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FACTORS INFLUENCING THE DEVELOPMENT OF ADVANCED METALLIC MATERIALS

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Abstract – Advanced metallic materials (AMM's) are man made heterogeneous materials utilising significant portion of knowledge and thus offering unique properties. They are essential especially for components working in extreme environments, particularly characterised by a combination of thermal loads, physico-chemical attack and resulting complex mechanical loads. Therefore they play indispensable role in all key technologies and thus significantly affect the future of every modern society. The development of reliable AMM's with excellent performance is very demanding and laborious work, which is influenced by many objective or subjective factors, including societal needs and political decisions. Modern approaches used for manufacturing of AMM's like nanostructuring, making of composites or novel structures still exhibit a lot of uncertainties. These factors together with challenges and opportunities are briefly discussed in the paper.

Keywords: advanced materials, metals, nanostructure, composites, foams

1. INTRODUCTION

The entire evolution of humankind is inseparable wedded with materials. The human existence is hardly conceivable without them; the products made of materials are unavoidable to ensure food, to protect body from unsuitable weather, or to defend humans from their enemies. Moreover, the materials are again needed for making the tools for the manufacturing of these products. The role of materials in human history is so important that even ancient periods were named according to their representative materials; thus we had Stone Age, Bronze Age or Iron Age. Each period was over, when new - more advanced material- appeared.

Now the era of dominance of particular material is relatively very short and cannot be considered as significant from historical point of view. Nevertheless this is not a sign, that the materials would recently play less important role in our society; just on the contrary - our further development without new materials is still more inconceivable. The high performance materials are the basis for all key technologies and thus the future of every modern society [1]. In our dynamic and competitive world we must meet demands for better quality of life, while reducing our dependence on natural resources and the burden we place on the environments. There is no escaping the fact that the breakthroughs for achieving these goals will only be made through substantial investment in fundamental research in material science [2].

1.1 What are advanced materials?

New materials appear almost every day and though one could anticipate, that this is a good reason for them to be "advanced" this feature alone seems to be not sufficient from today's point of view. Therefore more precise definition is needed.

Advanced materials should be man made. The natural materials, even though recently discovered, cannot be considered, as really new, advanced could be only their new use. Advanced materials should further exhibit increased performance or another benefit(s) extending the possibilities of existing materials or removing their drawbacks. Consequently, advanced materials must contain a significant portion of scientific knowledge, which nominate them into this category.

Contrary to the past, when the search for improved materials was characterized mostly by the use of empirical and trial-and-error methods, the development of today's advanced materials should be predominantly governed by enhanced understanding of fundamental processes. "Bottom-up" approach supported by highest level of knowledge makes a tool for development of materials possessing desired package of properties without excessive developing time and cost.

1.2 Why still metals?

Although the portion of metals in recent advanced material pool is slightly decreasing, metals will further play indispensable role in future products, because of following reasons:

- In comparison with plastics, metals possess almost one order of magnitude higher elasticity modulus, which leads to significantly higher stiffness of metallic structures at the same weight as in a case of polymer ones. Their strength is high over wide range of temperatures; they conduct heat and electricity, they do not significantly weaken under UV or other radiation.
- In comparison with ceramics, they are more ductile and thus tolerant to sudden fracture, which can have fatal consequences. They toughness and reliability in long-term exploitation is superior among all materials. Very attractive is the forming possibility, which assures lower manufacturing and also product costs.

- Moreover metals are materials with the best-developed recycling concepts. Repeatable use of them will save natural resources, energy and reduce excessive waste and pollution.

Of course the use of metals is accompanied also with some inconveniences. If compared with plastics and ceramics the metals are relatively heavy. Therefore only light-metals (Al, Mg, Ti and their alloys) can potentially bring profitable performance in lightweight construction. On the other way, high strength, elasticity modulus and sufficient ductility of advanced steels enable manufacturing of strong thin-walled structures, which can also be beneficial in this field.

Another problem is corrosion, although its detrimental effects have been already partially reduced by developing of new alloys with precisely limited amounts of corrosion initiating elements (e.g. HP magnesium alloys) or by novel coating techniques.

