electron heat-treatment methods will continue to develop, and the role of heat treatment in gas and electric furnaces, salt tanks, and conventional induction heating will diminish. The methods most promising with respect to structure formation and improvement of the properties are at the same time the most efficient from the standpoint of the energy intensity of the process, i.e., are the most economically expedient. If we recall that despite the high energy intensity of heat treatment it makes it possible to diminish the consumption of energy in the production process as a whole (from the raw material to the final product) due to the lower consumption of the metal, it becomes obvious that the volume of heat-treated parts produced in industrially developed countries in the beginning of the third millennium should be quite high; on the average, it should amount to 60%. Analyzing the state of the art in Russian machine-building plants, we will see that they predominantly employ the last of the mentioned kinds of heat treatment, whereas foreign countries offer partially or fully automated lines with advanced energy sources in the market. In fact, a new branch of industry, i.e., heat treatment, has appeared in Europe. This conclusion follows from an analysis of the structure of the organization of this treatment; there are companies that possess a single engineering and control center and a net of subdivisions spread all over Europe in the form of small enterprises that specialize in heat treatment. As a rule, they occupy one or two thousand m^2 in area and have 10 – 20 units of heat-treatment equipment and 50 – 100 workers. This unique commercial policy allows them to provide a high level of quality; the distribution in their countries provides closeness to potential clients and low burden, and all the factors taken together provide a high profit. One of the reasons behind this situation is the fact that when a heat-treatment shop is a part of a machine-building plant commonly managed by mechanical engineers, the heat-treatment specialists have to fight for their own technological and investment interests, even in Europe.

In the field of surface engineering, combined processes, which markedly enhance the service properties of the surface, promise to be developed intensively in the beginning of the twenty-first century. In the first place, this concerns the combination of classical diffusion processes of surface saturation with deposition of coatings 3 – 5 μm thick by the methods of chemical (CVD) and physical (PVD) deposition from a vapor phase. In Russia, these method have been tested quite well but have not found wide application in the machine-building industry. Therefore, we cannot exclude the necessity of a wide-ranging study on the problem of self-propagating high-temperature synthesis (SHS) that possesses a high technological potential. The method can yield various disperse materials (superhard compounds, heterophase and composite powder materials to be deposited on coatings of various types) and compact parts for structural and instrumental purposes. The level of development of this process by native scientists is such that they can organize both medium-batch and large-scale productions of SHS products. The latter will require the creation of fundamentally new systems of machines in the form of automatic rotor and rotor-conveyer lines.

Materials for space engineering will undoubtedly attract the interest of researchers in the twenty-first century, not only from the standpoint of fundamental research in the field of zero-gravity physics but in the first place from the standpoint of the organization of large-scale production of products in space, if it is unprofitable on earth. However, the number of such materials is still limited. Primarily, they include single-crystal gallium arsenide with improved stoichiometric composition for the creation of novel high-speed semiconductor equipment. Very expensive products required in low amounts can be produced in space too. These include the first commercial products obtained in space, for example, monodisperse latex spherical particles used as standard specimens by the National Department for Standards of the USA. The process of electrophoresis used for purifying medicines in the pharmaceutical industry or growth of crystals of special semiconductor compounds for optical electronics or IR radiation sensors is of obvious interest.

If we take into account that the new millennium begins in 2001 and that mankind goes from the epoch of PISCES to the epoch of AQUARIUS, the change in the epochs should lead to a change in the prevalent materials on the Earth. The epoch of PISCES was characterized by the creation of universal structural materials based on IRON, i.e., was, in fact, the epoch of CAST IRON and STEEL, whereas the epoch of AQUARIUS, where cognition is based on intuition and foresight, should become an epoch of essentially intellectual materials.