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MECHANICS OF INTELLIGENT MATERIALS

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Successive discovery and capability to manufacture elementary structural materials marked the stages of development of civilization. After Stone Age, Bronze Age, Iron Age we are at present in the "Composite Age" and on the threshold of a new era of intelligent materials. The aim of the present paper is to define clearly what is understood under the concept of intelligent materials, which may be regarded as a particular case of more general concept of the intelligent structures. On the base of the selected representative literature it is intended to provide a general overview and definitions concerning the concept of intelligent structures, and intelligent materials in particular within the context of mechanical sciences. The paper is to serve as stimulus for new research and innovations as well as to indicate the problems arising with this new promising field. Different aspects of intelligent materials will be discussed; namely, their specific features, types of utilized physical effects, and most serious limitations. According to the commonly accepted view, the key features simultaneously present in any intelligent material are combined properties of sensing, actuating and controlling. The key target in development and application of intelligent materials is lowering total life-cycle cost of various engineering structures. This is attained by increased functionality and performance, simplification of design and manufacturing, and facilitation of structure maintenance and decommissioning.

Key words: smart materials, shape memory alloys, piezoelectrics, intelligent structures, composites

1. Introduction

The countries strive for the wealth and quality of life of their communities. Development and proper maintenance of the state infrastructure in the form of technical installations and facilities for distribution of people, goods, energy and information are determinants of the country well-being. All these infrastructural systems are composed of many material elements with unique properties. However, these material elements act in synergy operating together as a specific system. Always, when a particular target is attained the resources by which the task is fulfilled are limited. There are limitations imposed on time, money and quality of service. In order to address particular issues listed above the so called management technologies have emerged, which allow for reduction of necessary time, needed money or increased quality of particular services. These led the engineers to the so called "whollistic" approach. Very often we hear about total quality management, total design, etc. The key factor in here is the efficient use of limited resources. For a long time people have been using, and they still do, specific materials for specific purposes. That I believe, can be hardly changed. However, the specific physical, mechanical, electrical, chemical properties of materials, raw (not profoundly transformed in technological processes) started to be insufficient. Very often in modern engineering the materials are necessary with characteristics of quite contradictory nature. For example, during the production stage we require easily workable materials, which, however, in the operation time must be hard and wear resistant. This led to the production of composites with their unique properties. Not only the structures are engineered at present but the materials for this structures as well. A moment of reflection on the biological solutions engineered by nature leads to the conclusion that in some respect the intelligent creatures like a man, with comparatively little effort and time in comparison to the other less intelligent creatures, won the domination in its environment. Hence, man must have used his resources much more efficiently.

When we search for the definition of what *intelligent* means in any popular dictionary we will find the definition similar to this "intelligence – 1. ability to understand surrounding circumstances and to find suitable purposeful reactions...". Though, such capability to the full extent is at the moment reserved for living creatures. There are works conducted on particular topics contained in this definition in a separate manner. For example, neural networks seem to have quite extensive capabilities for learning and capturing the key relations between intervening factors while shape memory alloys or piezoelectric ceramics can sense and react to altering environmental conditions. Adjective *intelligent* is quite often used interchangeably with adjective *smart* within the context of structures and materials. It can be stated that expressions *intelligent materials* and *smart materials* are synonyms in the context of technical sciences. What then is understood under these terms. We speak about an *intelligent structure* or *intelligent material* when it can purposefully *adapt* its behavior to changing environmental conditions (see Koval et al., 1995). Please note, that the word *understanding* is not present in the definition of intelligent structure or intelligent material. The above definition tacitly assumes high scale of the system integration, as is opposed to popular image of an *intelligent structure*, i.e. that it is a structure with many attached sensors and actuators whose operations are coordinated by a linked control system in such a way, as the sensors output signal is transformed by the controller and sent to the actuators so that undesirable responses of the structure to external conditions are diminished and desirable responses enhanced. Whenever adaptation enters the sequel the target of this adaptation process must be clearly defined and, in fact, usually a material or structure (intelligent or not) must be adequately designed for this particular purpose. Usually, some additional constraints must be satisfied as well. Intelligent structures or intelligent materials allow one to accomplish a particular goal while observing required constraints at a lesser effort or speaking slightly differently more efficiently than conventional ones. Increasing competition forced different companies to search for some other techniques of development beyond strictly technological one in order to win the technological edge. The word *total* started to play an important role in here. Engineers have to design their products having their life-cycles on mind. Only such an approach allows one to cut production costs, speed up delivery times, and increase product quality. This issues are addressed by such management technologies as: value engineering, total quality control, total maintenance, industrial engineering. They in a loop back give a seed for further development of basic technology.

When the material is multifunctional by its very nature or its operating envelope may be eminently increased at a small increase of the production cost, then the cost of total life-cycle of the product may be notably reduced (see also [16]). The research effort into new engineering materials with exceptional properties led to discovery of materials such as piezoelectric ceramics, shape memory alloys, temperature and electrically responsive polymers, magnetostrictive and photostrictive materials. These materials are naturally predestined to be used as intelligent materials to create intelligent structures. The difference between intelligent structure and intelligent material is worth explaining. Intelligent structure is designed to possess specific adaptive functionality on macroscopic level and it is rather an integrated system of materials usually consisting of many elements and many materials [16]. When the adaptive functionality (sensing, controlling, actuating), not necessarily as complex as in the case of intelligent structure, is present in the material by its very nature or its special design (composites) then we speak about *intelligent* or *smart* material. Special production techniques are being developed at present to produce *intelligent materials*. Novel production techniques of fiber composites, laminates, woven-fabric composites are at present available on the one side. And on the other side techniques enabling production of the so called nanomaterials, physical, e.g. gas-phase condensation approach (cf Ashley, 1995), ionized cluster beam method (cf Takagi, 1996), laser ablation (cf Pelton et al., 1994), and chemical, e.g. solution-spray conversion process (cf Ashley, 1995) are at present available. Development of those production technologies gives the opportunity to design and manufacture intelligent materials with exceptional properties. The research, development and practical application of intelligent materials can greatly enhance the overall level of technical products.

