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THIN-WALLED WELDED TRANSFORMABLE-VOLUME STRUCTURES OF SPACE PURPOSE

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The rational methods of construction of metal transformable shells with the aim of creation of the space-purpose structures were investigated. The mathematical modeling of the neutral shell surface movement of the transformable-volume structure (TVS) was performed, the result of which was used to set the reference surface at the kinematic modeling of its stress-strain states during a compact folding. The parameters of the process of welding thin shells of stainless steel were determined, guaranteeing the maximum approaching of physicomechanical properties of welded joints to similar properties of the base metal, thus providing their vacuum density. The methods of surface modification of thin metal shells of stainless steel, which allow improving the safety margin of TVS of space purpose without changing their mass and compactness were developed. The possibility was experimentally confirmed and the conditions of stability of complete reverse transformation of a multisectional conical-type TVS were formulated. 7 Ref., 12 Figures.

Keywords: *deployable structures, thin shells, microplasma welding, microstructure and weld metal, surface engineering*

The relevance of works on creation of transformable-volume structures (TVS) is predetermined by the contradiction between the need in creating shell-type structures of the necessary parameters and the possibility of their further delivery to the site of operation under the conditions, which exclude the feasibility of realizing their long-time and labor-intensive manufacturing process at the intended site. The most typical example of solving such problems can be the delivery of elements of aerospace engineering, based on shell-type structures, to the near-earth orbit. At the same time, the engineering progress has a demand for shells of ever-increasing volume, the range of application of which is restricted, first of all, by the lack of appropriate means of transportation.

The deployable shell structures allow simplifying the delivery of a payload to the near-earth orbit and represent a one of the areas of space technologies being actively developing. They are divided into three main classes: soft load-carrying; those, constructed on the base of a transformable frame and rigid ones. In the world practice, among the first TVS the transformable load-carrying soft shells found industrial application, which were used in building industry, during construction of aircrafts and spacecrafts. In the last decade, the attempts were made to test prototypes of inhabited transformable shell-type structures outside the earth's atmosphere. For today, the project of NASA and «Bigelow Aerospace» «BEAM» (Bigelow expandable activity module) was realized, which implements the task of creating a segment of the International Space Station (ISS) with a soft shell. In 2016, the module BEAM was delivered to the orbit in a nonsealed cargo container of the «Dragon» spacecraft; after docking the capsule to the ISS, the module was deployable by the inner pressure of the station until reaching the design dimensions — 4 m length and 3.2 m diameter, in this case the initial length increased by 1.86 times [1].

The modern materials with new properties allow creating space deployable structures [2], the ratio of linear transformation K_t of which can reach 10; however, the problem of combining these parameters with a sufficient strength, air-tightness and service life of shells remains unsolved. It is obvious that technologically acceptable characteristics with a simultaneous air-tightness are achievable only in rigid load-carrying shells, whose surface transformation into a more compact form requires extraordinary solutions in the field of technologies of cold volumetric deformation.

At the E.O. Paton Electric Welding Institute the possibility of transforming the volume of closed all-welded metal shells, which were called TVS, was theoretically grounded, and in empirical way the technological solutions for its implementation were found ([3, 4]). The use of existing modifications at the present stage required the selection of a type of load-carrying TVS acceptable for using in space technology, the working out of new design and technological solutions for load-carrying TVS and the creation of a universal computational model, which allows determining geometric and technological parameters during designing and manufacturing of a wide range of TVS using different structural materials in relation to the extreme conditions of operation in the open space. Thus, the general aim of the mentioned works was to develop the scientific fundamentals for the theory of construction of deployable shell structures of space purposes. Their practical embodiment is the applied development and the further investigations of all-welded thin-walled load-carrying TVS, which are optimized for applying in the open space and can be used during implementation of existing and future aerospace projects.

The fulfillment of the specified task required definition of the following:

- type of transformable surface, optimal for designing and manufacturing the metal long-length TVS of space purpose, as well as the designing scheme of TVS, which requires the creation of a computational methodology, which determines the relationship between its geometric, technological parameters and space environmental factors (SEF), under the action of which the structure is in the process of operation;
- universal algorithm for transformation of a surface of a selected type to a compact form, which allows structure deploying without losing its functional properties, and the technology of volumetric deformation, in which the specified algorithm should be implemented for real shell materials.

