The current state of the use materials with shape memory effect in the oil and gas and related industries

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Abstract. This paper discusses the use of materials with shape memory in various industries, including the oil and gas industry. The advantages and disadvantages of metallic and non-metallic materials with shape memory are presented. The possibilities of using composite materials with shape memory in the oil and gas industry are considered. The use of composite materials for the manufacture of diaphragms in diaphragm pumps to increase the energy efficiency of equipment is proposed.

1. Introduction
At the present stage of development of science and technology, a great attention is devoted to the study of innovative construction materials that have different functional properties, are able to work in difficult conditions, and at the same time will be easy to manufacture and cost-effective for practical application. The greatest interest among such materials are the so-called intellectual materials with special physical and mechanical properties. They are able to answer of changes in the external environment, adapting their properties in real time to work in new conditions.

The main representatives of intellectual materials are materials with shape memory effect (SME). They have the reversibility of inelastic deformation and are materials with a spontaneous shape recovery of a constructive element, which is observed both in isothermal conditions and temperature changes. When temperature changes such materials can repeatedly (more than 1 million cycles) reversibly deform and their ability to recovery can not be suppressed even with high force effect (1 gram of materials allows you to lift more than 140 grams of weight) [1].

For today, in the technical literature, you can find a large number of materials with the SME. This increased interest is due to the unique combination of high mechanical characteristics: tensile strength, endurance, yield strength, corrosion resistance, and special functional properties, such as sensibility, switchability, thermomechanical memory, and reactive strains based on thermoelastic martensite transformation.

The main characteristics of materials with SME are considered to be [2]:
sensibility — the ability of a material to respond of temperature changes; endurance — the ability of the material to perform switching operations when the temperature of phase transformations is reached; adaptability — the ability of the material to have of different kinds of unique properties, such as self-organization, self-restoration, self-control, etc; memory and recovery — the ability of a material to memorize the internal structure and geometric shape and to repeatedly recover after their change; energy intensity and energy conversion — the ability of a material to accumulate a significant amount of energy, and then convert it into mechanical energy of deformation; damping — the ability of a material to perceive high strains due to its microstructure and phase transformations.
2. Metal materials with SME

The main representatives of metal materials with SME are alloys based on titanium, copper and gold. The SME in them is based on thermoelastic diffusionless martensite transformations. The most common of such alloys for practical use are titanium-nickel alloys (Ni-Ti), which are called titanium nickelide or nitinol. Less commonly, cheaper copper-based alloys (Cu-Zn-Al and Cu-Al-Ni) are used [1].

It is believed that Ni-Ti alloys have the best combination of physicomechanical characteristics and thermomechanical properties, they have a greater reversible deformation — 8-10% (for copper-based alloys not more than 5-6%), higher maximum permissible heating temperature — up to 400°C (for Cu-Zn-Al and Cu-Al-Ni alloys 160 and 300°C respectively), the strength of titanium-nickel alloys is significantly higher, and their plasticity is several times higher than the plasticity of copper alloys. In addition, titanium nickelide has a high corrosion resistance, allowing for a long time to work reliably in contact with water and steam at operating temperatures of up to about 350°C, and Ni-Ti alloys have a high amount of recoverable deformation and a large number of cycles during thermal cycling (over 1 million cycles) [3].

Such metallic materials have found application in space and aviation technology, where different self-expanding and transforming structures are used, such as self-expanding antennas, masts, trusses, tanks etc; devices for controlling the flow of liquids and gases (chokes, valves, bellows); power drives (blocking undoing, turning mechanisms, locks, single-use technological tool); technological processes of assembly of detachable and one-piece connections [1,3].

Their application becomes economically advantageous due to the fact that they allow to reduce the geometrical dimensions of parts and reduce the mass of the apparatus.

The source [3] provides information that a spacecraft antenna was manufactured from titanium-nickel wire by Goodyear Aerospace Corporation and delivered into orbit twisted into a small collar. Such an antenna is restored its shape when heated by solar radiation. The manufacture of such structures from a material with SME allows to reduce weight due to the absence of additional drives and mechanisms, to keep its toughness when exposed to solar heat, and at the same time gives compactness to structures when they are delivered to space on board of the ship.

Of special interest is the use of metallic materials with SME in aircraft manufacturing processes, particularly for riveted joints in which such alloys are used to make rivets. In advance heat treatment is carried out to the memory, followed by cooling and plastic deformation in order to give the rivet shape convenient for assembly. Next, you should only insert it into the corresponding hole and heat it so that the rivet restored its shape and fastened the construction unit [1].

Due to its unique properties, metallic materials with SME are used in medicine: to the manufacture of filters for trapping blood clots and clots, vascular endoprostheses, artificial heart muscles, catheters for the treatment of atherosclerosis, prostheses for repairing teeth, staples for connecting bones etc [2].