2. Concept of intelligent materials

In Section 1 a general background has been discussed in which intelligent materials can find their natural niche. We have already said that in order to use the *resources* efficiently, they have to possess naturally or be designed in such a way as to possess three functional capabilities; i.e., sensing, actuating and controlling. This functionality is to be achieved in the material itself thus making it intelligent material by making use of specific material properties and perhaps adequate layout of homogeneous component materials on a smaller length scale. For example, the shape memory alloys naturally respond to thermal and mechanical stimuli. In the case of composites or nanomaterials more than one generic material is involved. They can only be treated as homogeneous materials on macroscale. The specific material properties of each component material are then exploited together with their special mutual arrangement. In principle, at least two physical fields will be involved in order to have an intelligent material and usually more will be employed with their mutual coupling being a significant factor. Classification of various phenomena resulting from coupling of different physical fields is given in Table 1 (see also Kelly, 1989). Although the present paper is devoted to investigation of intelligent materials within the context of mechanics we can not concentrate only on the couplings with mechanical fields.

Table 1. Classification of some phenomena resulting from different physical fields coupling

Inducing field ↓	Response field →					
	Mechanical	Thermal	Electrical	Magnetic	Optical	Chemical
Mechanical → (force/ deformation)	elasticity	latent heat of stress induced phase transition, piezoresistivity, piezocaloric effect	piezoelectricity, piezoresistivity	piezomagnetism	stress birefringence, triboluminesc.	stress induced chemical reaction
Thermal → (temperature heat flux)	thermal expansion, stress induced phase transformation (heat effect)	thermal conductivity	thermoelectricity, temp. dependent resistivity, thermo-luminescence	thermo-magnetism	temperature dependent transparency, thermoluminescence	soret effect, temperature induced chemical reaction
Electrical → (field/ current)	electrostriction, electroviscosity (suspension)	Joule effect, Peltier effect, temp. gradient effect	dielectric polarization, Hall effect	direct generation of magnetic field	electroluminescence, absorption by galvanic deposits, cold emission of electrons, Kerr effect	electromigration, galvanic deposition
Magnetic → (field/ polarization)	magnetostriction, magnetoviscosity (suspension)	adiabatic demagnetisation, temp. gradient effect, magnetoresistance, Joule effecte	magnetoresistance Hall effect, induction of voltage	magnetic susceptibility	Farraday effect, magnetooptic Kerr effect, deflection of charged particles	
Optical → (light)		heat due to light absorption	photoconductivity photoemission, photoelectro-magnetic effect ionization	photomagnetic effect,	fluorescence, scintillation	light stimulated reactions (photosensitive layers)
Chemical → (chemical composition)	osmotic pressure	heat of chemical reaction	dependence of T_c on ferroelectric composition	dependence of T_c on ferromagnetic composition	chemoluminesce-nce	

There might be combined cross-effects. Some examples are given in Table 2 (see also Kelly, 1989).

Table 2. Complex coupled effects in composite materials

First coupled effect		Second coupled effect		Final effect
Stress induced transformation	+	Temperature dependent resistivity	=	Stress induced resistivity
Piezomagnetism	+	Magnetoresistance	=	Piezoresistance
Piezoelectricity	+	Kerr effect	=	Polarization by mechanical deformation
Magnetostriction	+	Stress induced birefringence	=	Magnetically induced birefringence
Photoconductivity	+	Electrostriction	=	Photostriction

The inspiration for an entirely new class of materials, i.e. intelligent materials comes from the nature with its capability to adapt a structure, shape and properties according to the changing environment onditions and the current state of the structure. Analogies to nervous, muscular and cerebral systems are obvious. Let us investigate a simple example in here. A structural element in the form of a rod made of composite with NiTi fibers (NiTi is a shape memory alloy) is working in the structure, which during start up must pass the resonance eigenfrequency. As this frequency is approached the amplitude of vibrations reaches a specific level corresponding to the critical stress of phase transformation in NiTi alloy. The martensitic phase transformation starts to take place resulting in energy dissipation. This, in turn, results in heating up of the structural element, changing stiffness of NiTi fibers, and changing the resonance eigenfrequency value of the whole structure. The structure in that way can reach the operating range of parameters safely, avoiding excessive amplitude of resonance vibration. This scenario is not far from reality. The NiTi material behaved *intelligently* here. It *sensed* that particular conditions took place, and it *reacted* adequately in order to avoid some undesired situation. Nevertheless, it was the engineer who by purposeful engineering built in the proper *logic* of the material reaction, i.e. the moment when the material reacted. In the case described above that meant a proper selection of critical stress and temperature of the martensitic phase transformation. As this parameters are controlled by chemical composition of the alloy that would not be a very difficult task. However, functional *logic* was very simple in this particular case. In more advanced applications, circuitry built in the material on the nanoscale level might be *necessary. It is worth to underline again the* interplay of different physical fields (mechanical and thermal). The general scheme may be outlined as follows; one type of the physical variables is used for sensing (monitoring) purposes, the other type for reaction (actuating) purposes and still another one for controlling function. Sometimes the functions might be combined. Good example in here, once again, will be shape memory alloys in thermomechanical applications. They have the capability of monitoring varying temperature and at the same time the temperature difference between NiTi element and environment can be used for actuating purposes (no external power supply is necessary).

It has been already mentioned that there is no much, conceptual difference between smart materials and smart structures. The objective is common, i.e., to devise a material system that has capability for autonomous operation to deliver adaptive functionality, maximize performance, and minimize the product life-cycle costs [16]. The main difference lies in the length scale on which this tasks are realized and on which various materials synergistically contribute in order to create adaptive functions. In the case of intelligent structure it will be macroscopic dimensions, in the case of composites the length scale of optical microscope, while in the case of nanomaterials the dimensions one order greater than the single atom dimensions. The research connected with the concept of smart materials and structures is very recent topic as is indicated by the list of international conferences held on the Intelligent Materials and Structures listed by Takagi (1996).

The integrated autonomous behavior of intelligent materials as for the present is rather a target than reality. There is a need for initiation of research programs devoted to the integration of intelligent unit functional components into autonomous intelligent system or intelligent material. Also, there is still a need to maintain the research efforts into development of sensors, actuators, and controls having the aforementioned concepts of integration on mind. Some activities towards such an integration have been already undertaken. The Grumman X29 aircraft may be taken as an example, which makes use of the bending-twisting coupling in such a way that as the loads on an aircraft wing increase, the structure deforms but in such a way that it remains tuned to the aerodynamic requirements (cf Kelly, 1989). The wing is made of composite material. No additionally attached system of sensors and actuators is necessary to change the wing geometry during the flight. All the functionality has been achieved by proper engineering of composite properties changing along the wing (cf Kelly, 1989). Summarizing it can be said that some promising results have been already obtained in the field of intelligent materials and structures.

