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PROVIDING MECHANICAL CHARACTERISTICS OF WELDING-SOLDERED THIN-WALLED STRUCTURES OF FIVE-COMPONENT HEAT-RESISTANT ALLOYS

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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.

INTRODUCTION

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.

EXPOSITION

Suppose you want to connect two flat elements on the surface, which is a thin strip (fig. 1).

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.

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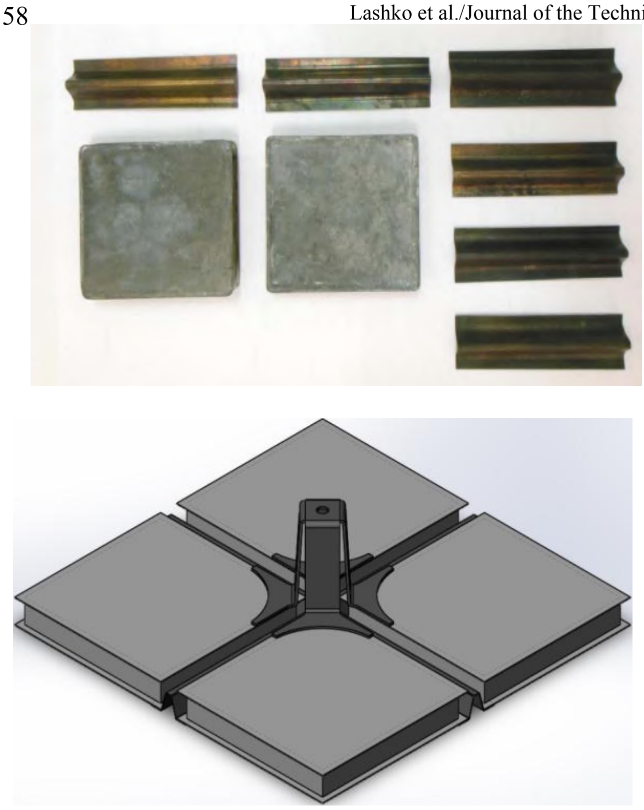


Fig. 1. *The unit that is exposed to soldering in a vacuum and its calculation scheme*

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

$$dQ_{\varphi} = E_n d\Omega dF \cos\varphi, \tag{1}$$

where $E_n = 4{,}9\frac{\varepsilon}{\pi}\left(\frac{T}{100}\right)^4$; 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.

$$\lambda\frac{\partial T(M,t)}{\partial n}\bar{l}_n = \sigma\left(T_2^4 - T_1^4(M,T)\right), \tag{2}$$

where

σ – constant Stefan-Boltzmann: σ=5,67×10^{-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:

$$\lambda\frac{\partial T(M,t)}{\partial n}\bar{l}_n = \lambda_2\frac{\partial T_2(M,t)}{\partial n}\bar{l}_n, \tag{3}$$

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:

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

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:

$$\frac{\partial T_1}{\partial n} = \alpha\nabla^2 T_1 + \frac{q}{c\rho},$$

$$\nabla^2 T_1 = \frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial\varphi^2} + \frac{\partial T^2}{\partial z^2}.$$

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: $\sigma_t = \alpha E T$.

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 2 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.

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.

