Experimental Studies of Elements from the Functional Intermetallic Cu-Al-Mn for Construction of a Heat Engine and Power Plant

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Abstract. The main objectives of the work are to study the thermomechanical characteristics and establish the patterns of reactive force generation by elements made of functional Cu-Al-Mn intermetallic compounds for their further use in heat engines of electrical power generation plants.
The objectives were achieved using a test setup with control and measuring instruments to determine the thermomechanical characteristics of elements made of functional intermetallic compounds with different geometric and physical parameters, and by plotting the force-temperature curves.
Based on the results of experimental studies, thermomechanical characteristics (dependencies of the reactive force developed by thermosensitive elements on their heating temperature) were constructed, and specific indicators of reactive force generation relative to the mass of thermosensitive elements were determined. It was established that samples at a heating temperature of +90...+100 °C restore their initial shape (after preliminary deformation) in 0.15 s. The specific indicator of reactive force generation relative to the unit mass of thermosensitive elements was determined to be – 0.97 W/g. The significance of the results obtained lies in the fact that the results of experimental studies and the established regularities will be used as a basis for the creation of a heat engine and, on its basis, an electrical installation for the generation of electrical energy operating with low-potential sources of thermal energy – secondary heat energy from technological cycles, water reservoirs of thermal and nuclear power plants, as well as thermal sources.
Keywords**:** functional intermetallic, heat engine, electric power generation, shape memory alloy.

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Studii experimentale ale elementelor din complexul intermetalic funcțional Cu-Al-Mn pentru construcția unui motor termic și a unei centrale electrice

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Rezumat. Principalele obiective ale lucrării sunt studierea caracteristicilor termomecanice și stabilirea modelelor de generare a forței reactive de către elementele realizate din compuși intermetalici funcționali Cu-Al-Mn pentru utilizarea lor ulterioară în motoarele termice ale centralelor electrice. Obiectivele au fost atinse utilizând un set de testare cu instrumente de control și măsurare pentru a determina caracteristicile termomecanice ale elementelor realizate din compuși intermetalici funcționali cu diferiți parametri geometrici și fizici și prin trasarea curbelor forță-temperatură. Pe baza rezultatelor studiilor experimentale, au fost construite caracteristicile termomecanice (dependențele forței reactive dezvoltate de elementele termosensibile de temperatura lor de încălzire) și au fost determinați indicatori specifici ai generării forței reactive în raport cu masa elementelor termosensibile. S-a stabilit că probele la o temperatură de încălzire de +90...+100 °C își restabilesc forma inițială (după deformarea preliminară) în 0,15 s. Indicatorul specific al generării forței reactive în raport cu unitatea de masă a elementelor termosensibile a fost determinat a fi – 0,97 W/g. Semnificația rezultatelor obținute constă în faptul că rezultatele studiilor experimentale și regularitățile stabilite vor fi utilizate ca bază pentru crearea unui motor termic și, pe baza acestuia, a unei instalații electrice pentru generarea energiei electrice care funcționează cu surse de energie termică de potențial redus – energie termică secundară din ciclurile tehnologice, rezervoarele de apă ale centralelor termice și nucleare, precum și surse termice.
Cuvinte-cheie**:** intermetalic funcțional, motor termic, generare de energie electrică, aliaj cu memorie de formă.

Экспериментальные исследования элементов из функционального интерметаллида Cu-Al-Mn для построения теплового двигателя и электростанции