3. Types and properties of smart materials

In this section some promising materials, notions and technologies will be listed, which after applying the concepts discussed above may be extended in their functionality to create intelligent materials or structures. The properties of materials with encouraging characteristics to be developed to become smart materials must be distinguished from their functional role. The concept of smart materials is quite fresh hence the development of integrated operational characteristics is in its infancy. On the other hand, the development of functional elements used for example in active adaptation is quite advanced. There are already commercially available elaborated sensors, actuators or controllers. However, they are rather treated as separate units of the technical system. In here we shall try to concentrate on those of them, which as their active component materials use those having capability to be extended in their functionality to create autonomous intelligent materials or structures.

3.1. Sensing

Efficient active vibration damping, acoustic attenuation, fire detection, structure *health* monitoring, etc., require data from sensors delivering information on the values of structure state parameters. Sensing capability can be built into the intelligent material (structure) by the use of material which inherently possess capabilities of sensing a particular type of the signal. These include optical fibers, shape memory alloys, piezoelectric materials, active polymers, tagging particles, etc. The list is by no means exhausted.

Optical fibers may be used in a number of ways for sensing purposes. The most simple operation is just transmission of light. Breaks in the transmission of light beam are used for position detection in robotics, detection of intruders in security services or smoke detection in the places where there exist fire hazards. However, more important from the point of view of intelligent materials are coupled effects as it is very important to have more subtle operational tools than zero-one signal. The change in characteristics of light transmission in the optical fibers with the change of some (investigated or monitored) structural parameter is the desired feature. According to [16] use of optical fibers for intrinsic sensing was started by NASA Langley Research Center in 1979 to measure strains in composites. A number of sensors using optical fibers were investigated using interferometric, refractometric, black body and other techniques. The most important advantages of optical fibers are their mechanical and chemical resistance, impunity to vibrations, electrical and magnetic fields.

The shape memory alloys (SMA) are used as detectors of changing stress, temperature or strain conditions. Basic underlying physical phenomenon used for these purposes is the solid-solid martensitic phase transformation. The martensitic transformation in these alloys may be induced by mechanical or thermal loads. Varying mechanical field may induce changes in thermal field and the opposite. This is exactly the effect required for a successful intelligent material. Depending on the SMA operating range of state parameters and the mode of operation it can exhibit large recoverable strains on the order of several percent or force recovery upon heating of SMA element above the phase transformation temperature. At present, two basic groups of SMA are commercially available, i.e. NiTi alloys and alloys on the base of copper with different binary and ternary components (cf Nowacki, 1996; Pelton et al., 1994). Alloys on the base of nickel and titanium are highly corrosion-resistant, have perfect mechanical properties, show very good and stabile shape memory effects, have good biocompatibility what allows for their application in medicine. However, they are expensive and very difficult in processing. Alloys on the base of copper show good shape memory effects, have reasonable price but they are very prone to wear and show little corrosion resistance. Very promising group constitute alloys on the base of iron, first of all, due to their low price. These alloys are corrosion-resistant, and can be much easier processed than NiTi alloys. Their main disadvantage at present is that only one-way shape memory effect with undesirable properties may be obtained for them. The most inviting in the context of intelligent materials is the use of SMA as *active* material built in the composites matrix.

The next promising group constitute piezoelectric materials, which can transform electric field into strain and reciprocally mechanical field into electric signals. The basic physical phenomenon underlying piezoelectricity is interaction of externally applied field with electrical monopoles present in the material and formed by offset location of ions in the crystal lattice of material. When e.g. electric field will be imposed it will pull the monopoles in the desired direction inducing strain in the direction of the applied field. The piezoelectric materials are piezoelectric ceramics such as lead zirconate titanate $Pb(Zr,Ti)O_3$ (PZT), lead lanthanum zirconium titanate (PLZT); piezopolymers such as polyvinylidine fluoride (PVDF); electrostrictive materials such as lead magnesium niobate (PMN) or magnetostrictive materials like Terfenol containing rare earth element terbium [16]. Generally, these materials exhibit a small amplitude of induced strain on the level of a tenth of a percent and this is the most striking limitation of their structural applications. It seems that most widely used for structural purposes are piezoelectric ceramics, which is also driven by their non-structural applications as transducers and in ultrasonic systems. Piezoelectric ceramics have some drawbacks, they are brittle and relatively heavy what imposes limitations on their application to weight conscious industries. The solution to that problems is once again composite, but then, in turn, manufacturing difficulties appear as processing of composite may require relatively high temperature. If the Curie temperature of piezoelectric ceramic will be crossed in the process the piezoelectricity effect will disappear. The answer to brittleness may be found in application of piezoelectric polymers like PVDF [16]. Piezoelectric polymers can be very easily formed into thin films and bonded to the surface of structural elements. Uniaxial films allow for sensing of stresses or deformations in a selected direction while biaxial films allow for measurement of stresses in a plane. Electrical response of such a sensor can naturally with no additional adapters be used for controlling purposes. The sensitivity of PVDF can be used in tactile sensors required in robotics. There are developed composites with polymer matrix; like, polyethylene, polypropylene, polyvinyl chloride, polystyrene, Kevlar with embedded piezoelectric powders. The drawback of polymers is their limitation regarding temperature. The maximum temperature of polymer matrix composites for continuous operation is limited to 400°C (usually 200°C). Piezoelectric composite materials were developed to overcome the brittleness of piezoelectric ceramics on the one side and the temperature limitations of piezoelectric polymers on the other and in that way the operating range of the sensors has been expanded. Interesting alternative for sensing and actuating functionality offer magnetostrictive materials like Terfenol-D. The magnetic domains of magnetostrictors rotate in response to external magnetic field in the direction of the magnetic field lines resulting in geometrical changes of the material. In comparison to electrostricitive materials magnetostrictors are free from the problem of arcing and hence can work in fire hazardous environments. They can be used in biomedicine where it is difficult to insulate e.g. electrostricitve sensor from electrically conducting fluids. Also they have better transformation energy densities when the displacements which come into play are on the larger level.

