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ON THE APPLICATION OF FUNCTIONAL APPROACH TO CREATING AND PROVIDING OPERATIONAL CHARACTERISTICS OF ULTRALIGHT THERMAL PROTECTION OF REUSABLE LAUNCH SPACECRAFT

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Abstract:
The main task of the research is to establish the regularities of the formation of a non-detachable compound of thin-walled elements from the Ni-20Cr-6Al-1Ti-1Y2O3 alloy and to determine the functional condition of the influence of soldering modes on the physical-mechanical characteristics of the compound. It has been shown the modeling of temperature fields in ANSYS 18.1. It has been established that the process of vacuum soldering should take place at a temperature of 1350°C for 15-20 min; the strength of the resulting compound is 390-420 MPa when the sample is stretched. The obtained information can be used as a theoretical basis for the development of the manufacturing process of the elements of the spaceship heat-shielding system.
***KEYWORDS**: WELDING; SOLDERING; HEAT TRANSFER; VACUUM; HEAT-RESISTANT MULTICOMPONENT ALLOYS*

1.INTRODUCTION

Thermal protective structures of reusable aircraft with an outer metal panel are developed by specialists of all leading space countries of the world. This thermal protection consists of individual tiles, fixed on the hull of the spacecraft, and consisting, as a rule, of the upper and lower casings, between which is the honeycomb aggregate. So, NASA Langley Research Center (USA) was developed thermal protection with high resistance to high-speed collisions with space trash in orbit (fig.1). The outer support panel was a three-layer honeycomb panel, which is made of Inconel 617 alloy and designed for operation in the temperature range 600-980 °C [1]. On the European demonstrator IXV for flight testing, the thermal protection was installed with the honeycomb panel «TIMETAL 1000» by «Astrium» company, designed for use at temperatures up to 850 °C and made of orthorhombic TiAl (Ti_2AlNb) or TiAl reinforced with TiB. (fig.2) [2].

The outer metal panel is fixed to the hull of the spacecraft with the help of racks, plates or other elements that ensure reliable retention of the tiles during the flight. Between themselves, the tiles are installed end-to-end or with some overlap.

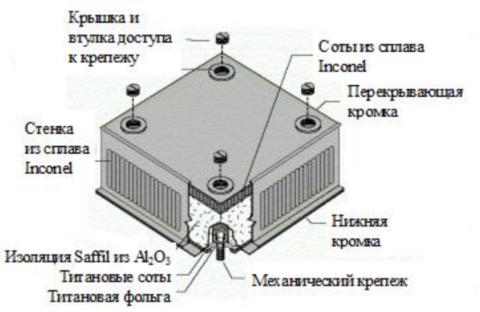


Figure 1 – Thermal protective structures with high resistance to high-speed collisions

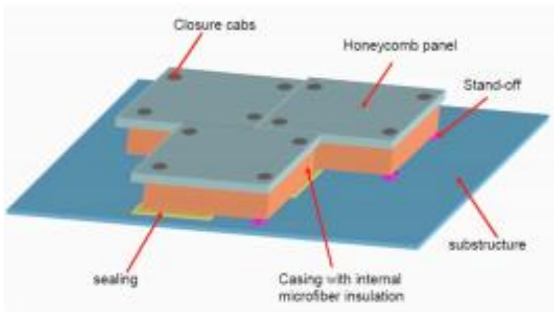


Figure 2 – Thermal protection with panel «TIMETAL 1000» by «Astrium» company

In this case, the main drawback of such structures is the possibility of penetration of hot gases into the gaps between individual tiles, which leads to an unacceptable increase in temperatures at the junction points with a violation of the thermal protection performance and the spacecraft as a whole.

Ukrainian experts are also developing thermal protective structures with a metal three-layer outer panel and internal thermal insulation for the windward part of the orbital spacecraft [3]. To ensure complete sealing action of joints and free movement of the edges of the tile with thermal deformations between them, it is proposed to use flexible connecting U-shaped elements acting as expansion joints for the temperature expansion of tiles (fig. 3). This structure completely excludes the penetration of hot gases and atmospheric moisture under the panel of tiles and does not prevent their expansion when heated. The principle of operation of the U-shaped element is shown in fig. 4.

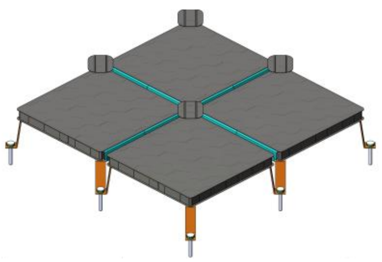


Figure 3 – Panel in assembly

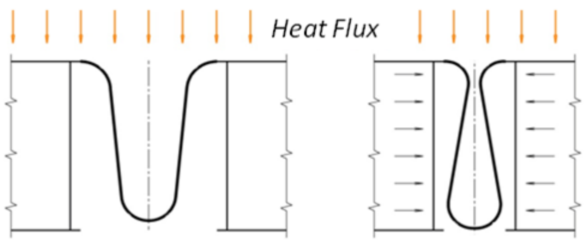


Figure 4 – Scheme of operation of the connecting element

In this case, the U-shaped element itself must be hermetically and reliably connected to tiles, the outer walls of which are thin, thermal resistant plates. Despite the fact that today there are significant developments in the field of welding (in particular, diffusion welding) and soldering elements from thermal resistant alloys [4], it is difficult to apply them for developing technologies for joining non-rigid thin elements into a single structure. The reason is that the materials used are obtained by powder metallurgy, followed by plastic deformation (rolling) to obtain the required sheet thickness. This changes the porosity of the workpiece, and thermal loads lead to structural-phase changes, the formation of intermetallide inclusions and oxides on the surface and in the surface layer, the removal of which is associated, as a rule, with a number of difficulties.