In creating of transformable shells a class of surfaces, theoretically capable of deploying into a plane is of the greatest interest. These are linear surfaces of zero Gaussian curvature: cylindrical, conical, and developable surfaces. The first two classes can serve as the base for construction of shell structures and are widely used in engineering. However, isometric transformation of a cylinder by the method of mirror reflection cannot be realized through the equalities of any its horizontal intersections, and transformation by movement in all the cases is reduced to partition a cylindrical surface into many adjacent flat polygons, similar to the «origami folding» transformation schemes [2]. The movement to the plane of a cylindrical shell of real sheet materials in such a case represents a bending with non-zero radii along the lines of their joining, which leads to the formation of stress concentrators, most pronounced at the assemblies of shaping fins, and a significant reduction in the compactness of a transformable shell. In particular, the simplest principle of transformation of TVS of cylindrical type with the use of the so-called hyperboloid fold (Figure 1, *a*, *b*) allows achieving transformation ratios K_t, i.e. the ratio of lengths of the structure in the deployed and compact state, which do not exceed the values $K_t = 4.0$–4.5.

The use of thin-sheet metals as a material for shells and the application of the considered methods of their transformation impose restrictions on the ratio of their height and bases diameters, which, ultimately, requires the sectioning of a long-length structural shell. Thus, the bases profiles of cylindrical TVS sections (Figure 1, *a*) are not flat curves at any moment of deformation, therefore, the adjacent sections cannot be joined with each other without rigid fixing on a flat circumferential contour. The influence of the edge effect near the shell rigid contour boundary leads to the characteristic distortion of rectilinear shell folds along the lines of generatrices (Figure 1, *b*, *E*), which are the main cause of a low compactness of the cylindrical-type transformable shells.

TVS of the conical type (Figure 1, *e*) is characterized by higher deformability, however, it is capable to compensate higher values of the load without losing stability. Except of high values of the linear transformation coefficient, it can reach the value of $K_t = 150$,

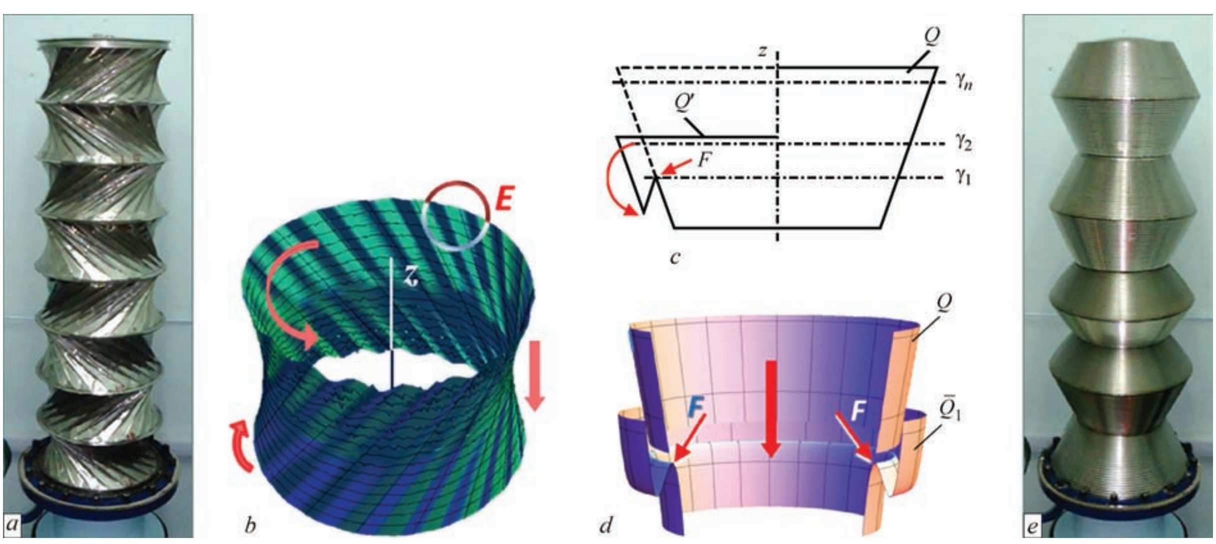

Figure 1. Cylindrical TVS (*a*) and topological model of transformation of neutral surface of cylindrical shell into hyperbolic folds (*b*); transformation of neutral surface of conical shell into circumferential folds: theoretical model of isometric transformation (*c*) and graphical interpretation of mathematical model of movement during formation of the fold *F* with non-zero bending radii (*d*); conical TVS (*e*)