Tagging is a sensing technique. The technique consists in adding *tagging* particles to a matrix material in order to obtain sensitivity to a particular measurand. In fact, this technique is very similar to production of composite with required properties. As *tagging* particles there are used the materials, which are inherently sensitive to a particular, interesting for engineer signal, e.g. piezoelectric or optically active materials. This technique is a step towards obtaining a distributed sensing system similar to that of the human nervous system.

The potential intelligent materials do not have to be necessarily in the solid state. They could possibly be fluids or gels as well. It is possible to produce electrorheological, magnetorheological or optorheological fluids, which change they reological properties like viscosity or elasticity parameters in response to electrical, magnetic or optical fields. They usually contain micron-sized particles reactive to the field of interest. They are used for damping control, for temperature and current sensing. Polymer dispersed liquid crystals are used as electro active materials.

3.2. Actuating

Materials that allow a structure to adapt to its environment are known as actuators. These materials have the ability to change the shape, stiffness, position, natural frequency, damping, friction, fluid flow rate, and other mechanical characteristics of intelligent material systems in response to changes in temperature, electric field, or magnetic field. The listed above potential intelligent materials posses functionality of sensing. Only some of them have simultaneously actuating capabilities. Very promising in this respect are shape memory alloys. When the need arises (there has been obtained a signal of particular conditions occurrence) the SMA wires can be simply heated by passing of electric current. In response, the remembered shape is recovered or when the structural element is restrained a large recovery force is induced. The drawback of actuation with SMA is that it is dependent on heating and cooling. While the former is quite easily attained the latter process requires usually additional technical precautions or proceeds quite slowly. Hence the response time of SMA actuator can not be expected to be as fast as for example the piezoelectric one, and it can be applied for attenuation of signals with rather low frequency.

The second group of materials which can be used for actuation constitute piezoelectric materials. Applied electrical fields produce maximum strains of $0.2 \div 0.3\%$, which is a serious limitation imposed on their application. Researchers are intensively working on extension of this range. Recently, the so called rainbow actuators have been developed increasing this range to 1% approximately (cf Ashley, 1995). However, when these very small deformations are constrained, similarly as in the case of SMA, very large forces could be generated, which are proportional to the applied voltage.

Next generic materials for actuation are magnetostrictive materials. These materials can produce strains of up to 1.4% in response to the applied magnetic field. They usually find application in the areas where high power is required which can not be easily delivered by electrostatic actuators due to their very small stroke [16].

3.3. Controlling

The last functional feature that is controlling seems to be the most difficult property to implement into the potential intelligent material. For many years there have been performed works targeted at implementation of intelligent control into machines. The adaptive control, neural networks approach, knowledge based and expert systems, information processing methods all of them as one of their scientific goals pose implementation of the features close to those of human intelligence into machines. The same task standing before the people trying to develop intelligent materials, has been already elegantly solved by nature with *bioengineering*. The task in itself, however, consists in implementation of large number of sensors, actuators and information carrying elements into the material not to mention about their sources of power. The nature solved the problem by structural approach. In fact, the hierarchical one, which is totally different from the central processor approach in man made processing centers, i.e., digital computers. It allows to achieve efficiency and reliability. And this, in turn, means savings in the resources. The signals and proper reactions take place on the level which is adequate for them and only when it is not enough there is a problem reporting to the next level of hierarchical structure. Information processing systems implemented into intelligent materials should also possess this feature. The architecture of control processing within intelligent materials will be the crucial factor determining their performance and capabilities. The used hardware elements and control algorithms will be very important as they will determine what is the optimal amount of sensors and actuators. It seems that in order to solve the problem of controlling there will have to be applied the methods used at developing composite materials but on far lower length scale than our macro world. There have recently appeared auspicious techniques, which allow to have hope in that respect namely techniques of production of nanomaterials (cf Takagi, 1996; Ashley, 1995).

4. Areas of application of intelligent materials

When speaking about application of smart materials it is not the question in what branch they can possibly be applied as it is essentially everywhere; e.g., in aerospace, marine, building, transport, automotive, power industry, medicine, telecommunication etc., but rather what problems they can solve. There are two substantial reasons why they could possibly replace traditional materials in certain applications. The first is dictated by the essence of intelligent material concept, i.e. increased functionality, while the second is dictated by their manufacturing methods. It seems, that intelligent materials will have hierarchical architecture, which will be build in on the length scale not only of micrometers but also nanometers. From the structural point of view it seems that techniques used at present for production of composites will be applicable. This gives the opportunity to obtain material properties not met in natural materials, which are not a simple sum of properties of constituent generic materials. It can also be expected that physical properties of the particular phase will be essentially different from the properties of the same phase in the bulk form e.g. it has been recently reported that copper-Monel[1] multilayer with 2-nm periodicity reached 60% of the system theoretical strength (cf Ashley, 1995). However, due to high initial costs and high risk usually connected with a new material the first applications of smart materials will be realized in those areas where performance requirements overcome the economic considerations.

The fundamental role of any material used in structural engineering is to transfer some kind of load mechanical or thermomechanical making the structure useful. However, more and more important are such features of the engineering structure as safety, reliability, quality, life-cycle costs. The answer to this problems could be the concept of smart materials. Such a material can monitor its own *health*, can undertake precautions against undesirable effects, can report on defect or excessive wear of the material, it can report on lack of capability for further safe service. Finally, the emergency states can be detected and impact of negative effects may be reduced. Let us investigate this problems on the example of smart ski, the project recently presented by Ashley (1995). The piezoelectric ceramic sensor/actuator system with a simple analog-logic electrical circuit included delivers the sought enhanced functionality. Any bending of the ski causes that distributed in the ski PZT elements generate electric current. The current is adequately transformed in the logical circuit. The generated strong oscillating electric field is supplied to

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[1] Monel is a nickel-copper alloy

the actuators resulting in quick suppression of externally induced vibrations. They are very quickly canceled out ensuring good control over the skis. The electric current also powers the diode indicator whose flashing is a signal of the system operation.

This example can serve to isolate the functionality, which can be delivered by application of smart materials (see also [16]). Some of these features have been listed below:

- Monitoring and assessment of the state of the operating material; health monitoring (e.g. overseeing the process of composite curing)
- Detection and reporting on material degradation (e.g. cracking, excessive plastic deformation, wear, debonding, etc.)
- Reporting on the need of service or overhaul
- Assessment of remaining life of the engineering system
- Active adaptation of the engineering structure to varying external conditions remaining within the range of operating conditions
- Performance enhancement by reaction optimization
- Monitoring of occurrence and suppression of undesirable phenomena (active vibration control, active temperature control, active stability control)
- Monitoring and reporting on emergency states
- Abridgment of effects of emergency states occurrence
- Optimization of the energy and other resources use
- A matter of further future seem capability for self-repair.