Serious drawback of metals is the possibility to speculate with their prices at the bourse, which brings a lot of uncertainties into the calculation of product's economical viability. However the large added value, typical for recent advanced metallic materials, considerably diminishes also this fear.

2. FACTORS STIMULATING THE DEVELOPMENT OF AMM

2.1 Objective factors

There are several factors stimulating the development of advanced materials. First group of them comprises objective socio-economic needs, generally requiring increased performance of materials, better design, reduced costs or impacts on environment. These requirements can be divided into following categories, whereas typically more of them are acting simultaneously:

Technological requirements deal with improvement of material's performance, mechanical property to weight ratio, resistance to corrosion, assembly, joining and surface quality or with ensuring of special properties together with existing ones (e.g. radiation resistance, damping, etc.). The concurrent special combination of apparently contradictory properties (e.g. good thermal conductivity and controlled thermal expansion) is always welcome.

Economical requirements usually comprise reduction of manufacturing cost (use of cheaper constituents or technological approaches), improving of quality and reliability of production technologies (elimination of rejected parts, reduction of energy) or enhancing of mechanization and computerization to avoid both high personal costs and uncertain "human factor".

Safety requirements are directed towards reduction of toxicity, possibilities of dangerous events (e.g. fire, explosion, destruction by high electric current impact, etc.)

Environmental requirements include ensuring of closed life cycle with full recyclability, reduction of waste and pollution, saving primary natural resources and energy, avoiding of toxicity and impact on health, etc.

2.2. Subjective factors

Second group are subjective factors motivating scientists to develop advanced materials and industry to manufacture them. They comprise strategic political decisions, economic competition on the market, or simply scientific curiosity. In distinction to objective factors from the first group, which generally valid for the long time, these motivation criteria are permanently subjected to changes according to political and economical situation. Unfortunately, these criteria are more powerful, because they define financial support and thus dictate further orientations in the development and manufacturing of AMM.

As the development and application of AMM usually takes several years, long-term projects assuring long-term financial support are necessary. Long-term projects in the field of AMM are relatively risky for industry, because the first benefits are usually expected after couple of years, often at different marketing situation. The scientific curiosity itself without adequate financial support is not sufficient enough for serious development to application. Therefore the main stimulus for the development of AMM comes from open government or similar funds according to accepted political priorities.

Political priorities also change during the time. Until the end of "cold war" at about 1975 the main motivation for the development of AMM was the competition in military sector or in exploration of the universe, aiming to increase the power or prestige of one or another side. Because of the character of this competition the research was performed strictly nationally in closed and relatively small groups under strong restrictions concerning publication of results and transfer of knowledge. The positive result of missing collaboration was the development of diverse technological approaches and variety of materials for certain application, thus creating valuable knowledge for later use. It must be noted, that the costs for the research didn't play a primarily role in this time.

In the next period (until about 1995) the main objective determining the development of AMM was an improvement of industrial competitiveness. Due to the globalisation effects the research was more international and open. The economical viability of the development became most important. This resulted in concentration on economically attractive materials; the research projects were shorter with lower portion of basic research. Number of basic research projects oriented to the development of really new advanced materials was reduced and the knowledge gained in previous era was thus almost completely exhausted.

Political decisions concerning research priorities are nowadays oriented towards "societal" needs, aiming to improve quality of life (increase safety and comfort) and reduce negative impacts on both employment and environment. The role of materials science, especially fundamental research, is reincarnated, integrated long-term project are adequately supported at least in selected topics and worldwide (European) collaboration is welcome [2]. This provides promising starting position for new era of AMM.

2.3. Supported research priorities

Political decisions concerning research priorities, which will be supported, are of course affected with certain degree of subjectivity and may not be always accurate. Then there's is a danger that the scientific community will move its interest towards particular topics (because of excessive favouritism) and other important themes remain underestimated (e.g. gigascience on nanosize [3]). However, it is reasonable to expect, that the inappropriate selection of priorities will be accommodated by sensible behaviour of majority of scientists.