the conical shell is the only one of the linear surfaces, the compact transformation of which can be implemented almost without tensions and compressions (Figure 1, *d*), and, so, with a practical approximation to the theoretical model of isometric transformation of surfaces $Q \rightarrow Q'$ by successive mirror reflection with respect to the cutting planes γ_1–γ_n (Figure 1, *c*). The totality of these advantages allows confirming the rationality of using TVS of the conical type when solving the problem of creating long-length TVS.

The considered task of creating a long-length load-carrying transformable structure was oriented to the solution of the actual problem of removing the payload (PL), i.e the research equipment of 40 kN weight beyond the limits of the own outer atmosphere of the ISS, the negative effect of which on the performance of PL devices is pronounced at the distance of 5 m from the space station outer surface. Some of the basic geometric parameters of TVS are predetermined by the characteristics of the transport compartment of the rocket-carrier (the maximum diameter of structure shell, its size in the transport state and the inner volume after deployment). In addition, TVS of the specified length in the conditions of the action of regulated inertial and temperature loads should have a double safety margin and provide the absence of deviations of a free end with a PL for more than 150 mm.

To construct a computational model of a multisectional conical shell, the ratios of the main geometric parameters of a long-length conical TVS were determined. Thus, the task of using the structure also predetermined its total length L = 5 m and the maximum diameter D = 400 mm, which allows presetting the radius of the larger base of the conical sections. The compactness of a multisectional structure is regulated by the value of its height in a compact state (h_{pack}) and the inner volume in the state of deployment (V_{TVS}). The acceptable angles of the shell conicity α were determined, at which its bending with compliance with the admissible values of relative circumferential deformations in structural materials is accepted. For metallic materials widely used in the aerospace industry with a ductility margin within the range of σ_y/σ_t = 0.3–0.8, admissible for realization of the task of volumetric deformation of the test shells, the values of relative deformations should not exceed the values $\varepsilon_{c.d} \leq$ 2.0–2.5 %. According to the scheme of deformation of a thin metallic shell, corresponding to Figure 1, *d*, the obtained values of relative circumferential deformations correspond to the values of the conicity angle α = 25–27°.

Further, an auxiliary parameter was introduced: the coefficient of volumetric transformation $K_V = V_1/V_2$, where V_1 is the volume of a truncated conical shell; V_2 is the volume of the shell in a compact state. At the preset values of the conicity angle α and the length L, as well as the known values of R, K_V, h_{pack} and V_{TVS}, the determination of the basic geometric characteristics of TVS is reduced to finding the radius of the smaller base r; the height of the conical section in the compact state h, which is accepted to be equal to the depth of the formed corrugation a; required, in accordance with the specified characteristics, compactness of the number of folds (corrugations) n_1, and, accordingly, to the number of TVS sections n (Figure 2).

Having expressed the coefficient of volumetric transformation K_V through the main geometric parameters of the transformable conical section

$$K_V = \frac{(R-r)\mathrm{ctg}\alpha}{3h}\left(1+\frac{r}{R}+\frac{r^2}{R^2}\right), \quad (1)$$

let us write the expression for r:

$$r = -\frac{R}{2}+\sqrt{\frac{3V_{TVS}}{\pi L}-\frac{3}{4}R^2}. \quad (2)$$

Then, it is possible to determine the parameters:

$$n = \frac{L}{\mathrm{ctg}\alpha(R-r)}; \quad h = \frac{h_{pack}}{n}; \quad n_1 = \frac{L}{2hn}. \quad (3)$$

Thus, after determining the thickness of shell material within the range δ = 0.1–0.2 mm, predetermined by the desire to limited decrease in the mass of the structure at a simultaneous providing the integrity of welded joints after extreme deformation, the task of construction of a complete calculation scheme of multiconical TVS was limited only by determining the optimal width or step of the fold (corrugation) *b*.