Various heat-resistant alloys are used for manufacturing honeycomb thermal protection. The most perspective of them is the powdered dispersed nano-reinforced material Ni-20Cr-6Al-1Ti-1Y2O3, which has significant perspective in use due to its thermal resistance properties.

Heat-resistant multicomponent alloys, in particular Ni-20Cr-6Al-1Ti-1Y2O3, are used in special engineering, since they successfully withstand the effects of high temperatures (up to 1100-1200 °C), while retaining satisfactory strength, bending linear hardness, other important mechanical characteristics.

Studies aimed at developing ways and methods for obtaining non-detachable compounds (eg, diffusion welding, soldering in vacuum, contact welding on a previously applied substrate), show that the most qualitative for today is diffusion welding in vacuum. The latter involves the creation of not only the high temperatures necessary to activate the diffusion process between the interconnected surfaces, but also significant pressures at the point of contact (up to 50-75 MPa), which, as a rule, are provided, due to the temperature expansion of connected elements those which are enslaved in a special equipment. Typically, such elements are firm and solid specimens, that withstand specified pressures without significant deformations, which lead to errors in the shape of the finished product.

The preparation of specimens, which are spatial non-rigid elements that contact several planes of a small area, did not succeed in this way, which requires the search for methods and techniques for carrying out similar operations with simultaneous optimization of the stiffness parameter of the seam and the absence of significant thermal deformations. An example of products that require the assembly of individual elements in a single design, is a three-layer cellular panel, used, for example, as the re-usable thermal protection of a space vehicle.

The multicomponent Ni-20Cr-6Al-1Ti-1Y2O3 alloy is sufficiently investigated by scientists and technical specialists [1-3], with some papers indicating that the alloy is satisfactorily exposed to diffusion welding and welding-soldering [1].

At the same time, it is noted that the traditional technologies of formation of an indivisible connection of thin plates by loading the junction zone with the nickel-based solder on the basis of nickel with stresses of 35-70 MPa with a subsequent shut-off at a temperature of 1250-1350°C for 15-20 minutes in a vacuum are ineffective. The reason lies in the fact that places for soldering of heat-protective elements are difficult to access; elements and systems of the cellular panels are not rigid, and it is practically impossible to provide such a level of prior compression of surfaces.

Suppose you want to connect two flat elements on the surface, which is a thin strip (fig. 5).

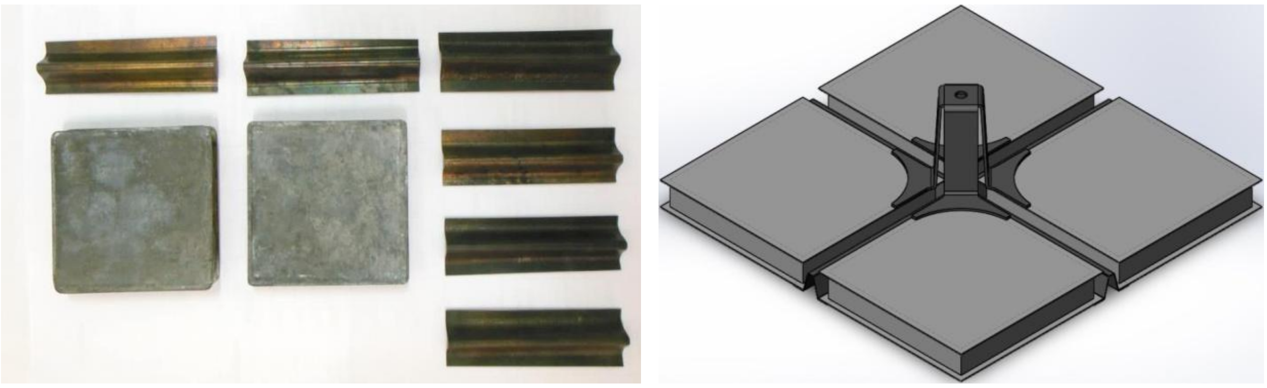


Figure 5 – The unit that is exposed to soldering in a vacuum and its calculation scheme

To ensure reliable welding of plates, two conditions must be fulfilled:

– the pressure between the welded plates should be at least p_{min};

– the temperature of the connection place should be T_n=1330-1350°C and be uniform throughout the length of the seam.

Variation of temperature can lead to incomplete soldering or to the appearance of burning and reflow zones.