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Аннотация. Основными целями работы являются исследование термомеханических характеристик и установление закономерностей генерации реактивного усилия элементами из функционального интерметаллида Cu-Al-Mn для дальнейшего их использования в тепловых двигателях электроустановок генерации электрической энергии. Цели реализованы с помощью созданной опытной установки с использованием контрольно-измерительных приборов для определения термомеханических характеристик элементов из функционального интерметаллида с различными геометрическими и физическими параметрами; построением характеристик зависимости усилия от температуры нагрева.
По результатам экспериментальных исследований построены термомеханические характеристики (зависимости реактивного усилия, развиваемого термочувствительными элементами от температуры их нагрева), определены удельные показатели генерации реактивного усилия, относительно массы термочувствительных элементов. Установлено, что образцы при температуре их нагрева +90...+100 ºС восстанавливают первоначальную форму (после предварительной деформации) за время 0,15 с. Определен удельный показатель генерации реактивного усилия, относительно единицы массы термочувствительных элементов, который составляет - 0,97 Вт/г. Значимость полученных результатов заключается в том, что полученные результаты экспериментальных исследований и установленные закономерности будут положены в основу создания теплового двигателя, и на его базе, электроустановки для генерации электрической энергии, работающих с низкопотенциальными источниками тепловой энергии - вторичная тепловая энергия технологических циклов, водные резервуары тепловых и атомных электростанций, а также термальные источники.
Ключевые слова: функциональный интерметаллид, тепловой двигатель, генерация электрической энергии, сплав с памятью формы.

INTRODUCTION

Modern theoretical methods and software-based multiphysics tools provide designers and researchers with the opportunity to achieve the highest level of optimization of technical device characteristics in terms of efficiency and reliability.

The process of further improvement and development of new technical devices is limited by the constraints of traditional electrical engineering materials [1].

The development of innovative components and mechanisms can be based on functional alloys, specifically the Cu-Al-Mn intermetallic, which is a high-tech material with unique physical properties that determine it as one of the “smart” materials, which have shape memory capability.

The use of such materials in electrical contacts ensures temperature control of the contacts and fixation of their overheating, stabilization of contact pressure, sealing of the contact connection and automatic removal of the oxide film on the contact surfaces [2].

The cost of Cu-Al-Mn (Camital) alloy is significantly lower compared to the group of nickel-titanium alloys (Ni-Ti).

Accordingly, the Cu-Al-Mn intermetallic (Camital), developed by [2], (wire, strip, rods, etc.) is economically affordable for the use in electric power engineering, specifically for temperature control and automatic pressure regulation in demountable electrical contacts; as modern means of protecting electrical installations from overheating – thermal relays, highly sensitive electrical fuses, circuit breakers with a single universal trip unit, power generators based on low-temperature heat engines; in agriculture – energy-saving vent drive systems in greenhouses and hotbeds, which operate based on changes in the air temperature of the rooms and do not require additional energy sources; in medicine – orthopedics, clothes, etc., [1,3,4].

The elements made of Cu-Al-Mn (Camital) alloy develop reactive forces of hundreds of MPa.

The elements made of shape memory alloys, which are able to convert three types of energy (thermal, mechanical and electrical), function within a specific temperature range as both a temperature sensor and an actuating mechanism simultaneously, and are the simplest “transformers” of thermal energy into mechanical work, [1,2,3].

ANALYSIS OF RECENT RESEARCHES AND PUBLICATIONS

The use of non-traditional advanced materials in electric power engineering is a promising component of its development. One group of such materials are functional alloys (FAs) – shape memory alloys. By converting three types of energy (thermal, mechanical, electrical), they function as both a working medium and a mechanism simultaneously within the temperature range of 200…+200°C. For functional alloys, it is an undeniable fact that power properties are combined with actuating capabilities within a single material, rather than in a mechanism.

A relevant direction of the application of functional intermetallic compounds is the development of solid-state heat engines for power generation installations that use thermal energy from low-potential sources. However, the high cost indicators of Ni-Ti (Nitinol) alloys limit their widespread use in electric power engineering. There is an alternative to these alloys – copper-based functional intermetallics, e.g. Cu-Al-Mn (Camital), which is economically affordable for the use in electric power engineering, [1,2,3].

Table 1 presents the parameters of two alloy groups – Cu-Al-Mn (Camital) and Ni-Ti (Nitinol), [1,2].

Table 1

The parameters of Cu-Al-Mn (Camital) and Ni-Ti (Nitinol) alloys.