The fundamental difference in the transformation scheme for real materials (Figure 1, *d*) from the scheme of isometric transformation in Figure 1, *c* is

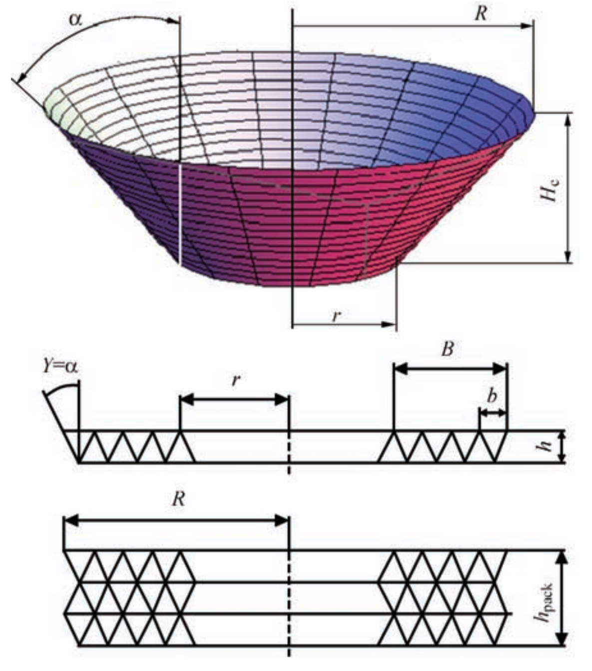

Figure 2. Calculation scheme of multisectional conical shell

the introduction of nonzero radii of bending r_c of the fold *F*, which are determined, first of all, by the TVS shell thickness. To determine the geometric parameters of the conical shell corrugation of metallic materials of a preset thickness, an adaptation of its finite profile to the known requirements of not exceeding the minimum bending radius for thin plates and shells was carried out. The determination of the minimum bending radii of the fold (4) was carried out by the admissible value of thinning at the apexes of corrugations formed:

$$\Delta\delta = \frac{\delta^3}{4(2r_{\text{cirv.}} + \delta)^2}, \quad (4)$$

where Δδ is the size of thinning; δ is the workpiece thickness; $r_{\text{curv.}}$ is the radius of the curvature of middle surface, $r_{\text{curv.}} = r_c + \delta/2$.

From the formula (4) it follows that the maximum reduction in thickness (at $r_c = 0$) amounts to approximately δ/4 and at $r_{\text{curv.}} \geq 5\,\delta$ the thickness at bending remains almost unchanged (Figure 3, *a*).

The relative radius of rounding the support fins r_c can be found as a circle radius using the semi-graphical method in the medium Wolfram Mathematica, being maximum approximated to the profile of corrugation flat apex (Figure 3, *b*), and corresponds to the ratio:

$$r_c = 0.15b, \quad (5)$$

where *b* is the corrugation pitch.

Having chosen the mean value of material thickness δ = 0.15 mm from the specified range for preliminary calculations, according to (5) and the ratio $r_c/\delta = 5$, it is possible to determine the value $r_c = 0.75$ mm, which corresponds to the corrugation pitch *b* = 5 mm. It is obvious, that the obtained geometrical ratios of a corrugation of a metal shell correspond to its highest compactness, i.e. the smallest radius of rounding at the fold apexes.

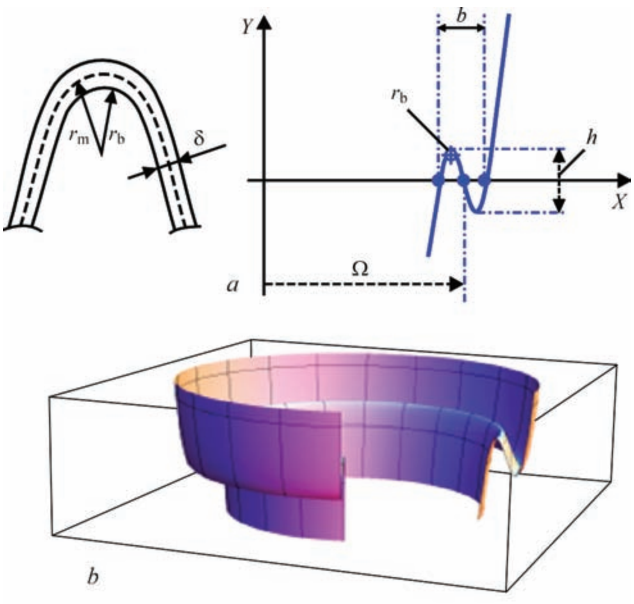

Figure 3. Determination of minimum bending radii of fold according to the admissible value of thinning near the apexes of corrugations (*a*) and graphic interpretation of mathematical model of shape transformation of the truncated conical surface with the formation of a circumferential fold (*b*)