The strong support concerning AMMs is expected in [1]:

- Advanced process engineering
- Multiscale modelling of structure-behaviour relations (on nano-micro-macro scale)
- Understanding of phase transformations
- Interface science and microstructure design (corrosion, heat resistance)

Interdisciplinary character comprising metallurgy, physics, chemistry, biology, mathematics and informatics will be required to obtain:

- Lighter, stronger, stiffer and more affordable products
- Failure tolerant material systems
- New design of structural parts (wider load distribution almost up to material limits, less framing, etc.)

3. CHALLENGES AND OPPORTUNITIES

The engineering materials are conventionally distributed into classes (e.g. metals, ceramics, plastics, composites) according to typical properties, which also predestine their applications. The utilisation of metals is indispensable in:

- structural components for high temperatures with high fracture toughness (more than 20 MPa.m$^{1/2}$[4])
- structural components with excellent stiffness to weight ratio, long term endurance and sufficient tolerance to fracture
- functional components with specially required physical properties (e.g. thermal or electrical conductivity, magnetism, etc.)

A major challenge of today's top-end products and systems is their performance in very demanding operational conditions. The environment in which materials have to operate is often characterised by a combination of thermal loads, physico-chemical attack and resulting complex mechanical loads. The possibilities to improve properties of metals by "traditional" strain hardening or alloying with subsequent thermal treatment are almost exhausted and new classes of metallic materials are therefore needed for such operating conditions. These AMM are tailored to obtain required properties using modern approaches, which allow full exploitation of the advantages of metals while avoiding their weaknesses.

Among others, these approaches comprise nanostructuring [5,6], making of metal matrix composites [7, 8] or making of novel structures like metallic foams [9] (see table 1). Al these approaches have own challenges and opportunities; to meet them is the only way how to make AMM's ready for efficient application.

Table 1. Effect of various approaches on properties of metals

property	alloying +HT	nano-structuring	making MMC's	Foaming
density	**o**	-	+-	-
strength	+	+	+	-
ductility	-	+	-	-
stiffness	**o**	**o**	+	+
toughness	-	+-	+-	-
fatigue	+-	+-	+-	-
corrosion resist.	+	**o**	-	**o**
creep	+	-	+	-
conductivity	+-	**o**	+-	-
magnetism	+-	+	+-	**o**
thermal expansion	**o**	**o**	+-	**o**
machinability	+-	-	-	**o**
formability	+-	+	-	-
joinability	+-	-	-	-
recycling	-	**o**	-	**o**

\+ *property increases* - *property decreases* **o** *no notable effect*
+- *depends on combination of constituents (possible tailoring)*

3.1 Nanostructuring

Nanostructuring is an approach based on the control of materials structure nearly at the atomic level, which can lead to dramatic changes in material's properties; the most striking example being the graphite and diamond structure of the carbon [6]. Metallic materials (with exception of special metallic glasses) possess crystalline structures, i.e. their atoms are arranged in a crystal lattice and form grains of the size of some thousands lattice parameters. The grains are separated by boundaries where marked difference in the metal structure occurs. At these boundaries especially the regular atomic structure is markedly modified, which leads to changes in inter-atomic spaces and changes in numbers of neighbouring atoms, etc. The difference between the structure inside the grain and in the grain boundaries increases with decreasing orientation of the adjacent grains (high angle boundaries). In case of sufficient volume fraction of atoms belonging to grain boundaries it is possible to speak about "double phase" material, in which one component is formed by the arranged crystalline phase and the second component are the grain boundaries. These two "phases" have markedly different properties and so the increase in the portion of grain boundaries can markedly influence the bulk material properties. It is natural that the volume fraction of grain boundaries in material increases with decreasing grain size. The common metallic materials have grain size of the order of a few micrometers. In this case the volume fraction of atoms in grain boundaries is negligible. However, if the grain size is reduced to a few nanometers the number of atoms in the boundaries dramatically increases (to 50 % for 3 nm, to 30 % for 10 nm, however only 3 % for 100 nm grain size) [6]. Thus with grain size decreasing under 100 nm a qualitative change in deformation behaviour of metal can be expected (e.g. the role of dislocation in plastic deformation is dramatically reduced). The immense importance of amount of grain boundaries on materials properties has been already shown by the preliminary experimental results: so it was confirmed a fivefold increase in palladium strength due to decrease of average grain size from 50 nm to 12 nm; similar results have been reported for AlTi20, CuNb20, CuV18 systems [6, 10]. As the strengthening is obtained by "making finer grains", it is possible to prepare high-strength materials also from pure metals, while other properties are retained, especially good electrical and thermal conductivity, thermal expansion, biocompatibility (e.g. for pure titanium), etc.