In [1,3,4] another possible field of application of alloys with SME is described: thermomechanical connections (couplings) of pipelines and cylindrical structural elements. To do this, first the expansion of the inner diameter of the coupling is carried out, then the ends of the connected pipelines are inserted inside the coupling, then it is heated and due to this, it restores its shape, is compressed and is intruded in the solids of the connected pipes with its sealing belts, forming a strong and hermetic connection. This technology allows you to connect pipes of various diameters and thicknesses, as well as pipes and cylindrical elements from different materials, including those that are not subject to welding and soldering; requires significantly less ambient space for installation; the connection has a high vibration and corrosion resistance, is characterized by simplicity and speed of assembly, by absence of zones of thermal influence and electrical effects; unlike the processes of electric welding and soldering, where the quality of the resulting connection is affected by the qualifications of the employee, the “human factor” is practically absent.

Such couplings are used to connect the pipelines of the F-14 jet fighter hydraulic systems, and no accidents involving oil leakage were noted. They are also used for pipelines of nuclear submarines, for the repair of pipelines for pumping oil from the bottom of the sea, and for these purposes, large-diameter couplings are used — about 150 mm. In some cases, the Cu-Zn-Al alloy is also used to make
couplings of this type. Besides, they can be used for installation at great depths of large-sized marine underwater construction [1].

3. Polymers with SME

The ability to remember and restore its shape is characteristic not only of metallic materials, but also of functional polymers, which in some cases outperform well-known titanium-nickel alloys. SME in polymers is manifested in two-phase systems in which each phase has its own range temperature of glass transition $T_g$ and melting $T_m$. However, a two-phase system can also be formed under mechanical mixing conditions.

Examples of functional polymers with SME are glassy and crystallizing polymers [5].

Glassy (polycarbonate, polyvinylchloride, polymethyl methacrylate, epoxy polymers) or amorphous polymers are able to restore their original dimensions after heating to glass transition temperatures.

Such polymers are widely used for the manufacture of heat-shrinkable films used as packaging material; for the manufacture of heat-shrinkable tubes for electrical insulation; for the manufacture of parts and profiles in a compressed state, convenient for transportation; for the manufacture of rivets, fittings made of epoxy polymers (primarily couplings), which make it possible to form strong and hermetic structures from different (including dissimilar) materials that can withstand significant internal pressures of gas or liquid without breaking. This quality is achieved due to the fact that together with a heat-shrinkable coupling, made of good adhesion material to various substrates, epoxy glue is used. The temperature-time regimes shrinkage of the coupling and curing of the glue are selected so that first shrinkage occurs, and then curing; due to this, non-glues are eliminated and the thinnest adhesive layer is formed, which ensures maximum bond strength [6].

Crystallizing polymers are divided into amorphous-crystalline homopolymers, (polyethylene, polypropylene) and copolymers (thermoplastic polyurethane).

In amorphous-crystalline homopolymers, the transformation occurs due to the realignment the structure of the amorphous phase with its possible crystallization; destruction and recrystallization of existing crystallites having an imperfect shape, as well as due to thickening of crystalline blocks and melting of crystalline phases [6].

Microporous polymers are used to filter liquids, deaerate and separate fluid into fractions. In chemical current sources, they are necessary to perform the functions of separators-membranes, which are permeable to electrolytes and divide the space between the anode and cathode. For example, to exclude the possibility ignition of lithium batteries, it is necessary to prevent overheating of current sources, which is achieved by shrinkage of the separator material, during which the through pores are closed and the battery operation is interrupted [6].

Also, additional possibilities for regulating the heat-shrink characteristics of polymers can occur when a mesh of chemical nodes occurs in them. This mesh can be created by radiation, chemical or photochemical crosslinking. Due to these processes, an increase in the tensile strength occurs, heat-shrink characteristics are improved, which contributes to the expansion the field of application of polymers in the electronic, aviation industry, automobile and shipbuilding, as well as in space technology [6].

The main material of the copolymers are thermoplastic polyurethanes, which have a low cost, manufacturability of products creation, high resistance to external influences, wide temperature range for practical application of SME, and a high degree of shape recovery. In the region between the glass transition temperature $T_g$ and the melting temperature $T_m$ of the crystalline phase, these polymers are in a highly elastic state. Upon deformation in the interval $T_g < T < T_m$ and subsequent cooling under load to $T < T_g$, the required shape is fixed. If the material is then heated again to a temperature $T_g < T < T_m$, the original form will be restored to its original form [5,6].

In such materials, along with the shape memory, a significant change in the elastic modulus is observed in the region of the glass transition temperature, which suggests that they also have elasticity memory.
4. Composite materials with SME

The use of pure polymeric and metallic materials with SME may be limited by their disadvantages, for example: low resistance of metallic materials to the presence of pure diffusive hydrogen, which reduces their functional properties; low resistance of some polymeric materials to the presence of aggressive gases; the high cost of raw materials etc.

The creation of composite materials (CM) with SME can help get rid of the above disadvantages. Such materials consist of a matrix, which is responsible for construction strength, and a reinforcing element, which is responsible for physical and mechanical properties.