For quantitative evaluation of stress-strain states (SSS) in the process of formation of corrugations, the numerical modeling applying the finite element method was used, realized with the help of universal software systems of finite element analysis. For generalization of the obtained results, the equivalent deformations ε_e and equivalent or total stresses σ_e (von Mises) were used according to Mises–Guber's theory of strength (ductility), or the theory of the highest specific potential energy of shaping. As a criterion of strength during calculations of a transformable shell, the achievements of values of yield strength in its material by equivalent stresses were accepted, i.e $\sigma_e < \sigma_{0.2}$.

The comparison of kinematic finite element model of formation of folds of conical shell with the theoretical (Figure 3, *b*) model of bending the neutral surface while using different sheet materials: steel, titanium and aluminium, and also the plotting of fields of stresses distribution (Figure 4) in the folds being formed allowed in each case to determine the conformity of the shell material with the accepted strength criterion. Thus, the influence of physical and mechanical properties of different structural materials of the shell on geometric parameters of circumferential folds and on the technological process of compacting of the conical surface was determined. As was noted above, for calculations as a shell material, the metals with a characteristic ratio of the yield strength σ_y to the tensile strength σ_t were selected, which are widely used in the processes of cold volumetric deformation and can theoretically provide the necessary characteristics of structural strength.

Deformation of the shell is accompanied by occurrence of stresses in it, the values and nature of distribution of which is substantially changed in the process of loading. In all the variants of calculations, the highest stresses cover insignificant geometric regions and sharply reduce their values at their removing from local stress concentrators: the lines of the shell bends. The highest values of equivalent stresses σ_e on the face surface of folds are noted on the shell of steel AISI 321 (171 MPa), for the shell of titanium VT1-0 and aluminium AMg-5 they amount to 125 and 55 MPa, respectively, which illustrates the conformity to the accepted criterion of strength of each of the deformed shells with the selected ratios of geometric parameters of corrugations. The highest values of residual equivalent stresses σ_e on the neutral surface are noted in the shell of titanium VT1-0 (64.2 MPa). The corresponding values σ_e for the shell of steel AISI 321 are 50.4 MPa and have the smallest values in the shell of aluminium AMg-5 (15.8 MPa). The given result indicates the presence of smaller, as compared with