The atomic density on the grain boundaries is usually lower than in well-ordered crystals. The high volume fraction of grain boundaries therefore markedly increases the diffusivity at the boundaries, which has important influence on plastic properties of the metallic material – it is possible to shape the material at lower temperatures and at higher speeds, at increased temperatures even super plastic stage can be obtained. Hence nanostructured bulk metals in this way furnish potential for removal of the "everlasting compromise" between strength and plasticity.

The current fundamental problem in the scope of world research on this topic is the preparation of fine graded metallic materials in amounts and thickness, which would enable practical industrial application in machinery and other structures. Two main approaches are currently used:

"Bottom up" approach uses ultrafine-grained powders or thin ribbons prepared from molten metals by suppressing the grain growth via rapid solidification (Fig.1). They have to be compacted to make them suitable for structural purposes. During compacting a certain level of shear strain must be reached; therefore compacting is usually performed by extrusion and often at elevated temperatures to decrease the materials flow resistance and promote yielding. However increasing temperature can lead to the excessive grain growth (above 100 nm) with the consequent loss of expected material properties. The compacting method, which does not result in coarsening of initial fine grains, is still a challenge [11]. Promising way is the use of aperiodically crystallised powders or ribbons consisting of relatively large quasicrystals in amorphous or fine-grained matrix. Quasicrystals have a portion of atoms covalently bonded to each other, which gives them unique mechanical properties (e.g. very good stability at higher temperature, high strength and sufficient ductility) [12].

"Top-down" approaches are based on destroying of originally coarse grain structure by severe plastic deformation (true strain > 10). These large values of deformation are obtained either by multiple drawing or extruding of the initial material [10,13]. In parallel a rather large reduction of the original cross section occurs (the ratio is more than (150:1). This practically leads to the result, that the nanostructure is obtained in thin wires or thin strips, which are again not well suited for structural applications and the compacting brings the same problems as mentioned above. The alternative to traditional drawing and extruding are the newly developed methods, where no substantial change in original cross section occurs, especially the method of equal channel angular pressing – ECAP [14]. The angle between the input and output channels in the pressing tool furnishes intense shear deformation without changes in external shape of the original precursor. This approach enables repeated pressing in the same pressing tool, during which the originally coarse grains are continuously being refined due to accumulated plastic deformation. The rotation of the precursor after each pressing operation enables shear deformation in different directions and in this way it is possible to prepare isotropic nanosturucture with high angle grain boundaries and without any marked texture. This technique has been intensively developed world-vide during last five years, because it is especially suitable to be applied in a relatively simple way for large-scale industrial production. However, also this technology has some drawbacks [15]:

- a limit (often above 100 nm) always exists, at which the further reduction of grain size is ceased
- the resulting structure is extremely unstable (at higher temperatures an uncontrollable increase in grain size accompanied with loss of required properties occurs)

Therefore the challenge is to stabilise the grain boundaries either thermodynamically or by strengthening them via proper inclusions.

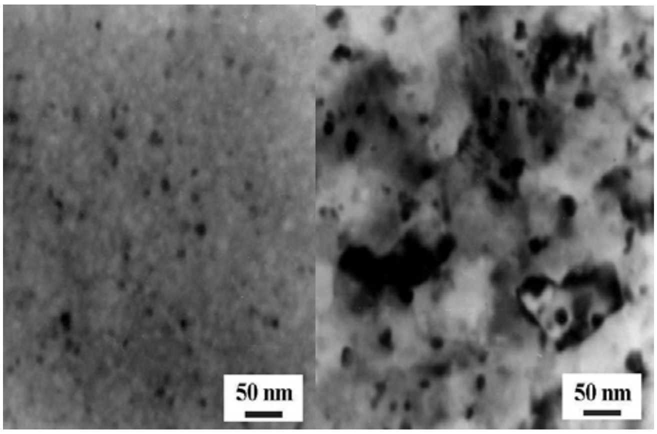

Fig.1. Structure of partially crystallised amorphous AlFe7Nb3 alloy after heat treatment (left 30 min 300°C, right 30 min 420°C)