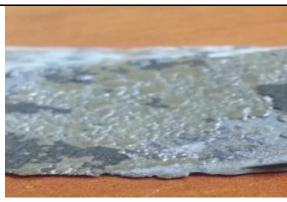
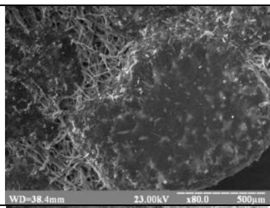
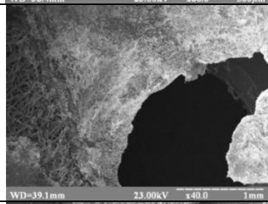
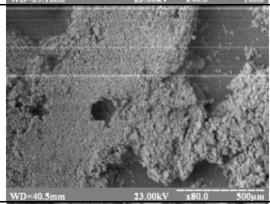
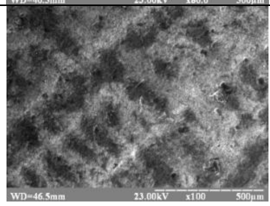
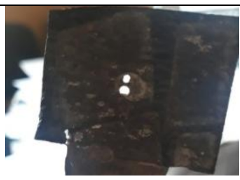
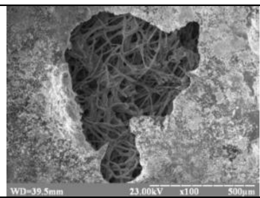
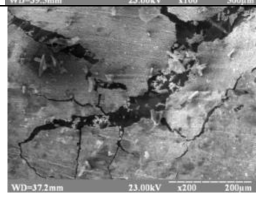
Since the connection is performed in a vacuum, the heating of the welding zone is mainly due to heat radiation and, to a lesser extent, due to the contact of one of the welded elements with a heated base.

Microelectronic and photo-optical studies of the state of elements exposed to soldering in a vacuum are systematized and summarized in table 1. The composition of the material of the plates exposed to soldering, the tendency to form intermetallide inclusions and various defects of the structure during heating, as well as high activity of the components to carbon, necessitated the complete abandonment of graphite-containing substrates and expanded stacks, since in this case, the processes of adhesion were actively manifested and there was no qualitative seam; the microelectronic investigation showed the presence of a graphitized layer, which reduces mechanical properties, mainly in the zone around the seam. Lowering the temperature to prevent curvatures deprived the ability to receive a molten solder in the contact zone of connecting elements (as a result of which the seam simply crumbled), and the temperature rise of more than 1750 K resulted in the combustion of samples on the stocks.

We also observed a characteristic of the alloy, manifested in involuntary start the exothermic reaction in some points of the surface, as a result of which it could be formed burnout of the material.

Use nickel powder without additives as solder led to the fact that the melt layer acquired a fibrous structure and did not provide a seam density. At the same time, the small amount of W in the solder precedes the occurrence of pores in the steam and the area around the seam.

Table 1 – Condition of elements and defects that occur when soldering

Research result	Soldering modes	Macro and micro photos	
Adhesion of the specimen before the substrate	T=1300°C, τ=20 min, p=10^{-1} Pa		
Burnout of the part of material, fistula formation	T=1380°C, τ=15 min, p=10^{-1} Pa		
Incomplete soldering with a fault under the action of a bending moment	T=1250°C, τ=20 min, p=10^{-1} Pa		
Deformation of the finer part of the connection	T=1380°C, τ=15 min, p=10^{-1} Pa		
The appearance of the fistula and the porosity of the seam	T=1400°C, τ=15 min, p=10^{-1} Pa		
Cracking and fracture of a thinner plate	T=1380°C, τ=20 min, p=10^{-1} Pa		

At this stage, a number of unsatisfactory results were received which can be divided into the following groups:

1) Adhesion of the specimen before the substrate;
2) Combustion of the specimen when there is cobalt in the chamber;
3) Incomplete soldering with a fault under the action of a bending moment as a result of temperature deflection in the furnace from a cycle given by controller during asymmetrical loading of the chamber;
4) Burnout of the part of the specimen, fistula formation;
5) Deformation of the finer part of the connection due to the temperature act and asymmetry of the applied load;
6) Cracking and fracture of a thinner plate;
7) The appearance of fistulas (both in machining and during sintering) and the porosity of the seam.

To improve the quality of solder connections and ensure the strength optimization was conducted full-scale experiments.

The regulated parameters were chosen: the maximum temperature of the process T, °C, and excerpt time at the maximum temperature (τ, min), stress in the contact area σ_k, created by the compression of elements between themselves by force P. An additional factor was chosen h – the thickness of the workpiece. Getting regression models that connect the output parameters to each other - the strength of the connection σ and temperature deformation, which manifest them in the error of form ρ_i – and the entrance – carried out according to the classical technique. Total number of experiments $N=2^k+2k+k_0=25$, where $k=4$ – number of factors; $2^k=16$ – full factorial experiment (plan core); $2k=8$ – star points (magnitude star shoulder $\alpha=2$); k_0 = 1 – experiments in the center of the plan.

Levels of variation of factors are shown in table 2. The samples were examined by means of electron microscopy and subjected to mechanical tests. In order to detect the effect of many repetition of soldering cycles on mechanical properties of Ni-20Cr-6Al-1Ti-1Y_2O_3 alloy elements, six times the duplication of heating (according to the thermal soldering cycle) was performed. Such studies are due to the fact that the complete assembly of the honeycomb system in one cycle is complicated.

For soldering using solder: P1 - ВПр36 (composition 0,2% C, 8…10% Cr, 2.5-6,0% Al, 1,4…2,0% Mo, 2…5% Nb, 2…6% W, 2,5…3,0% B, other – Ni); P2 - finely divided powder Ni; P3 – composition Ni, 5% W, 1,0-1,5% B, other - Ni. Soldering was performed by stepped temperature increase on 450-500 °C with short endurance (near 10-15 min) at each level of temperature.