No.	Parameters	Alloys	
		Cu-Al-Mn	Ni-Ti
1	Melting point, ºC	1000-1060	1300
2	Density, g/cm^3	7.05	6.45
3	Resistivity, μΩ·cm	9…11	70…100
4	Thermal conductivity, W/cm·ºC	45…60	8.5…18
5	Young's modulus, GPa, for stages: beta stage martensite	 90 85	 83 28…41
6	Thermomechanical stress, MPa, МПа, for stages: beta stage martensite	 500 200	 195…690 70…140
7	Mechanical strength limit, MPa	600…800	895
8	Transformation temperature scale, ºC	-120…+200	-200…+110
9	Maximum permissible relative deformation, %	4.2	7

In addition to its significantly lower cost, Cu-Al-Mn alloy is more attractive for the use in electrical installation due to the following parameters: resistivity, thermal conductivity and transformation temperature scale.

Purpose. The aim of this work is to investigate thermomechanical properties of the elements made of functional intermetallic based on Cu-Al-Mn alloy for their use in heat engines to generate electrical energy.

Research Objectives. To achieve the stated goal, the following tasks need to be accomplished:

1) to develop an experimental rig with the use of control and measuring instruments as well as the elements for monitoring the indicators;

2) to determine thermomechanical properties of the elements made of functional intermetallic with different geometric and physical parameters;

3) to plot the characteristic dependency of the force on the heating temperature;

4) to draw conclusions based on the obtained experimental data and the use of the elements in heat engines.

Literature Review. In the papers [5,6,7] a study has been conducted that demonstrates the potential of monocrystalline shape memory alloys Cu-Al-Mn (SMA – shape memory alloys) for their use as intelligent actuators in deployable thermal radiators in order to reduce the cost and the weight of a space ship. The suggested in [6] SMA actuators provide axial displacement due to bending up to a half of the initial length, which minimizes storage space and maximizes the deployment stroke of the radiators.

In the work [8], it is noted that the actuating elements made of shape memory alloys convert thermal energy into mechanical work and they have much greater output deformation compared to piezoelectric or magnetostrictive materials. Thus, SMA is a suitable actuating material in the areas that require large displacements and high energy density. The aim of the work [8] is the development of shape memory alloys that can operate at temperatures lower than the temperature of liquid nitrogen.

As it is stated in the paper [9], self-aligning seismic-resistant systems have attracted the attention of researchers due to their promising potential in controlling seismic residual drifts and, thus, the reduction of associated costs for the repair of structures. The use of rods made of Cu-Al-Mn SMA has been investigated for the displacement of a plastic hinge in concrete beams by means of experimental-numerical calculation. The operation of four bundles of rods made of different materials has been tested. The first was reinforced with steel bars, while the other three were reinforced with a combination of SMA and steel bars. The arrangement of SMA strips was different for each bundle under investigation. The beams were loaded in such a way that the moment diagram was zero at the midpoint and maximum at the ends, in order to simulate the expected seismic moments. The results of the experimental-numerical calculation have proved the ability of the beams with SMA elements to re-center.

In the works [10,11,12], the aspects of applying various SMA alloys of Ni-Ti and Cu-Al-X groups as actuating elements have been discussed. The advantage of the first group is slightly higher levels of generated mechanical stress and the values of relative permissible deformation as compared to the properties of copper-based alloys. However, as it has been stated above, the cost of nickel-titanium group exceeds several times and this is the main argument for further in-depth study and use of the properties of copper-based alloys.

The problem of the improvement of copper-based alloys has been investigated in the works of [13,14,15]. When using porous material technologies, a segmented powder sintering process has been developed, which led to the achievement of synergistic improvement in the final strength and the damping properties of Cu-Al-Mn porous alloys. The mechanism of the influence of pore structure and microstructure, caused by the segmented sintering process, on strength and damping has been revealed. The study of the peculiarities of obtaining high-temperature shape memory alloys is important for aerospace and space industries. In addition, the study of the characteristics and patterns of the heat treatment of products made of copper-based alloy is important in order to obtain the necessary functional parameters.