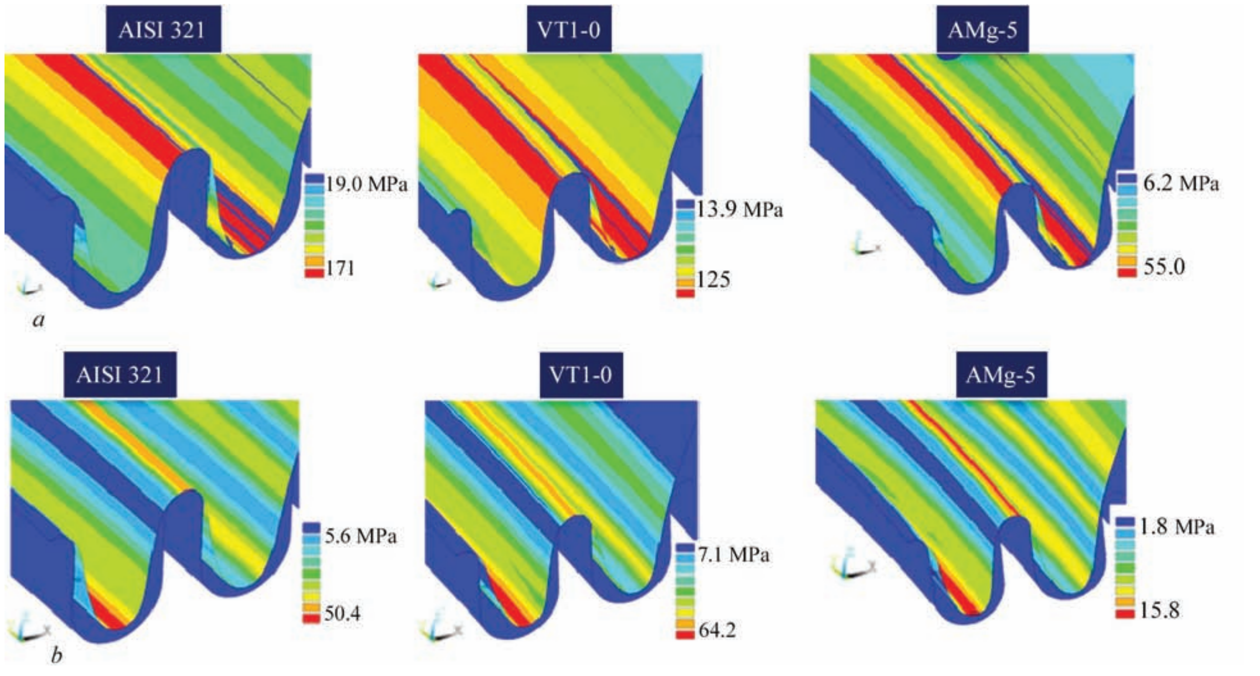

Figure 4. Equivalent stresses in the upper face surface of folds of conical shell of TVS from different materials being formed (*a*) and equivalent stresses at the neutral surface of the formed folds (*b*)

titanium, tensions of the neutral surface of steel shell during the formation of corrugations, i.e., its closer approximation to the desired isometric transformation. Further, the values of elasticity modulus for titanium and, especially, aluminium, lowered as compared to steel, show the high deformability of structures, made of these materials, during operating conditions under the action of SEF. An additional argument in favor of choosing the steel AISI32 as a material, is the best manufacturability of its welding process and repeatability of the joints quality, absence of need in special preparation of semi-products and complete protection of the inert gas welding zone.

In the process of shaping the each successive corrugation of the depth h, the height of the conical shell H_c decreases by a value, equal to $2h$. Hence, the coefficient of linear transformation of the shell K_t equals to $2n_1$, where n_1 is the number of corrugations; at other equal conditions, a structure made of discs with a larger number of corrugations will have smaller dimensions in the transportation state. At the known value $K_t = L/h_{pack} = 30$ and $D = 400$ mm, the length of the transformable area of conical shell is $B = (K_t/2)b = 75$ mm. Thus, the radius of the small base of the conical shell of TVS is $r = 125$ mm, the height of the conical section at $\alpha = 25°$ is $H_c \approx 160$ mm, respectively, the total number of shells at the maximum test length of TVS $L = 5000$ mm is $n_1 = 31$. The design scheme of a multiconical TVS, whose geometric parameters can be specified by the results of a complex of calculations of the structure for strength and stability under the conditions of action of specific factors of space environment, is shown in Figure 5.

In general, the optimization of geometric characteristics of the conical TVS during designing is reduced to finding the most advantageous combination of shell strength and its compactness, or the transformation coefficient K_t at the least possible mass. Reducing the angle of conicity and the approach of structural sections to the configuration of the cylinder, which is the most advantageous in terms of resistance to the action of non-axisymmetric loads, leads to the decrease in the coefficient of TVS transformation. The opposite approach (increase in α) significantly decreases the spatial rigidity of the structure but allows increasing K_t and simplifying the process of compact folding.

It is obvious that welding is almost the only method for construction of metallic air-tight shell structures. One of the main problems in creation of TVS shells is the achievement of combination of high physico-mechanical characteristics at the simultaneous vacuum tightness of rectilinear welds which undergo a complex of mechanical loads and specific aggressive external factors (SEF). The scheme of the shell