Table 2 – Intervals of variation of factors

Name of factors	Levels of variation		Interval of variation
	-1	+1	
T– soldering temperature, °C	1200	1450	175
τ – duration of the process at maximum temperature, min	15	90	37,5
σ_k – pressing pressure, MPa	0,1	1	0,45
h – workpiece thickness, mm	0,1	1,5	0,7

As a result of optimization of the soldering process, it was possible to obtain a satisfactory qualitative connection of two plates with different thicknesses overlapped with an overlap of 7,2 mm. The area of the adhesive contact during measurements is 68 mm^2, cracks and leakiness at the contact point are completely absent. The thickness of the soldered joint is 0,05-0,15 mm and is due to the initial spatial deviations of the blanks at the point of contact.

To check the accuracy of predictive calculations for a rational mode of soldering, soldering 4 plates of different thicknesses into a single structure was performed in accordance with fig. 3.

Microelectronic studies of the soldering place and mechanical tests have shown the following. On a plate of the largest (0,8 mm) thickness, when a load greater than 25 N was applied, one joint was destroyed. There was also a spreading of solder on the contact surfaces, which not only worsened the appearance of the joint but also changed the mechanical properties of the plate. This is especially dangerous both from the point of view of a slight increase in the mass of the system and from the point of view of the changes in modulus of elasticity and the relative elongation of the base material.

An electron microscopic analysis of the samples shown that in the process of vacuum soldering of the blanks between the united surfaces a nickel adhesive layer is formed, which for solder P2 has a clearly pronounced porous structure, and for solders P1 and P3 – uniform dense (fig. 6). The absence of pores can be explained by the presence B, which somewhat reduces the melting point Ni, and W, which is as a reinforcing layer. Attempt to enter WC instead of W according to results [13], did not give the desired result: even minor content or contact with carbon-containing materials resulted in active carbon erosion of thin plates.

The presence in P1 Al in the solder leads to the formation of intermetallide combinations, which adversely affects the complex of physical and mechanical properties. Spherical aluminides of nickel were also observed in the study of the surface of the adjoining zone, which is conditioned by a slow (about 3-4 hours) cooling of the workpiece together with a vacuum furnace. Such intermetallide inclusion provoked the appearance of grid of microcracks in adjoining zone, which greatly reduced the fracture resistance of connected elements. So, when attempting to perform bending of the plate, the relative elongation of the material on separate layers within 2-3% caused the destruction of the workpiece, and in the crack there was a layered structure due to previous operations of multi-stage rolled sheet and emerging microcracks.

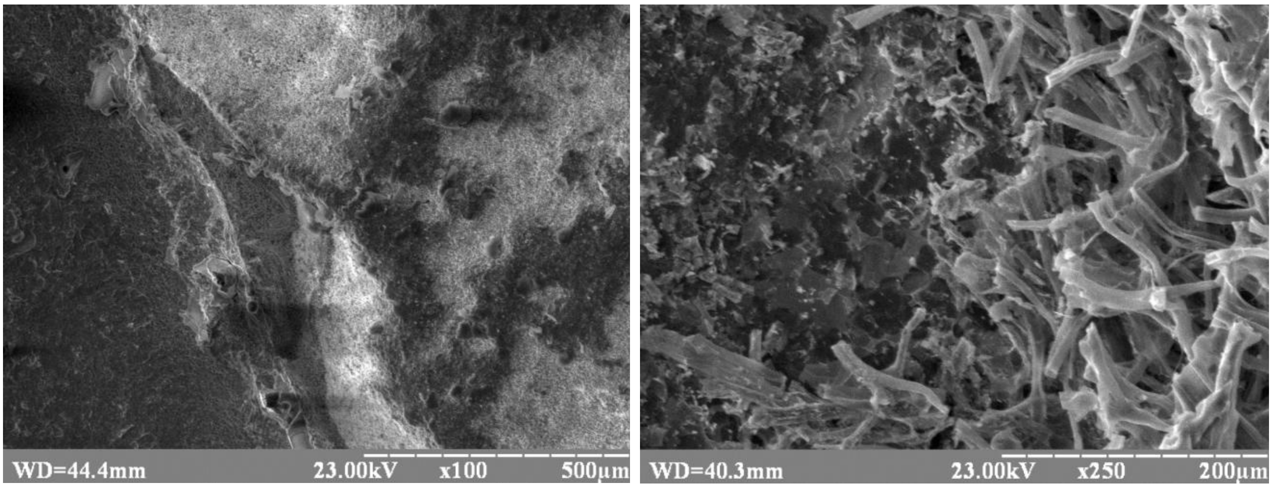


Figure 6 – Comparison of the heat affected zone, formed with the use of tungsten-containing (a) solder P3 and solder without tungsten P2 (b)

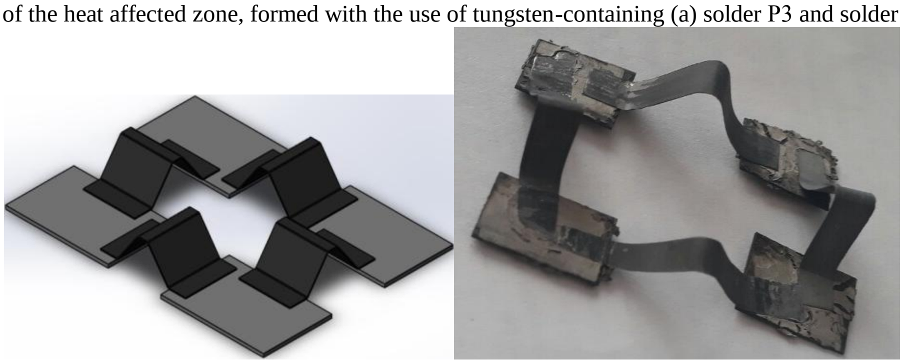


Figure 7 - Soldered structure from 4 plates of different thicknesses: 0,15 mm, 0,4 mm and 0,8 mm. The dimensions of the plates are 6×6 mm, the width of the connecting u-like tapes is 2,0 mm, the thickness of the tapes is 0,15 mm, the theoretical contact area is 7,0 mm^2

Such a conclusion is made for the following reasons. The layer of solder that spreads on the surface has a porous structure, and in the case of alternating cyclic loads, it can cause cohesive damage of the material at the places of contact with the surface by the growth of microcracks oriented at angles to the contact surface.