The practice of applied use and research of shape memory alloys shows that in each case of application of thermosensitive elements made of shape memory alloys, modification of their functional characteristics and parameters to meet specific application requirements is required. The modification of characteristics and parameters can be performed both at the alloy production stage – the ratio of its constituent components and at the heat treatment stage of the already finished thermosensitive elements.

One of the producers of functional SMA copper-based intermetallics is ALOTEK Technology (Camital is the trademark of the alloy) [2]. In addition to its production activity, ALOTEK Technology has a research center, within the framework of which the search for applications of Cu-Al-Mn alloy in electric power systems has been conducted, e.g. the development of heat engines [16,17] and further creation of the means of electricity generation [18,19,20]. An important motivational argument of such a study is the possibility to use thermal energy from secondary low-temperature sources – heated air, gases or water after a certain technological cycle.

In order to create a heat engine made of shape memory alloy, the main characteristics of the output power of a two-crank heat engine have been investigated in the work [16]. A wire made of TiNi alloy with the outer diameter of 0.75 mm was used as a thermosensitive element. The material was heat-treated to memorize the shape of the spiral. According to the investigation results, the following conclusions have been obtained: the output power of an engine increases with the increase of water temperature; the rotational speed, at which the output power is maximized, shifts towards higher speeds; the maximum output power decreases within the range above a certain water temperature; the output power increases as the deformation of the spiral made of shape memory alloy increases. The obtained patterns from the research results coincide with the determined patterns in the work by [20].

The transition to renewable energy sources, such as geothermal energy, is desired due to the current energy crisis and the challenges of global warming caused by fossil fuels [17].

Geothermomechanical energy conversion using heat engines made of shape memory alloys (SMA) is a new and sustainable approach to the use of geothermal energy. In the work [17], the design and the efficiency of a heat engine made of SMA, which uses the model of geothermal heat source for controlling mechanical work, has been investigated. A thermosensitive element (a spring) alternately interacts with the high-temperature geothermal environment and a cooler absorber, using a shape memory effect to create mechanical movement. Due to the combination of geothermal energy and SMA technology, this system has a potential solution for the production of energy from renewable sources in remote or off-grid locations. The output power and thermodynamic efficiency have been studied in the work as well. A model has been suggested to simulate the behavior of the engine, and a number of experiments have been conducted on the output power and the engine efficiency. In the experimental part of the work, the engine developed the maximum power of 3.5, 8.5, and 11.5 W at 60, 80 and 90°C, respectively. The suggested geothermomechanical system of energy conversion based on SMA offers a promising solution to the effective, reliable and large-scale collection of geothermal energy. The conducted research in [17] contributes to the development of new and efficient technologies for converting geothermal energy and supporting global goals regarding renewable energy and the reduction of greenhouse gas emissions.

The review of various types of heat engines based on SMA technology is presented in the work [19]. The review has been conducted based on the following classification features: conceptual design, the main motion model, engine efficiency and the limitations of an engine. It has been determined that a NiTi-based SMA heat engine with a crankshaft produces the highest output power of 4 W, while an unsynchronized NiTi-based SMA heat engine, with an engine efficiency of 11.3%, has the highest performance.

In the work [20], the investigation of thermosensitive elements based on Nitinol material has been conducted. A wire with the diameter of 1.0 mm in the form of springs can potentially be used in the design of a thermal engine for an electrical energy generation system, having appropriate geometric parameters. The study [20] makes it possible to determine the thermomechanical properties of the springs made of this alloy, particularly study the influence of pre-deformation values of such elements on the generated force. Thermal hardening of the Nitinol wire was conducted at the temperature range of 400 - 500 ºC during 4.5 hours. The study of the thermomechanical properties was carried out by heating a termosensitive element (a spring) in water at the temperature of 25 ºC - 100 ºC, the force measurements were performed using a spring dynamometer.