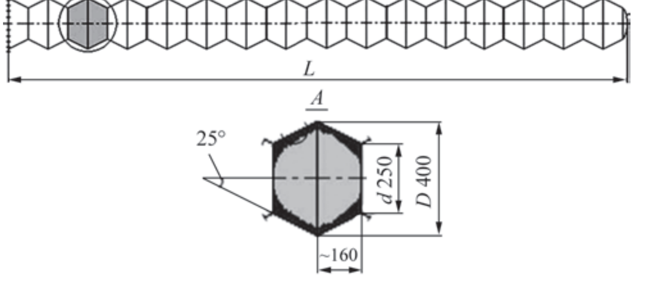

Figure 5. Designed scheme of multiconical load-carrying TVS of space purpose

isometric transformation requires the isotropy of the structural material; therefore, a weld should have the physical and mechanical properties almost equivalent with those of the structure base metal. While choosing a method for welding butt joints of stainless steel with a thickness δ = 0.1–0.2 mm, the advantage was given to microplasma welding. This method allowed a significant simplifying the preparation of edges of the deployable conical semi-product for welding, thereby increasing the efficiency of the TVS manufacture, and reducing the thermal deformations of a weld using the previous flanging of edges welded. During welding the semi-products of stainless steel, a flanging of edges at a value, equal to two thicknesses of the material welded, was used. In addition, the microplasma method allowed providing almost a complete repeatability of the fixed result of welding.

During experimental welding of specimens of steel of grade AISI 321N with a thickness δ = 0.175 mm in pulsed mode at the value I_w = 6 A, U_w = 12 V and welding speed V_w = 3.1 mm/s, the quality formation of welded joints was achieved at the value of energy input Q_{input} = 17.59 J/mm. In the technologically accepted range of pulsed current frequencies, the given value Q_{input} corresponds to the combinations of parameters τ_i = 4 ms; τ_p = 1 ms at the pulsed welding current frequency f_w = 200 Hz and τ_i = 30 ms; τ_p = = 10 ms at the frequency f_w = 25 Hz, where τ_i is the duration of the current pulse, ms, τ_p is the duration of the pause, ms. At the same time, the change f_w, and, consequently, the character of the dynamic effect of the plasma column on the area of the molten pool, which is in the state of solidification, also contributes to the improvement of its structure, reduction in the size of the grains (crystallites), breaking the cells (nuclei) of their formation [5]. Therefore, the task of the investigation was to determine a certain range of combinations of frequency and duty factor of the welding pulsed current, corresponding to the optimal macro- and microstructure of the vacuum-tight welded joint.

The results of metallographic examinations of characteristic specimens from the series of welded joints, produced at different combinations of welding process parameters, are presented in Figure 6. The nature of the heterogeneity of the weld metal, near-weld zone and the base metal of the TVS shell was determined. The microstructure of specimens produced at a frequency f_w = 200 Hz (Figure 6, *a*), measured by Vickers in the microhardness meter Leco M-400, is characterized by a considerably higher homogeneity and coaxiality of the cells at a simultaneous reducing in microhardness deviations along the horizontal and vertical axes of the weld. The size of the equiaxial cells corresponds to a range of 5–7 μm in the entire weld section, the deviations of the measured value of microhardness in any of the directions of the intersection does not exceed 5 % of its value for the base metal.

Comparing the presented results with the results of tests of a series of similar specimens for static tension and bending, which simulates the real operating conditions, the approximation of the elastic-plastic properties for the base metal and welded joints is noted with increasing the pulsed current frequency. Thus, for a typical specimen of the strip AISI 321 of 0.175 mm thickness with a weld produced at the pulsed current f_w = 200 Hz, the ultimate rupture strength $\sigma_{t.w}$ = 489 MPa, which amounts to 90 % $\sigma_{t\,b.m}$, the conditional yield strength $\sigma_{0.2\,w}$ = 256 MPa (Figure 7, *b*). For a similar specimen of the base metal, $\sigma_{t b.m}$ = 543 MPa, $\sigma_{0.2 b.m}$ = 256 MPa (Figure 7, *a*).