In CM with SME, titanium nickelide is used as a reinforcing element, it is used in the form of a wire or fiber, and so that it can fully realize its functional properties, a material with sufficient deformability should be selected as a matrix. As an example, can consider the following CM with SME.

In [7] a composite with a carbon fiber matrix and a reinforcing element in the form of a titanium nickelide wire of the TH1 grade (55.7% Ni) investigates, which is proposed for use in the manufacture of medical products. As a result of research and tests, it turned out that such a material can withstand fairly high loads, including cyclic, with no visible signs of fatigue failure, which indicates its high reliability, and the presence of a reinforcing element in the form of a titanium-nickel wire makes it possible to provide the necessary combination toughness and elastic deformation.

In [8] another composite “bioceramics (porcelain) – titanium nickelide” was investigated and proposed for use in medicine. From the point of view biomechanics, the functional materials used for implantation into the body in their properties should be similar to tissues, i.e. have elasticity. The bioceramics used in the medical industry (most often porous) have high mechanical strength, non-toxicity, maximum biocompatibility, but at the same time they have a serious defect - fragility. The introduction of titanium nickelide into the composite allows not only to increase the strength characteristics, while maintaining the through porosity necessary for tissue germination, but also to give the material the necessary elasticity.

In [9] the properties of the multifunctional composition “basis – material with SME were investigated. The composition was obtained under conditions of high-energy influences (argon-arc and laser cladding, plasma and high-speed cladding) with the formation of structures of various dispersion — from fine to nanoscale. C45E, AISI 5135, AISI 321 were taken as the basis and alloys based on TiNi, TiNiCu, and NiAl were used as the material with SME. Titanium-nickel alloys were used as powders (PNi55Ti45, PNi80A20 and three-component based on TiNiCu) for surface modification. To ensure better adhesion of the surface layer and base, on the steel a nickel sublayer was applied, also in the form of a powder. Experimental research have shown the effectiveness of the developed technologies for creating the composition to increase the wear resistance, endurance limit, and durability under friction-cyclic low-cycle material loading.

Based on the analysis, can conclude that the creation of CM with SME is a actual and poorly studied topic. In addition, it should be noted that at present this material has a limited scope of application which is also due to its insufficient study.

5. The use of materials with SME in the oil and gas industry

The use of materials with SME in the oil and gas industry is very limited. Primarily, this is due to insufficient knowledge the work of this material in an aggressive oil environment, and secondly, the sensitivity of these materials to aggressive oil gases and pure atomic hydrogen. However, this material begins to be used in various construction of oil and gas equipment, for example: in locking elements of packer devices, in control units, in locking valves etc.

The following patents can be considered as an example of the use of materials with SME.

Different types of locking packer elements [10]. In this invention, the locking elements of the packer consists of a metal sealing element made of a material with SME, one end of which is connected to the carcase and the second on the sleeve, with the possibility of movement along the axis
of the carcase. The device is equipped with elastic grids with SME, one or two elastic diaphragms made of heat-resistant material.

Device for selective completion of wells [11]. In this invention, an element made of a material with an SME is used as a drive to provide alternating movement of the thrust drive.

Valve for selective completion [12]. The actuator of the valve is permanently connected to its spool and is made of at least two working elements made of a material with SME, each of which is constantly or periodically located in the area of operation of the electric heating element.

The authors also presented a work in which a material with SME an electron-phase intensifier shown in figure 1 is used as a diaphragm drive [13-15]. This material allows you to reduce energy consumption per 1 cycle of raising the reservoir fluid, change the overall dimensions of the production equipment, increase the reliability of pumping equipment and increase the overhaul period.

![Figure 1. Schematic diagram of the processes of suction and discharge of a pump with Nitinol filaments [13,14].](image)

Assessing the energy efficiency of the presented modernization, it is necessary to take into account that the field of its application is low-production wells with a fluid rate of up to 12 cubic meters per day.

Analyzing the results presented in figure 2, it can be seen that a modernized pump with a diaphragm made of materials with SME is 2.6 times more effective than electric drive centrifugal pumps during continuous operation and more efficient than downhole sucker rod pumps with 1.8 times continuous operation with a flow rate of 5 cubic meters per day, and its effectiveness is maintained up to 12 cubic meters per day. The data also show that the equipment is not more efficient than periodic operation, but it should be taken into account that the use of this type of operation has its own drawbacks, which limits its scope [16].

![Figure 2. Comparison of the energy efficiency indicators of oil production processes [14].](image)
6. Conclusion
Based on the analysis of the works carried out by the authors, one can conclude that about possibility to use materials with SME both metal, polymer, and composite to create reliable and high-tech equipment. At present, the authors carry out calculations and numerical experiments for the rational selection of materials for the creation of CMs with SME polymer-titanium nickelide and the subsequent manufacture of membranes and diaphragms from it.

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