As a result of the conducted experiments, thermomechanical properties of the spring has been determined at various values of its deformation. The plotted graphs show that the functional dependence of the maximum generated force on spring deformation is close to linear. The experimental studies presented in [20] show that the significant influence on the magnitude of the force generated by the spring made of Nitinol alloy is caused by the pre-deformation value of the spring. At the spring deformation of 160 mm and the temperature of 100 ºC, the generated force was equal to 4…4.5 N, while at the deformation of 100 mm – 1.75…1.85 N.

Scientific novelty of the work. The scientific novelty of this study is to obtain thermomechanical characteristics of a functional copper-based intermetallic - Cu-Al-Mn and to establish patterns of reactive force generation depending on the temperature of the beginning of the restoration of the shape of the samples and their geometric dimensions. It was also found that the samples at a heating temperature of +90...+100 ºC restore their original shape (after preliminary deformation) within 0.15 s. For the first time, a specific indicator of the generation of reactive force relative to a unit mass of thermosensitive elements was obtained - the specific power generated by a Cu-Al-Mn alloy plate is 0.97 W/g.

The obtained results of experimental studies make it possible to assert that in the presence of a heat source with temperature fluctuations, it is advisable to use heat-sensitive alloy elements with different temperatures of the beginning of shape recovery. In this case, the heat engine can be designed as a single unit with a sectional structure.

MATERIALS AND METHODS OF RESEARCH

Cu-Al-Mn is a functional intermetallic that belongs to shape memory materials. Elements based on Cu-Al-Mn alloy are more suitable for use in electrical equipment and installations in terms of physical parameters and, especially, significantly lower cost [2].

The methods used in the research were the general methods of theoretical analysis based on the regularities of the influence of physical (electrothermal, thermomechanical) properties of functional Cu-Al-Mn-based alloys, obtained in the process of the experimental studies on specialized test benches.

In the study of functional Cu-Al-Mn-based alloys intermetallics, an experimental rig was used in order to determine the reactive force when the temperature of a thermal agent changes.

In the research, 5 Cu-Al-Mn-based plates with corresponding geometric parameters and shape recovery temperatures were used (Table 2).

Fig. 1. Elements made of functional intermetallic.

Table 2

Geometric parameters and shape recovery temperature of plates made of Cu-Al-Mn alloy plates

No. of a plate	Length, mm	Width, mm	Thickness, mm	Temperature of the onset of shape recovery, ºC
Plate №1	352	11	1.3	55
Plate №2	300	10	1.3	55
Plate №3	250	10	1.5	55
Plate №4	335	14	1,0	28
Plate №5	350	12.5	2.0	35

The study was conducted for the plates with the temperatures of the onset of shape recovery temperature of 28ºC, 35ºC and 55ºC.

The arrangement of thermoplates in the experimental rig is presented in Fig.3

Fig. 2. Experimental samples of plates made of Cu-Al-Mn alloy.

Fig. 3. Arrangement thermoplates in the experimental rig.

In the study, a single-plate configuration (a) and a double-plate configuration (b) in the experimental rig were used in order to further determine the generated force.

Results and discussions. The experimental studies have established the following: at the temperature of +90…+100 ºC, plate No.5 recovers its shape and moves the free (mechanically unfixed) end at the distance of 350 mm within 0.15 seconds. Thespeed of shape recovery is 2333 mm/s, or v=2.33 m/s. The maximum force that is generated by the plate is equal to F=27 N. The weight of the plate is P=62 g.

During its shape recovery, the plate develops the following maximum mechanical power – P=F·v=27·2.23=60.21 W. The specific power of the plate in this case is 0.97 W/g.

a) b)

Fig. 4. Configuration of thermoplates in the experimental rig.