Many of this features are already present on the engineering system level e.g. taking the power plant as a whole but not on the level of individual elements of the system. Implementation of the concept of smart materials will lead to increased reliability, safety, quality, increased performance and lowering of life-cycle costs.

In order to characterize the state-of-the-art of the discussed branch we shall give some examples. The concept of smart materials and structures originated according to [16] from three application problems: vibration control of large space structures, health monitoring of aircraft using fiber optics sensors and active structural acoustic control of underwater vehicles. This initially military technologies at present also diffused to civil applications.

Shape memory alloys are used at present for weldless fastening and sealing tasks. Various types of pipe joints, electrical connectors, fastening elements, hermetic sealings are produced. The SMA actuators are used for reliable remotely activated deployment devices. A special, so called Frangibolt fly, has been developed, which allows for replacement of more hazardous and expensive pyrotechnic release mechanisms. NiTi springs have been used to develop fully automatic cooling system for a truck engine with SMA fan clutch SMA thermostat. SMA actuators are used for gripping purposes in robotics. Overtemperature shut-off valves where SMA fulfilling simultaneously the role of sensor and actuator are produced. Similarly, automatic temperature controlling device for refrigerators has been developed. SMA actuators are used for vibration damping purposes. Finally, NiTi alloy has found broad application in medicine. It is used in surgical instrumentation. There are stents and implants made of shape memory alloys.

Piezoelectric ceramic elements often in the form of composite containing active particles are used as sensors and actuators in structural engineering for the purposes of active vibration control, active and passive dampening, for underwater acoustic control, estimation of motors performance. Piezoelectric materials have also found widespread use as sensors in deformation measurements, in accelerometers, in situ monitoring, etc. PZT and other piezoelectric materials are very useful for damping vibration in order to perform high-precision measurements e.g. astronomical or when actuation with very broad bandwidth is necessary. Flexible composite sensors containing piezoelectric ceramic material in a polymer matrix have been used in acoustic transducers. Further examples of systems using piezoelectric actuators are: positioning and tracking devices, ink jet printer heads, adaptive optical systems, loudspeakers. Recent research is focused on application of PZT actuators to sophisticated control systems to perform active acoustic attenuation, active structural damping, and active damage control. There are also developed electrically active *paints with piezoceramic additives, which are useful for structures with com*plicated shapes for monitoring the state of stress and strain.

A magnetostrictive material, like Terfenol-D is used in those applications where high power is required, not available when electrostrictive materials would be employed, e.g. in low-frequency high-power transducers; high-force motors; high-power actuators. There are also developed active vibration damping systems using magnetostrictive materials.

Optical fibers are used mainly as sensors for monitoring purposes e.g. of the state of composites, like GRP (Glass Reinforced Plastics), which have at present the largest volume of commercial use. They are also embedded for health monitoring purposes in composites like CFRP (Carbon Fiber Reinforced Plastics) which have been very intensively developed for the last fifteen years. Breaks in the light beam are used for precise positioning of objects in robotics applications. Optical fiber sensors are used for temperature measurements. There are research works performed into integration of optical fibers and piezoelectric ceramics in composite materials a step towards obtaining intelligent material. They are also used for investigation of the state during curing of composite materials in order to understand damage mechanisms of composite materials. Fiber optics are examined as magnetic field sensors, dynamic strain sensors, they are used in accelerometers and vibration sensing.

Thin films of polymers are used for real-time control. Pressure sensitivity of piezoelectric polymers has been used in keyboards, touch pads, and other input devices Thin films of polymers have been used in robotics applications, as well.

Electro- and magnetorheological fluids can be used for construction of valves, switches, dosing devices. They are also successfully used for production of adaptable dampers, vibration attentuation systems, smart binders.

5. Engineering of smart materials

The successful implementation of the concept of intelligent materials would not be possible without development of adequate manufacturing techniques. In the case of intelligent materials this would be mainly the techniques applied to production of composites but also those applied to electronic chips production and some other special techniques, e.g. nanomaterials technologies. The knowledge of manufacturing technologies gives the mechanician a good idea about possible failure mechanisms of the material, expected performance and possible properties of the final material, as well as the idea of what factors might be important when modeling the material behavior.

It can be expected that the dominant form of future smart materials will be a composite structure with embedded (in situ architectured) elements securing the functionality discussed in Section 4. Hence composite manufacturing technologies must be carefully surveyed within the smart materials manufacturing context. The manufacturing technology depends strongly on the type of composite. The very definition of the composite is as follows after Kelly (1989) "...a composite material can be defined as heterogeneous mixture of two or more homogeneous phases which have been bounded together. Provided the existence of the two phases is not easily distinguished with the naked eye, the resulting composite can itself be regarded as a homogeneous material...". The internal microstructure of the composite is not determined in this definition and may adopt many possible layouts, i.e. it can take the form of random dispersion of aggregates of some shape in composite matrix, it may be in the form of aligned filaments or random grid in the composite matrix, it may be in the form of continuous laminae. From the point of view of intelligent materials we should expect it to be in the form of some matrix with randomly or orderly distributed sensing and actuating elements connected by a signal transfer grid architectured on micro or atomic level. Hence, production techniques of composites with similar structure should be rather investigated and developed in this context. The aforementioned composite matrix may be metal matrix, polymer matrix or ceramic matrix depending on the working conditions required for the material. The fibers or woven fabrics used in traditional composites as reinforcement in the context of smart materials would have to be replaced by sensing and actuating elements, what does not exclude their secondary in here reinforcing function.

One of the commonly at present used types of composite is the laminate composite where layer upon layer of unidirectional material (with fiber reinforcement) according to requirements for ply profile and fiber orientation are placed. This process in early years of composites manufacturing has been made by hand but now due to their wide application in aerospace industry there are available fully automated techniques with numerically controlled ply profiling or filament winding. The fully automated process seems to be an indispensable condition for successful implementation of intelligent materials without prohibitive cost of the production. In this context it can be imagined that there will be placed one or more load carrying plies then a ply with sensing, actuating functionality and data transfer network, next consecutive load carrying plies according to the needs and requirements. Automatic ply profiling has been enabled by application of broadgood systems used in tailoring industry with two-axis numerical control. However, laying plies into mold is still a manual process, at large. Combination of ply profiling and their placement in the mold into one operation has been achieved in the so called tape-laying technology. At the moment the technology is available for flat elements and very intensive works are conducted to develop it for curved surfaces.