We also proved the conclusion about the need for a correct geometric docking of the elements before welding, since the existing spatial deviations are not satisfactorily reflected in the strength of the joint.

Testing the strength of the resulting connection by force loading of the plates on the bursting machine showed that the destruction of the specimen occurred when the load reached 520 N, corresponding to the voltage at the intersection of the gap of 320±10 MPa, and the destruction itself was not on the welded seam, but in the zone of spreading solder on a plate, in a place in front of a soldered seam. The difference in the claimed strength limit of 991 MPa can be explained by the following reasons:

1) thin specimens exhibit somewhat different properties compared to the specimens in the form of rods, thick plates, etc.;

2) after welding by volumetric heating in the material, certain processes of intermetallide formation probably take place, which can reduce the ultimate strength, yield stress, elasticity and elongation of the material. To clarify these circumstances, more research is needed;

3) in the place of destruction, there are defects that can be stress concentrators, which reduces the resistance to fracture of the material.

In order to improve the soldering of products and increase the strength of the joining, it is advisable to use a function-oriented approach.

Functional approach to development and creation of new machines, objects and complex technical systems was studied by many researchers, in particular, E.I. Galibardov [6]. He states that any material object is characterized by a certain totality (matrix) of functions among which it is possible to single out useful, harmful and neutral functions. Unlike a material approach, a functional approach is based on the fact that the product is made to perform a number of functions provided by corresponding material carriers (the cheapest ones or the ones with the least costly manufacturing steps).

This approach can also be applied to working technologies: the manufacturing process expressed through material carriers is to be minimized according to criteria taken into consideration – working time, cost price, quality. Systemized data of this approach are presented in a number of papers, e.g. [7]-[9].

The idea of modularity of technological processes (TP) and their functional orientation can develop in the following direction.

As all types of functions (useful, neutral and harmful) are available in a final product, manufacturing steps are to be oriented in such a way that harmful functions be weakened and useful ones, in their turn, be obtained in the minimum number of steps. Under these conditions a technological process can be considered prospective if weakening or complete elimination of harmful functions takes place along with creation of useful functions during the steps.

Analysis of typical products of mechanical engineering from the point of view of functional approach reveals that practically always creation of a particular useful consumer function F_p will go together with manifestation of neutral F_n and harmful F_v functions. Then a product having only useful (under certain conditions) functions is ideal from the point of view of operation:

$$F_p = F_{pz},\ F_v = 0,\ F_n \rightarrow \min, \tag{1}$$

where F_{pz} – product useful functions having the following matrix of consumer properties:

$$\boldsymbol{P} = \sum_{i=1}^{l} F_{pi} + \sum_{j=1}^{m} F_{nj} + \sum_{k=1}^{p} F_{vk}. \tag{2}$$

Hence, an equation of restrictions (1) and optimization (2) makes it possible to choose the most rational material carriers of functions on the basis of morphological analysis, then to pass to material carriers in the technological process creating these functions.

As there is a functional interrelation between separate functions, i.e.

$$F_v = pF_p,\ F_n = qF_p. \tag{3}$$

taking into account the fact that a function is created by a separate TP step in the form of transformation element W_p (2) can be presented in the following form:

$$\boldsymbol{P} = \sum_{i=1}^{l} W_{\mathrm{p}} F_{pi} + \sum_{j=1}^{m} W_n q F_{pj} + \sum_{k=1}^{p} W_v p F_{pk}. \tag{4}$$

Taking into consideration the fact that TP cannot be aimed at creation of harmful functions and properties in the product, minimization of the unnecessary functions is expressed by dependence:

$$\boldsymbol{P} = \sum_{i=1}^{l} W_{\mathrm{p}} F_{pi} + \sum_{j=1}^{m} \overline{W_p} q F_{pj} + \sum_{k=1}^{p} \overline{W_p} p F_{pk}, \tag{5}$$

or, after transformation, in the following way:

$$\boldsymbol{P} = \sum_{i=1}^{l} F_{pi} \left(W_p + \overline{W_p} q + \overline{W_p} p\right). \tag{6}$$

Approaching of the totality of the product properties to the ideal implies transformation of summands $\overline{W_n q}$ and $\overline{W_v p}$ into zero, which is possible under the condition of absence of functional relation between useful and harmful properties of the product or under the conditions that the process of obtaining useful properties due to a particular TP step is at the same time the inverse one as to the occurring harmful functions. Availability and interrelation of TP separate elements enable presentation of (6) in the following way:

$$\boldsymbol{P} = \sum_{i=1}^{l} F_{pi} \left(W_p + \overline{W_p} q + \overline{W_p} p + \overline{W}_p (p+q)\right). \tag{7}$$

For totality of alternative variants of TP the obtained equality is supplemented by quantitative signs of every function the integral sum of which is equal to 1, then

$$I = \sum_{i=1}^{l} F_{pi} \left(b_{ki} W_{pi} - b_{vi} \overline{W_{pi}} p - b_{ri} \overline{W}_{pi} (p+q)\right). \tag{8}$$

under the condition that $\overline{b_{ni} W_{pi}} q = 0$. Here b_{ki}, b_{vi} – corresponding weight coefficients of each of the useful, harmful functions; b_{ri} – weight coefficients of interaction of independent steps revealing reserves in improvement of output properties of the final product.