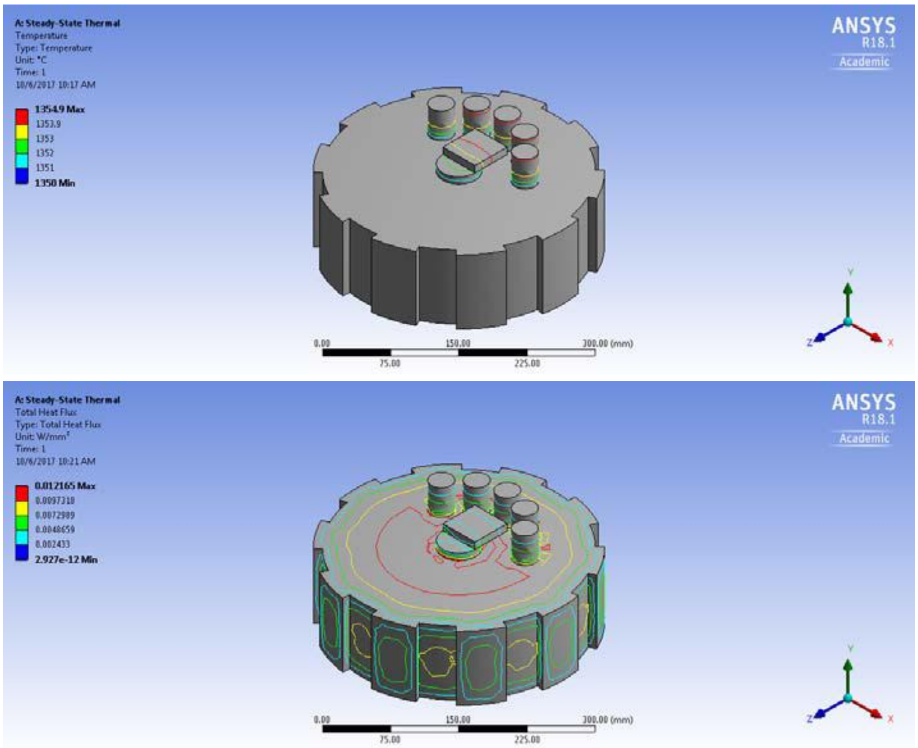
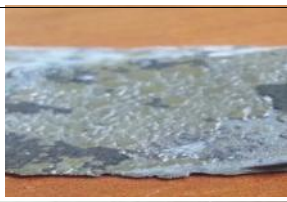
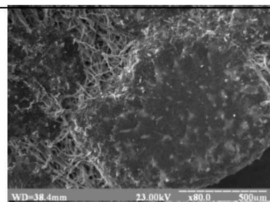
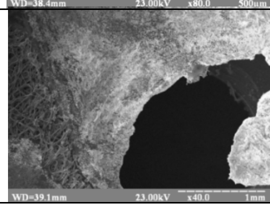


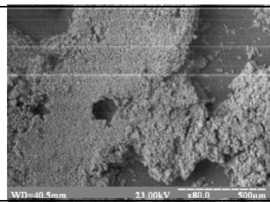
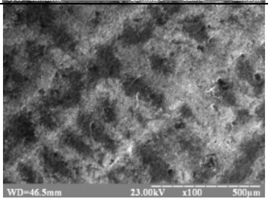
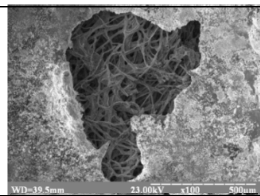
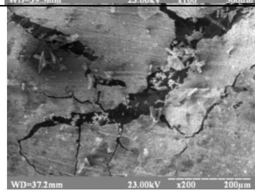
Fig. 2. *Temperature fields and radiation of heated bodies in the chamber of vacuum furnace*

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 intermetallic 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.

Table 1. *Condition of elements and defects that occur when soldering*

Research result	Soldering modes	Micro and macro 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		

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.

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.

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.

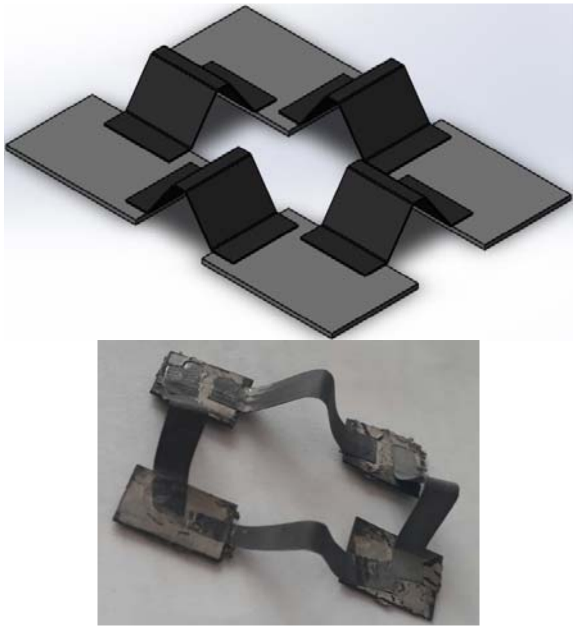


Fig. 3. Soldered structure from 4 plates of different thicknesses: 0,15 mm, 0,4 mm and 0,8 mm. The dimensions of the plates are 6×6 mm, the width of the connecting u-like tapes is 2,0 mm, the thickness of the tapes is 0,15 mm, the theoretical contact area is 7,0 mm2

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 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 processability 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.

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.