Based on the conducted research, the dependency graphs of the force (N) that the plate generates during heating (ºC) have been plotted. The graphs in Fig.5 show that the thermomechanical properties of thermosensitive elements develop practically the same maximum force within the range of 14.0-14.5 N. At the temperature of the onset of shape recovery of t_{rec}=35ºC plate No.5 develops greater maximum force – 27 N (Fig.6), which is due to its larger geometrical parameters.

In order to find the ways to improve the efficiency of a heat engine at the fluctuations of the heat carrier temperature, the study of the thermomechanical properties of the stack of plates No.2+No.4 at the temperature of the onset of shape recovery of t_{rec}=55ºC and t_{rec}=28ºC, respectively, as well as of the stack of plates No.2+N.2, was conducted.

Fig.7 shows that the maximum force increases almost twofold and is equal to 34 N for the stack of plates No.4 and No.2.

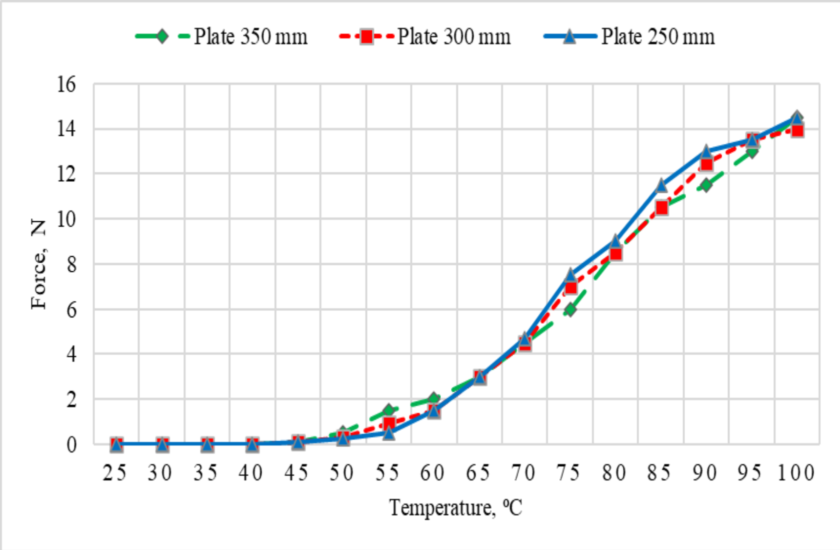

Fig. 5. Thermomechanical properties of plates No.1-No.3 (t_{rec}=55°C)

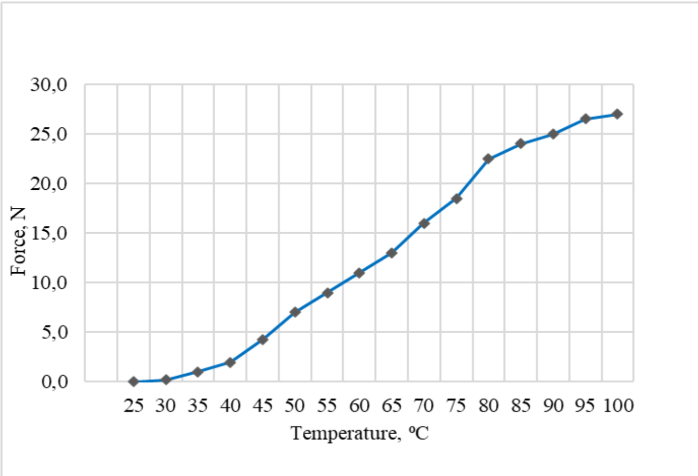

Fig. 6. Thermomechanical properties of plates No.№5 (t_{rec}=35°C)