3.2 Metal matrix composites

Metal matrix composites (MMC) are heterogeneous materials, in which percolating metallic matrix contains additional, preferably ceramic, ingredients. They are made to combine attractive properties of constituents and reduce some of their drawbacks. In distinction to nanostructuring, making of composites provides also the possibility to increase stiffness-to-weight ratio and to tailor special combinations of physical properties (e.g. high thermal conductivity and controlled thermal expansion) in one material. MMC's possess higher toughness than ceramics, and better structural stability, wear and heat resistance than plastics. These are the positive factors attracting the interest of industry in this class of materials. Moreover, changing of natural physical properties of metals requires considerably higher level of knowledge and it is therefore curious and challenging also for many scientists. In spite of this, MMC's have still not been used widely in commercial applications. The main factors limiting the broader use of MMC's are [16]:

- high costs of reinforcing constituents, especially fibres
- still unsatisfactory properties of reinforcing elements
- complicated and thus expensive processing
- insufficient reproducibility of the properties
- more complicated secondary processing (forming, machining, joining, coating)

- difficult recycling (sometimes even missing concepts)
- lack of reliable models and data for prediction of properties, simulation and modelling (realistic links must be established between structure and performance)
- conservatism of designers (they are not willing to redesign the structure in order to be MMC's familiar)

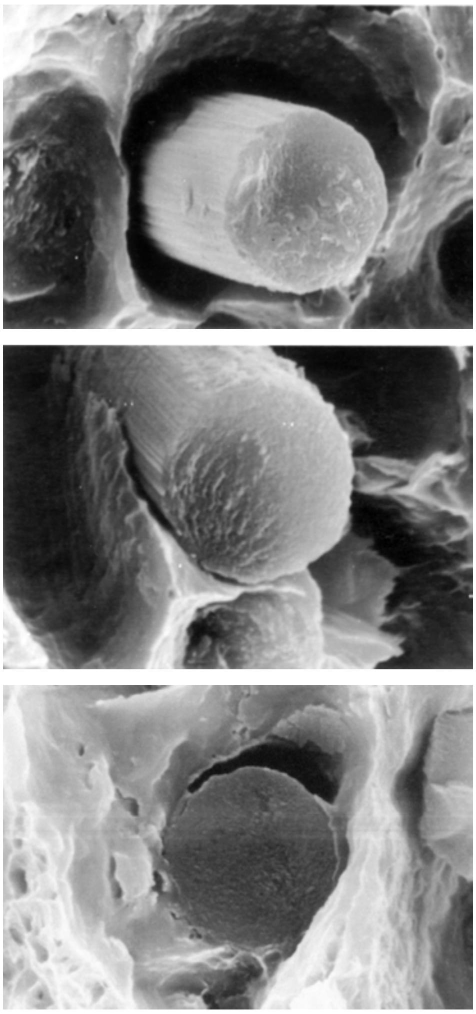

Fig.2. Effect of interfacial strength on the fracture mechanism in short C-fibre reinforced Al composite after annealing at 600 °C. (from the top to bottom: not annealed, 60 min., 600 min, 3000x)

The most serious uncertainty concerns interface between metallic matrix and reinforcing phase, because the composite's constituents are almost always chemically and physically incompatible. Chemical incompatibility leads to creation of interfacial phases with hardly predictable properties, which usually considerably differ from the properties of original constituents. The overall performance of composite is radically affected by the presence of these phases (they influence load transfer from matrix to reinforcement, control displacement and stopping of cracks, weaken corrosion resistance, etc. – see also Fig.2.). Physical incompatibility (e.g. large difference in elastic moduli or in coefficients of thermal expansion) may result in excessive internal stresses sometimes leading to distortion of components geometry or premature fracture under "safe" loads.