The critical factor influencing admissible operating range and manufacturing technologies applied is the type of composite matrix, which might be polymer, metal or ceramics. The second main factor is the reinforcing fibers. At present only polymer matrix composites manufacturing methods are developed on fully commercial scale due to relative ease of bonding fibers with the polymer matrix. Manufacturing of metal matrix and ceramic matrix composites is at the research and development stage. The reason for that lies in difficulties to obtain good bonding stability of strong fibers of carbon, boron, silica or silicon carbide with metal matrix. The poor wetting of fibers by the metal creates a problem. Also only recent development of refractory fibers promise further progress in these types of composites regarding their intended operating temperatures. The same problems are only more pronounced in the case of ceramic matrix. Mastery of manufacturing technologies in commercial quantities of refractory and oxidation resistant fibers, like, alumina and silicon carbide, silicon nitride increased research and development activity concerning ceramic based alloys.

Manufacturing methods of polymer based composites inseparably depends on the matrix used which might be thermosetting (which irreversibly hardens under temperature increase; e.g., Epoxy resins, Polyurethanes, Formaldehydes-based) or thermoplastic (which are reversibly melt processable; e.g., Polysulfones, Polyketons, Polyether sulfone (PES), modified polyimides), and the fibers (which may be glass, carbon or aramid). There are available the following manufacturing techniques for polymer matrix composites, after Kelly (1989):

hand and spray placement – in this technique chopped filaments or woven rowings are placed into polished mold with the surface previously treated with non-stick agent and then liquid resin is worked into reinforcement by hand with the aid of brush or roller,

press molding – in this technique a composite material is manufactured by molding feedstock in heated male/female tools,

vacuum molding – in this technique chopped fibers or woven rowings soaked with liquid resin is placed on a one-part mold and overlaid by a flexible membrane which next is sealed around the edges of the mold. Then air is evacuated between mold and membrane and vacuum is maintained during the time of resin cure. Hence, the atmospheric pressure is used effectively to consolidate the composite,

autoclave molding – in this technique the component in adequately tailored flexible bag is laid up on a mold of appropriate shape. First, from the bag all the air and gaseous products are evacuated, and then the assembly is put in an autoclave for resin curing time. In the autoclave pressures up to 1.5 MPa may be applied and internal temperature can be raised adequately. This method allows one to manufacture elements with high mechanical integrity,

resin transfer molding – in this technology only fibers or so called preform is enclosed in the mold initially and next resin is injected to fill the cavity,

reaction injection molding (RIM) – this technique differs from the resin transfer technique in that instead of precatalised resins with a long cure time rapidly reacting components are supplied and mixed just prior injection into the mold. This allows to obtain high production rates,

pultrusion – the technology allows for production of profiles with cross-sections prescribed continuously as opposed to the aforementioned methods producing discrete moldings. Continuous rowings are passed through a bath with resin followed by carding plates where the excess of resin is removed. The impregnated fibers are next drawn through a heated die in which resin gels and cures. In the end, the product is cut to a desired length,

filament winding – in this technique fibers soaked with resin are continuously wined onto a former which is withdrawn after resin has cured. Very complex shapes may be produced in this technology as a result of application of automation and numerical techniques.

Manufacturing methods for the metal matrix composites are on laboratory scale rather and are as follows:

liquid metal infiltration – in this technique typically continuous bundle of filaments pass through a bath with molten metal and then through orifice, which shapes the bundle to the required cross-section. The biggest problem in this technique is to obtain a proper wetting of the fiber surface,

squeeze casting – in this technology fibers or other reinforcement is infiltrated with molten metal under high pressure originating from hydraulic press. Sometimes this process is performed under vacuum conditions to avoid oxidation of the fibers,

stir casting and compo-casting – this technology consists in adding reinforcement particulates into vortex region of liquid metal. It may be difficult to obtain a homogeneous distribution of reinforcement due to a difference between fiber and matrix material density. Hence, compo-casting technique has been developed to reduce or avoid this problem. In this technology stirring of the mixture takes place as the metal undergoes solidification,

precursor production – consists in production of preimpregnated sheet that can be used in manufacturing of more complicated shapes. Usually, it is achieved by using continuous monofilament or bundles assembled to required spacing by winding on a drum. The filaments are next coated with metal by plasma spraying, electroplating or with the aid of chemical deposition techniques. The thus manufactured precursors have to be shaped, stacked, consolidated and bonded to make the final product,

consolidation and bonding methods – these methods are used for densification and bonding of precursor material. It is obtained by hot and cold pressing, hot rolling, explosive welding, etc.

Finally, the manufacturing methods for ceramic matrix composites are:

hot pressing of sheet material preforms – in this process first, the so called preforms (initially formed intermediate products) are manufactured from a sheet of unconsolidated ceramic matrix with reinforcement and next these preforms are hot pressed to obtain a final product,

chemical vapor deposition – in this technology fiber preform is infiltrated with ceramic matrix by its deposition from gaseous phase.

It can be easily imagined that all the described above techniques may be applied when producting intelligent materials.

We shall now shortly discuss principles of the main streams of the so called nanotechnologies. Recent research into the so called nanomaterials rapidly reduce the technological barriers for effective manufacturing of intelligent materials. The name "nanomaterials" comes from the length scale of the material structure created in the manufacturing process. It means that in these methods it is possible to control the arrangement of matter on atomic level. In general, nanostructured materials are composed of clusters, filaments or layers of the characteristic dimension of 1 to 100 nm. It is, at present, possible to manufacture multilayered materials of the 2 nm periodicity (see e.g. Ashley, 1995 or Takagi, 1996). There are techniques, which allow one not only to dream about smart materials. They can also create an intermediate step towards intelligent material technology as high performance surface layers can drastically improve properties of now conventional engineering materials.

The manufacturing processes can be conveniently divided into the chemical and physical ones. The chemical are, e.g. sol-gel methods where a thin film is obtained by evaporation of the solvent from the sol in order to obtain thin film gel, e.g. through solution spray process. Another group of chemical methods are the Langmuir-Blodgett techniques where the adsorption phenomenon is used in order to obtain the required thin film on adsorbent surface. The disadvantage of chemical methods is that it is usually hard to avoid contamination with the solvent or other chemically active element of the process.