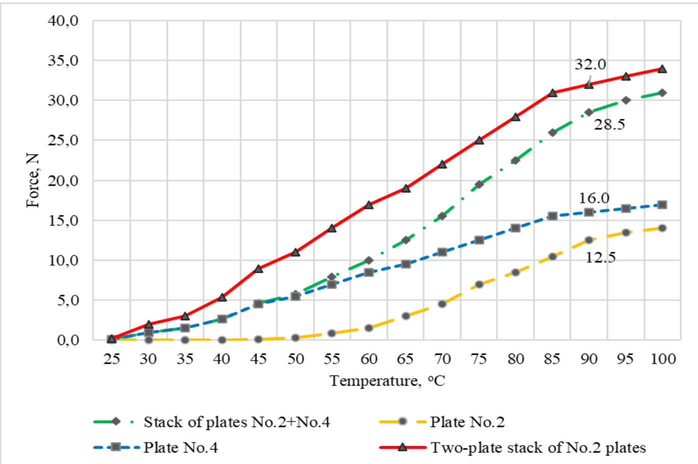

Fig. 7. Thermomechanical properties of plates No.4 and No.2 (t_{rec}=28°C and t_{rec}=55 °C, respectively) and stack of plates No.4+No.2 and No.2+No.2

At the same time, it is to the point to specify the factors from the studies [18,19,20], as they are of significant importance in the process of designing heat engines [16,17]. Based on the graphs of thermomechanical properties (Fig.7) of plates No.4 and No.5, it can be concluded that at the heat carrier temperature of +25 – +55 ºC, plate No.2 (t_{rec}=55 ºC) does not generate force while plate No.4 generates force. Thus, for the cases of heat carrier temperature fluctuations, it is efficient to use alloy plates with different temperature of the onset of shape recovery.

Fig.7 shows the numerical values of the generated force of single plates No.2 and No.4, their joint stack and a two-plate stack of No.2 plates at the heat carrier temperature of 90 ºC. In the process of developing heat engines, it is necessary to take into consideration the temperature gradient factor of the two media, one of which heats the actuating elements while the other one cools them. In case of using two No.2 plates, the maximum force on the thermomechanical property is 32 N, and in case of using the stack of plates No.2+No.4, it is equal to 28.5 N. When moving plates No.2+No.2 to the medium for cooling, the generated force decreases from 32 N. At the same time, it should be taken into account that due to thermal inertia of the process of plate cooling, the residual force counteracts the generated force of the thermosensitive elements, which are located in the medium for heating. In case of using the stack of plates No.2+No.4, the maximum force is 28.5 N (at 90 ºC). When moving the stack of plates No.2+No.4 to the medium for cooling and when the temperature value of the plates reaches 55 ºC, the resisting force decreases significantly compared to the value when the stack of plates No.2+No.2 is used.

The development of the production technologies of the alloys, which are specified in the works [1,16,17], the improvement of their characteristics, their unique physical property to transform three types of energy (thermal, mechanical and electrical) and the fact that they are the simplest "transformers" of thermal energy into mechanical, provide the foundations for creating heat engines [18,19,20].

Heat engines based on shape memory alloys use the ability of the material to change its shape under the influence of temperature. This phenomenon allows to convert thermal energy into mechanical without using traditional piston or turbine mechanisms.

The main advantages of such engines are the following:

1. *High engine efficiency at low temperatures* – the ability to operate at slight temperature fluctuations, which allows the use of low-potential energy sources (solar, geothermal, industrial waste, etc.).

2. *Quietness and configuration simplicity* – the absence of friction between the moving parts reduces the wear of the parts and the maintenance costs.

3. *Environmental friendliness* – does not require fuel combustion, can operate on natural heat sources.

4. *Compact size* – the possibility to create miniature and lightweight systems, which is important for autonomous devices.

The selection of an alloy for manufacturing thermosensitive elements is important for solving the tasks of creating a heat engine. At the beginning of the paper, the parameters of two alloy groups – the copper-based one and the nickel-titanium one, have been provided. Copper-based alloys (e.g. Cu-Al-Mn, Cu-Al-Ni or Cu-Zn-Al) are one of the most promising for application in heat engines due to the following advantages:

- *low cost and affordability* – copper is significantly cheaper and more common than nickel or titanium that are used in other SMA alloys;
- *high corrosion resistance* – copper-based alloys have good resistance to the exposure to moisture and aggressive environments, which is important for long-term operation;
- *good mechanical properties* – high plasticity and strength provide long-term exploitation without significant efficiency losses;
- *stability of phase transformations* – compared to other materials, copper-based alloys have good repeatability of the shape memory effect under cyclic loads.