Better understanding of the processes in the interface and their controlling is therefore most important challenge for composite makers. Development of cheaper manufacturing techniques will certainly also bring considerable benefits for wider acceptance of this class of AMM's.

3.3 Metallic foams

Metallic foams are really strange AMM's; they consist of percolating metallic alloy in which high volume of gas (usually air) pores are uniformly dispersed. The pores cannot improve the properties of metals at all, nevertheless metallic foams possess a set of unusual properties (they are crushable, exhibit a plateau stress if compressed, change the Poisson ratio on deformation, etc.). The excellent combination of high stiffness and low weight is a primer advantage. In addition the cellular metals absorb high impact energies regardless of the impact direction, are highly efficient in sound absorption, electromagnetic shielding and vibration damping. It is obvious that the properties significantly depend on the porosity, so that a desired profile of properties can be tailored by changing the foam density. This is one of the most attractive features of these remarkable materials. In fact, most of the individual foam properties can be achieved also with another materials, sometimes even more effectively. However, metallic foams offer several (apparently contradictory) utilities with one material, which is very promising from the cost point of view [17].

In spite of these benefits, the material has not been put into the large commercial production up to now. The main problem causing this surprising reality is inappropriate design of foam applications. Several factors are responsible for this:

- reliable calculation approaches are missing
- foam's properties are unsatisfactorily defined
- foam is not able to reliably withstand tensile stresses

In case of metal foam it is really difficult to distinguish between material and structure. If the foam is material, it is very problematic to define geometry independent material's characteristics (for instance the strength or elasticity modulus); if it is a structure made of certain metal it is almost impossible to define its stochastic cross section.

Because of the low reliability to withstand tensile stresses, the foam is typically used as a filler or space holder in various hollow components or sandwiches and its main role is to increase inertial moments of initially hollow cross section. Foam filled components possess thus increased stiffness and exhibit higher resistance to buckling. However, the utilisation of foam insert considerably increases the weight of original part, and of course, its costs (cost and weight of foam insert are added to those of original profile).

The challenge for designer is to use metallic foam as load bearing materials without need to combine it with bulk profile. This will be possible only if potential foam component is redesigned in a way, which mostly avoids tensile loading of the foam. The utilisation of reinforcements similarly as in a case of reinforced concrete seems to be very helpful in this case (see Fig.3) [18].

Fig.3. Beams made of aluminium foam after buckling (left fractured plain foam, right buckled reinforced foam of similar weight)

3. ECONOMICAL VIABILITY

There is no doubt, knowledge based AMM's are usually much more expensive than traditional materials. Their high price comprises notable portion of research and development costs and of course high costs due to complicated (also advanced) manufacturing. AMM's are therefore applied only in niche-applications, large scale production is still a challenge. The economical viability is the main factor influencing their broader penetration into the market; the unique properties play unfortunately only secondary role. The way out of this situation is the development of cheaper manufacturing techniques. It is often very difficult if even possible to simplify the technology, on the other hand the manufacturing costs can be effectively reduced by using of tailored-to-purpose machinery instead of expensive universal equipment, and by high level of mechanisation and computerisation instead of expensive manual work. This will additionally radically improve the quality and reproducibility of the properties of AMM's. However, this way requires large investment and can be accomplished only if large-scale production is anticipated and this is viable only if manufacturing cost are low and thus we are again at the beginning.

This is a challenge for potential manufacturers and end-users. Although very risky, the decision about large-scale production must be made; otherwise the AMM's remain ever in niche-market.

It should be noted, that in a case of AMM's the significant portion of relatively high R&D costs are covered by open funding via granting systems – decision making authorities (politicians) simply accept societal needs and support the development of AMM's. However, financial support for bringing these materials in large-scale production, though very important, is still lacking.

4. CONCLUSIONS

Advanced metallic materials form the class of man made, knowledge-based materials with unique properties, which make them indispensable for future progress of almost all key technologies. Their development is mostly influenced by the decision-making authorities, which define the funding of the research in this field.

The variety approaches has been developed aiming to improve properties of traditional metals and some of them are already successfully applied. The high manufacturing cost and unwillingness of designers to fit the existing structures to AMM's still create the main disincentives to broader utilisation of these remarkable materials.

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