Describing the object by setting its initial condition C_n, as a totality of parameters characterizing the form and dimensions of the workpiece, its physical and mechanical properties and final condition C_k via particular forms (dimensions, relative position of the surfaces, physical and mechanical properties, etc.), the technological transformation function φ_0 is presented as:

$$\varphi_0 : \begin{Bmatrix} C_{n1} \\ C_{n2} \\ \vdots \\ C_{nR} \end{Bmatrix} \rightarrow \begin{Bmatrix} C_{k1} \\ C_{k2} \\ \vdots \\ C_{kT} \end{Bmatrix} \qquad (9)$$

where C_{nR} – r -th elementary property of the workpiece; C_{kT} – t -th elementary property of the product; R, T – total number of parameters of the workpiece and the product, respectively. The function $\varphi_0 = \Sigma W_i E_j$, E_j – the product separate elements creating its properties.

As the product separate functions expressed via obtaining parameters of geometric accuracy, condition, structure, etc. can be generated in different ways, it is expedient to create morphological tables that may provide the basis for search of more rational variants of combination of technological actions.

The product properties are generated as a result of a number of manufacturing steps during which a complete or partial change of the initial properties takes place. Technological transformation of a workpiece into a product is achieved by purposeful total technological impacts $W_{ij}(t_k)$ of material $S_o(t_k)$, energy $E_o(t_k)$ and information $I_0(t_k)$ types which enables presentation of a scheme of output properties generation according to Fig.3 and writing down:

$$W_{ij}(t_k)=S_o(t_k)\cup E_0(t_k)\cup I_o(t_k).$$

Then, on the grounds of the condition that tool technological impacts on the product are to be performed at the levels from nano-areas to the product on the whole, and the product is a 3D object, to realize the totality of variants of technological impacts the morphological matrix will correspond to the following form:

$$A_3^{\Pi} = \begin{Vmatrix} \Pi_{11}^S & \Pi_{12}^S\ldots & \Pi_{21}^S & \Pi_{22}^S\ldots & H_{11}^S & H_{12}^S\ldots & H_{21}^S & H_{22}^s\ldots & E_{11}^S & E_{12}^S\ldots & E_{21}^S & E_{22}^S\ldots \\ \Pi_{11}^t & \Pi_{12}^t\ldots & \Pi_{21}^t & \Pi_{22}^t\ldots & H_{11}^t & H_{12}^t\ldots & H_{21}^t & H_{22}^t\ldots & E_{11}^t & E_{12}^t\ldots & E_{21}^t & E_{22}^t\ldots \\ \Pi_{11}^v & \Pi_{12}^v\ldots & \Pi_{21}^v & \Pi_{22}^v & H_{11}^v & H_{12}^v\ldots & H_{21}^v & H_{22}^v\ldots & E_{11}^v & E_{12}^v\ldots & E_{21}^v & E_{21}^v\ldots \end{Vmatrix}$$

where Π_{11}^s, Π_{12}^s, ...; Π_{21}^s, Π_{22}^s, ...; $\Pi_{11}^t, \Pi_{12}^t, \ldots$; $\Pi_{21}^t, \Pi_{22}^t, \ldots$; $\ldots \Pi_{11}^v, \Pi_{12}^v$, ...; Π_{21}^v, Π_{22}^v, ...; ... – variants of discontinuous technological actions along the corresponding axes *s*, *t* and *v* of the coordinate system of *s, t, v;* H_{11}^s, H_{12}^s, ...; H_{21}^s, H_{22}^s, ...;. H_{11}^t, H_{12}^t, ...; H_{21}^t, H_{22}^t, ...; H_{11}^v, H_{12}^v, ...; H_{21}^v, H_{22}^v, ... – different variants of continuous technological actions along the axes *s*, *t* and *v* of the coordinate system of *s, t, v*; E_{11}^s, E_{12}^s, ...; E_{21}^s, E_{22}^s, ...; – different variants of one-time technological actions.

Presence of variants of discontinuous technological actions makes it possible to consider processing of one element of the product in the form of a successive totality of different actions. In this case if the element geometric characteristics (e.g. flatness, accuracy of linear dimensions) are its output index, this process can be realized by different types of actions that more completely correspond to the properties of the workpiece elements.

For the problems of ensuring the quality of soldering, we need to provide such a redistribution of temperatures, in which the optimum must to be a warmed end-to-end zone of soldering, and minimal - the planes of the honeycomb.