The scope of application of heat engines based on shape memory alloys.

1. *Autonomous actuators and mechanisms* – can be used for opening / closing valves, creating self-regulated systems in ventilation and cooling.

2. *Industrial heat recovery systems* – the use of secondary heat from industrial processes for electricity generation or mechanical work.

3. *Space and aircraft equipment* – SMA heat engines can operate under low gravity conditions and at extreme temperatures.

4. *Medicine* – application in implants, micropumps or drug delivery systems that are activated by body heat.

5. *Robotics* – the elements of controlled movement (artificial muscles, heat-sensitive elements).

6. *Ecological systems* – the engines can work on solar energy, seawater or geothermal heat.

Shape memory heat engines can be integrated into power generating units that operate on the principle of conversion of temperature changes into mechanical work and further into electrical energy.

The examples of the possible applications are the following:

- *industrial power engineering* – the use of waste heat from enterprises for additional electricity generation;
- *household application* – small power generators that operate on solar energy or domestic heating systems;
- *distributed power generation* – the creation of autonomous power plants in remote locations;
- *transportation* – application in electric vehicles for engine heat recovery or in brake systems.

Fig. 8 presents the general view of the operating prototype of a heat engine with thermosensitive elements (plates) made of Cu-Al-Mn alloy.

Fig. 8. General view of a heat engine with thermosensitive elements made of Cu-Al-Mn shape memory alloy

This engine design provides for the use of 9 thermosensitive plates made of shape memory alloy, which tend to restore their shape from parabolic to straight along the guide spokes during heating. Since the center of the guide spokes connection is displaced by a certain distance from the main axis of rotation of the working wheel, conditions are created for the generation of torque. The value of the torque depends on a number of geometrical dimensions of the engine, thermosensitive elements and their thermomechanical properties. In this design of a heat engine, a water tank (which is a heat agent) is divided diametrically into two parts, and the water temperature is different in these two parts, e.g. +15 and +50 ºC.

CONCLUSIONS

1. The results obtained from the experimental research suggest the feasibility of using thermosensitive elements made of Cu-Al-Mn alloy in thermal machines for electricity generation.

2. The experimental studies have shown that at the temperature of +90…+100 ºC, a plate made of Cu-Al-Mn alloy (with the following geometrical dimensions: length 350 mm, width 12.5 mm, thickness 2.0 mm) recovers its shape and moves its free (mechanically unfixed) end to a distance of 350 mm in 15 seconds. The speed of shape recovery is 2333 mm/s, or v=2.33 m/s. The maximum force generated by the plate is F=27 N. The weight of the plate is P=62 g. During its shape recovery, the plate develops the maximum mechanical power of $P=F·v=27·2.23=60.21$ W. The specific power of the plate in this case is 0.97 W/g.

3. The determined thermomechanical properties of plates made of Cu-Al-Mn alloy can be used as a basis for designing heat engines.

4. The results of the experimental studies make it possible to state that if there is a source of thermal energy in which temperature fluctuations occur, it is advisable to use thermosensitive elements made of alloy with different temperatures of the onset of shape

recovery. At the same time, a heat engine can be designed as a single unit with a sectional design and a control system for switching the sections on and off at the fluctuations of the heat carrier temperature.

5. Heat engines based on shape memory alloys is a promising technology for the efficient conversion of heat into mechanical or electrical energy. The use of copper-based alloys makes them affordable, reliable and cost-effective. Such units can be used in industry, energy sector, medicine, transportation and robotics, contributing to the development of environmentally-friendly and efficient technologies.

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