The physical processes of thin film depositing which may be and are used in order to obtain structure of nanomaterials are, e.g. vacuum vapor deposition, sputtering, laser ablation, epitaxy methods or ICB (ion beam clustering; see Pelton et al., 1994; Takagi, 1996). In conventional method of vaccum vapor depositing the whole process takes place in technical vacuum. Crucibles containing component materials are heated, e.g. using electric current in order to create their vapors. Evaporated molecules deposit on a substrate forming thin film. A variation of the technique, i.e. heating crucibles alternately allows for manufacturing of multilayered nanostructure. In this method it is easy to satisfy contamination free conditions due to high vacuum but when alloyed films are manufactured it might be difficult to control the required composition due to differences in vapor pressures of component materials.

The sputtering process takes place in a chamber with inert gas atmosphere. A strong electric field is generated in one direction of the chamber (usually horizontal), in which plasma is maintained. The plasma is composed of particles knocked out by inert gas from the target made of the material to be deposited in the form of thin film. The transport of target particles takes place in the direction perpendicular to that of the electric field. They condense on the substrate placed opposite to the target. In this method it is hard to avoid contamination by the inert gas used in the process. The advantage of the method is that it is not difficult to control precisely composition ratio of the thin film.

The method, which allows one to control precisely composition and avoid contamination is laser ablation method. This process takes place in a vacuum chamber. Laser beam strikes the target made of material to be deposited creating plume of excited atoms. They deposit in the form of thin film on a substrate also placed in the chamber. The deposition, in here, takes place not by thermal but by photochemical processess. Hence, deposition rate is not sensitive to vapors of component materials pressures and it is easy to obtain a composition of thin film very close to that of target composition.

There also exist other promising methods, however, the very basic problem with all manufacturing methods of nanotechnologies is their capacity. For example, sputtering process to produce 300 microns thick coating with 150 000 layers took 22 hours (cf Ashley, 1995). High rate deposition processes are required in order to cut the production cost and make the technology available for widespread engineering applications.

Manufacturing techniques for production of intelligent materials must ensure the possibility of implementing internal distributed network of sensors, actuators, their power sources and information transfer network. For that purposes techniques used for production of electronic chips could be useful. However, materials used in electronics are different from those good candidates for intelligent materials listed in the previous section. Adequate adaptation of electronoc industry technologies for smart materials manufacturing would be necessary to use them.

6. Problems with Intelligent materials

The concept of intelligent materials definitely constitute an edge of the technology at present. We have already pointed out that it is more a trend with promising initial results than common engineering practice. There are several reasons for that state and while they have already received some attention of researchers increased effort can be only expected. First of all, the field of intelligent materials is truly interdisciplinary. It will require cooperation of specialists from many branches, mechanicians, material scientists, chemists, control engineers to mention a few. It is necessary to initiate research programs devoted to the integration of intelligent material functional components within the "matrix" material. The effort of the people working in these programs will be focused on (micro-) structural design of the smart materials for particular purposes. The answer will have to be given on, e.g. pitch of spatial distribution of sensing elements, their geometrical layout, methods of signal transfer, selection of active material to be applied, methods of control, etc. Such activities will have to be performed taking into account latest development in sensing, actuating and controlling technology.

Discussed in the previous sections issues of intelligent materials allow to identify major tasks for mechanical community in the field. They may be divided into several groups.

Within the field of experimental mechanics new methods will have to be advanced for assessment of smart material properties. As it has been already mentioned structural smart materials will probably have some form of composite material. Anisotropy is a feature to be expected in smart materials. Large differences in relative magnitudes of the properties does not allow one to assign one type of test specimen for all types of microstructures of the material. Hence, new standards for testing will be necessary - special design of the samples. Some approaches were already proposed [15]. Another problem is increased in comparison to standard structural materials number of mechanical failure mechanisms e.g. interfacial shear cracking, delamination or splitting, fibers fracture and interfacial debonding, matrix cracking. New experimental measurement techniques have to be developed for reliable assessment of mechanisms of damage in progress. Smart material itself may play a role in here as a tool. Manufacturing techniques of composite materials discussed in previous section indicate that void traction in smart materials may constitute a problem. Measurement techniques, non-destructive if possible, for its evaluation seem to be necessary. Besides, measurement techniques for identification of mechanical properties, the other techniques must be developed to assess smart materials sensing, actuating efficiency. It may happen that control functionality of the material is lost without loosing to a critical degree mechanical properties. Some benchmark standards for testing overall smart material efficiency e.g. in vibration attenuation or other specialized tasks will have to be developed. Special measurement techniques will be necessary for thin films and nanomaterials.

Within the field of theoretical mechanics several fundamental problems take a new weight within the context of smart materials. It seems that the research into behavior of the material in the neighborhood of the interface of two microstructural components appears on the horizon as one of them. It must be remembered that in the case of nanomaterials with layer thickness of e.g. 10 nm most of the material volume can be categorized as lying in the interface neighborhood. Similarly, in the case of martensitic phase transformation on which the shape memory effect is based on, the number of appearing interfaces and their kinetics have key effect on the material behavior. It is on the interface where debonding or splitting takes place in composite materials. This mechanisms must be carefully studied and relevant theoretical models for them must be developed in order to predict safely the smart material strength.

The next fundamental problem on which research works are necessary is the problem of transport through porous media, and possibly seepage and diffusion. Many composite material manufacturing techniques consists in soaking of the fibers rowing or reinforcement microstructure with resin or metal matrix. The terminal material properties and strength will fiercely depend on that how well the matrix material will penetrate the reinforcement. The problem is by far not easy as besides mechanical (e.g. molding pressure), thermal and chemical effects will possibly strongly interfere.

The fundamental problem consists in determination of properties of smart materials depending on their microstructure. The problem has been already very intensely addressed within the context of composite materials and all the time obtains careful attention (see e.g. Nemat-Nasr and Hori, 1993). However, in the case of smart materials coupled fields will intervene what complicates the problem even further. The number of non-negligible factors is so large that no success in here can be imagined without development of proper numerical algorithms and putting computers into work. Under the term "properties" not only mechanical features but also other, e.g. thermal or electrical are understood in here. We shall make a remark that the properties of smart materials in comparison to standard materials are amazing and often counterintuitive. Take the SMA as an example. It is well known fact that the higher the temperature the lower stress is necessary to induce plastic flow in steel. In the case of SMA material the higher the temperature the higher stress is necessary to induce phase transformation flow of the material. Totally opposite to that of steel behavior. Explanation of this fact is simple, the mechanism of flow is different in each case. Researchers and engineers must acquire and develop new intuition regarding intelligent materials behavior.