It is known that the amount of energy emitted by a surface element dF, oriented at a spatial angle $d\Omega$ and φ - the angle between the direction of radiation and the normal to the surface, will be determined as

$$dQ_\varphi = E_n d\Omega dF \cos\varphi\,, \qquad (10)$$

where $E_n = 4{,}9\dfrac{\varepsilon}{\pi}\left(\dfrac{T}{100}\right)^4$; ε – the degree of blackness of the radiating body; then

$$dQ_\varphi = 4{,}9\frac{\varepsilon}{\pi}\left(\frac{T}{100}\right)^4 d\Omega dF\cos\varphi\,.$$

Since the heated body has a sufficient length, the temperature regime at each particular point can be determined by the third-generation boundary conditions

$$\lambda\frac{\partial T(M,t)}{\partial n}\bar{l}_n = \sigma\left(T_2^4 - T_1^4(M,T)\right),$$

where σ – constant Stefan-Boltzmann: $\sigma=5{,}67\times10^{-8}$W/(m^{2}K^4); $\bar{l}_n$ – vector normal to the surface of the body; λ – coefficient of thermal conductivity of the absorbing body.

Simultaneously with the transfer of heat by radiation, the specimen will receive heat and from the base on which it is located, which is determined by the boundary conditions of the 4th genus:

$$\lambda\frac{\partial T(M,t)}{\partial n}\bar{l}_n = \lambda_2\frac{\partial T_2(M,t)}{\partial n}\bar{l}_n\,, \qquad (11)$$

where λ_1, λ_2 – the coefficient of thermal conductivity of the absorbing and radiating body, respectively.

The simplified amount of transferred heat Q_Σ from the N heating lamellae of the vacuum chamber, taking into account the partial reflection from the body, which is heated, predetermined ε, can be defined as:

$$Q_\Sigma = Q_k + NQ_z - Q_o = \frac{\lambda}{H} ts(T_1 - T_2) + N\gamma s\sigma T_1^4 - F\omega\cos\beta\varepsilon\sigma T_1^4 \qquad (12)$$

where φ – coefficient of «not blackness», ω – the corporal angle in which radiation occurs, β – the angle between the direction of radiation and the normal to the surface.

For a cylindrical coordinate system, the temperature change T on the surface of the plate, which receives heat by radiation from heaters:

$$\frac{\partial T_1}{\partial n} = \alpha\nabla^2 T_1 + \frac{q}{c\rho}, \quad \nabla^2 T_1 = \frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial\varphi^2} + \frac{\partial T^2}{\partial z^2}.$$

Here r, φ and z – radial, angular and axial coordinates respectively.

An increase in the temperature of a specimen causes its thermal expansion, which for a plate is defined as follows: $\Delta l = \alpha T l_0$ then the emerging stresses with a solid latching of plate will be: $\sigma_t = \alpha ET$.

Since the heating of the plate occurs with several lamellae, located around the base at a certain distance, and the plate itself is on the heat insulating surfaces, it is quite difficult to obtain a picture of the temperature deformations in general. To solve this problem, and taking into account the configuration of the body, which is heated, perform modeling of temperature fields in ANSYS 18.1. Let's take into account the real design features of the used vacuum equipment: the diameter of the platform for installation 320 mm; plate dimensions 75×75 mm; plate thickness h_1=0,4 mm; h_2=0,14 mm. The soldered elements are located on ceramic plates in the thickness of 7,5 mm; the thermal conductivity of which is much less than the thermal conductivity of the base and the soldered elements.

The transition from the plate to the assembled cellular structure requires taking into account the temperature change in height and on the surface of the heated body. In order to prevent the overheating of the cellular structure during the soldering, thermal ballasts in the form of heat sinks made of solid alloy are installed on the table. Their diameter is d_b=35 mm, h_b=50 mm.

Figure 8 shows the results of calculations of the thermal field at the time of heating end and the picture of thermal radiation of elements that are on the table.

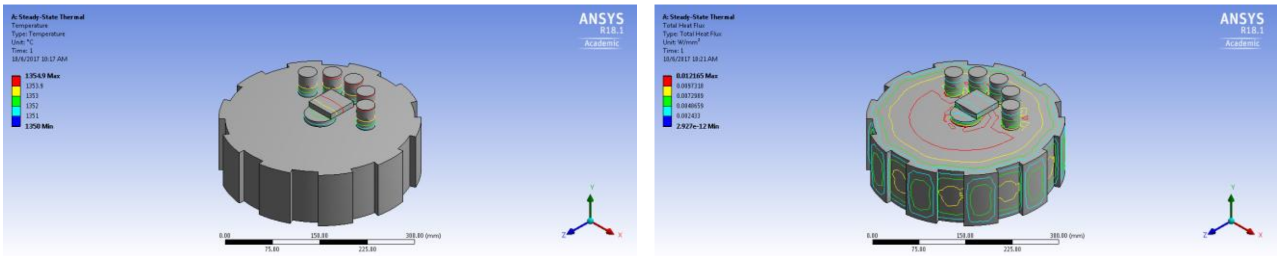
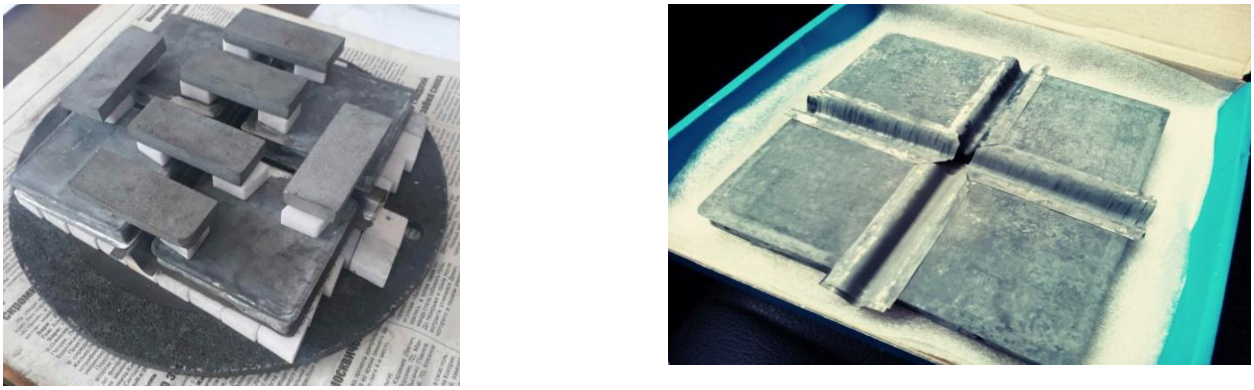