The most serious problem concerning smart materials is development of adequate constitutive relations for theoretical description of their behavior. The task is by far not easy. We shall try to illustrate what kind of difficulties may be expected on the example of shape memory alloys (see also Ziółkowski, 1995). The phenomenon of shape memory effect itself has been reported in metallurgical literature already in the 1930s and was described in detail for the first time by Kurdyumov and Khandros in 1949. Subsequently, numerous experimental and theoretical works followed. However, only in the nineties the theoretical models have been adequately advanced to enable relatively reliable modeling of their behavior and only in the so called pseudoelastic range of behavior. The primary obstacle has been lack of mutual cooperation of metallurgist running research into martensitic phase transformations and continuum mechanics specialists. While the first tried to apply well established concepts of equilibrium thermodynamics to the description of the phenomenon or concentrated their works on purely geometrical investigations, the second applied oversimplified mechanistic models or thermodynamic models, which did not grasp underlying physical phenomena already known in metallurgical community. The both approaches could not end up with a success. The key factor in description of shape memory alloys is mutual coupling of thermal and mechanical phenomena. The experimental works on Shape Memory Alloys (SMA) delivered information on forming microstructures and kinetics of thermoelastic martensitic transformations, while in the scope of theoretical research the adequate theoretical methodology has been advanced, namely the formalism of non-equilibrium thermodynamics. Joint efforts resulted in the works by Huo and Müller (1993), Raniecki and Lexcellent (1994) in which theoretical constitutive models for shape memory alloy were presented, one-dimensional and three-dimensional respectively, grasping essential features of

SMA behavior in pseudoelastic range. An open scientific problem is development of theoretical models for SMA to describe one-way and two-way shape memory effects. In order to do that, the microstructures of forming thermoelastic martensite must be studied, the factors which influence or determine formation of particular microstructures must be identified. Next, on the base of this information adequate parameters must be proposed in theoretical models and their respective evolution equations. It is this microstructure which decides on macroscopic properties of the material. In here, the situation is still more complicated than in classical composites as in the composites the microstructure is fixed, while in this case it evolves together with the load adapting itself to it. Determination of macroscopic properties of the material for particular microstructure is a task that has been already mentioned, and which did not lost its validity (see also Nemat-Naser and Hori, 1993).

Similar difficulties arise in the case of other potential smart materials, i.e. piezoelectrics, optical fibers, pyroelectrics, active polymers. In the case of these materials the theoretical works are even less advanced than in the case of SMA. Let us investigate thermopiezoelectrics as an example. Dunn (1994) proposed the constitutive relations for thermopiezoelectrics but they were only formal one. The work itself is concentrated on obtaining estimates of effective moduli appearing in macroscopic constitutive relations for two-phase pyroelectric composite. However as the author admits himself there is no available experimental data enabling direct comparison of experimental results with modeling predictions. Taya (1995), similarly to Dunn has devoted his work to assessment of effective moduli for electronic composites. It can be concluded that in the case of piezoelectrics the theoretical works are at the stage of identification of theoretical models parameters and there is required coordinated effort of materials scientists with mechanicians in order to propose relevant coupled constitutive equations for these materials.

The last but not least is the problem of modeling nanomaterials. In here, the theory is rather undeveloped. It may be expected that interfacial (or interaction) energy between particular micro-constituent materials will predominantly influence overall smart material properties.

7. Final remarks

Participation in development and practical application of intelligent materials constitutes a new challenge for mechanical community. This truly interdisciplinary field requires not only broad knowledge of mechanical sciences and their further progress but also calls for a close cooperation of specialists in separate branches, i.e. material scientists, chemical engineers, specialists in control engineering and robotics, possibly neurologists or social science researchers. Implementation of this new concept may result in increased products performance, ease of use, safety, and by lowering their overall cost may increase the products competitiveness. This new concept gives a stimulus for new basic research programs connected with development of constitutive relations for such materials necessarily within the context of coupled fields, for development of adequate production techniques as well as investigations devoted to development of efficient control algorithms and optimization techniques. Intelligent systems built on the base of smart materials may not only be the technology of a very near future but may be a requirement posed before scientists and engineers in the move into the 2lst century.

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Mechanika materiałów inteligentnych

Streszczenie

Odkrywanie kolejnych materiałów konstrukcyjnych i opanowanie technologii ich wytwarzania znaczyły kolejne kroki rozwoju cywilizacji. Po epoce kamienia, brązu i żelaza jesteśmy obecnie w "erze kompozytów" i na progu nowej ery materiałów inteligentnych. Celem niniejszej pracy jest jasne określenie co się kryje pod pojęciem materiały inteligentne, które to pojęcie może być rozumiane jako szczególny przypadek szerszej koncepcji konstrukcji inteligentnych. Na podstawie wyselekcjonowanej literatury został dokonany, w kontekście nauk mechanicznych, przegląd koncepcji i definicji dotyczących konstrukcji inteligentnych, zaś materiałów inteligentnych w szczególności. Wskazano nowe tematy badań oraz problemy jakie się pojawiają w związku z rozwojem nowej obiecującej dziedziny jaką są konstrukcje i materiały inteligentne. W pracy zostały przedyskutowane różne aspekty tych materiałów, tj. ich specyficzne własności, typy wykorzystywanych efektów fizycznych jak i pojawiające się najpoważniejsze ograniczenia. Zgodnie z powszechnie przyjętym poglądem, zasadnicze cechy funkcjonalne jednocześnie obecne w każdym materiale inteligentnym to cechy czujnika, sterownika i siłownika. Nadrzędnym celem przy rozwijaniu i stosowaniu materiałów inteligentnych jest obniżenie kosztu "całkowitego życia" różnych konstrukcji inżynierskich poprzez zwiększenie ich funkcjonalności lub wydajności, uproszczenie konstrukcji lub procesu wytwarzania, ułatwienie konserwacji i w odpowiednim czasie wycofanie z eksploatacji.