Figure 8 – Temperature fields and radiation of heated bodies in the chamber of vacuum furnace

It is shown that on the plate the temperatures are distributed unevenly, which will result the hogging of the plate or the structure as a whole. It is possible to reduce deformation of elements by using clamping plates, the mass m_p of which should be sufficient to prevent hogging, and at the same time, not cause significant deformations of the construction for which $\sigma_в^{1500\ K}$=45 MPa.

Thus, solving the problem of ensuring the quality of solder joining of elements in a single design requires the definition of rational solder conditions, the placement of ballasts for changing the conditions of absorption of radiant heat, as well as the scheme of loading the seams with clamping elements.



a b

Figure 9 – Scheme of placement of elements during soldering the design on the palette of the vacuum furnace (a) and layout after soldering in the vacuum furnace (b)

In order to detect the effect of several soldering cycles on the mechanical properties of Ni-20Cr-6Al-1Ti-1Y2O3 alloy elements, we performed a duplication of heating with a thermal soldering cycle. It was established that after a 3-fold heating, thin plates of the experimental specimens began to be rapidly destroyed with the formation of end defects in the form of burns and fistulas.

Thus, since the soldering temperature of the elements with high-temperature solders is 1350-1375°C, it can be concluded that it is desirable to assemble the construction with the minimum number of operations (possibly one).

Consequently, as a result of our work, we were able to gradually test the technologies of obtaining the welded-soldered joints elements into a single system and prove the perspective of using Ni-20Cr-6Al-1Ti-1Y2O3 material for use in ultra-light thermal protection of reusable spacecraft with appropriate technological upgrading of the design, refining it to process ability and adapting to the conditions of assembly into a single system.

CONCLUSION

As a result of the work, samples of permanent joints were obtained: a single plate, a model of a multiplanar system with u-shaped bridges; sample mock-up.

It has been established that a dense non-porous seam is obtained with the use of solders ВПр36 (WPr36) and own solder with a content of W 8-9%, and the process of vacuum soldering should take place at a temperature of 1350°C for 15-20 minutes. The strength of the obtained compound is 390-420 MPa when the specimen is stretched by a tensile machine (with the appearance of tangential stresses). Surfaces for connection must be cleaned chemically and mechanically up to *Ra* 1,25-2,5 µm, non-flatness and deformation of the surfaces are not allowed (permissible deviation is 0,03 mm/100 mm of reference length).

The soldering of the heat-protective system is desirable to be carried out in a single setup in a vacuum chamber, while the control of the process should be carried out at the temperature in the soldering spot.

Promising is the approach of using heat shields and heat conductors, which at the same time serve as means for compressing the soldering zone to a value of 0,6-0,8 MPa.

4. REFERENCE

[1] Metallic Thermal Protection System Requirements, Environments, and Integrated Concepts / John T. Dorsey, Carl C. Poteet, Kathryn E. Wurster et al. Journal of Spacecraft and Rockets. 41 (2) (2004) 162-172.

[2] Improving Metallic Thermal Protection System Hypervelocity Impact Resistance Through Numerical Simulations / Carl C. Poteet, Max L. Blosser. Journal of Spacecraft and Rockets. 41 (2) (2004) 221-231.

[3] Metallic Thermal-Protection-System Panel Flutter Study / Roger R. Chen, Max L. Blosser. Journal of Spacecraft and Rockets. 41 (2) (2004) 207-212.

[4] Poteet C.C., Blosser M.L., Improving Metallic Thermal-Protection-System Hypervelocity Impact Resistance Through Numerical Simulation, journal of spacecraft and rockets Vol. 41, No. 2, March-April 2004.

[5] European Directions for Hypersonic Thermal Protection Systems and Hot Structures/ David E. Glass NASA Langley Research Center, Hampton// 31st Annual Conference on Composites Materials and Structures Daytona Beach, FL, January 22, 2007.

[6] Заявка на патент Украины № И 2013 13658 от 25.11.13г., Потапов А.М., Шевцов Е.И., Тихий В.Г., Гусарова И.А., Скороход В.В., Фролов Г.А., Солнцев В.П., «Багатошарова теплозахисна система багаторазового космічного апарату».

[7] Проблемы создания теплозащиты возвращаемых аэрокосмических аппаратов / Гусарова И.А., Потапов А.М., Манько Т.А. – «Технологические системы», - г. Киев, - 2017.

[8] Багрянский К. В. Теория сварочных процессов / К. В. Багрянский, З. А. Добротина, К. К. Хренов. – К.: Вища школа, 1976. – 524 с.

[9] Коперсак В.М. Теорія зварювальних процесів-2. Фізико-хімічні та металургійні процеси при зварюванні : текст лекцій / В.М. Коперсак. – К.: Вид-во НТУУ «КПІ», 2011 – 252 с.