Determination of nature of the transformation of the middle surface of a truncated conical shell allowed designating the criteria for approaching to the isometricity in the process of its movement and, accordingly, to provide the absence of a local loss of stability in the deployable state. However, the values of stresses and displacements of the deformed shell are subjected to an accurate evaluation. The plotting of distribution fields of the mentioned values allows concluding about the possibility of realization of the calculated parameters

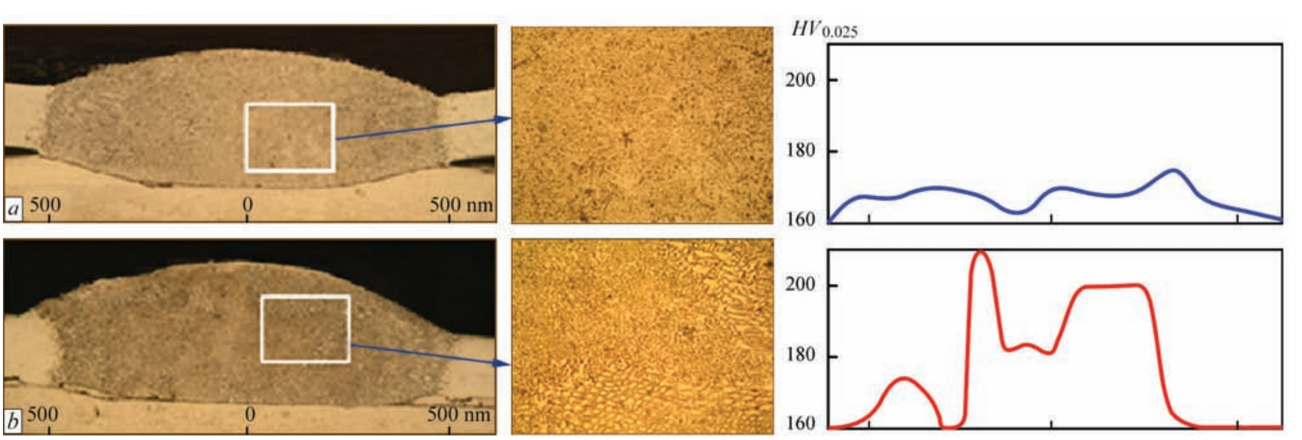

Figure 6. Results of metallographic examinations of a series of specimens of welded joints of foil with a thickness of 0.175 mm from steel AISI 321, produced at equal values of energy input by microplasma welding method at a pulsed current of 200 (*a*) and 25 Hz (*b*) frequency

of the process of isometric transformation without local loss in the stability of the TVS shell and to confirm the validity of the selected calculation scheme. In the course of the work, numerical calculations of stress-strain state of TVS with a rigid fixation around the contour of the base, corresponding to Figure 5, with the influence of characteristic factors of space environment on it and their combinations was carried out.

The finite element model of the multisectional structure was performed in a three-dimensional statement using shell finite elements of general statement. As the calculation values, the values of loads were taken into account, to the effect of which the structure could be subjected in the deployed state, during arrangement on the outer surface of the basic spacecraft (ISS). The characteristic effects at the stage of transportation to the orbit (vibration, pressure drops, acoustic effects) were excluded from the consideration, since the structure in the transport state is characterized by a significant safety margin and is equipped with devices for recording the displacements.

For the accepted designing scheme of TVS, the temperature loads in the ranges, given below, were modeled The static problem of radiant heat exchange with the Sun was considered, in which at the same time the maximum and minimum temperatures of the corresponding range at the opposite generatrices lines of the structure shell are reached. In all of the considered variants, the TVS shaping was characterized by the deviation of free end of the shell to the side with the smallest values of the applied temperature.

Dependence of maximum displacements of free end of TVS (cm) on ΔT, °C

ΔT_1 = 100– –125	6.2
ΔT_2 = 150–1125	7.6
ΔT_3 = 200– –125	9.0

The regions with the highest values of stresses are located on the surface which is very limited in area, their values are sharply reduced with the removal from the fixation zone. The results of modeling allow concluding about the conformity of maximum displacements to the allowable values of deviation of the free end, which are accepted for this type of structure (up to 150 mm). The schematic presentation of the TVS with a PL, rigidly fixed on a universal workplace on the outer surface of the ISS service module, is shown in Figure 8.

During general calculation of the effect of accelerations in the presence of PL, the unit of scientific equipment with a mass of 40 kN, rigidly fixed at the free end of the TVS in six degrees of freedom, and also thermocyclicity, depending on the own frequency (ω) of the structure, the following values of acting accelerations were taken. According to the results of calculation, the frequency of the natural oscillations of the structure was ω = 22.43 Hz, taking into account the load concentrated

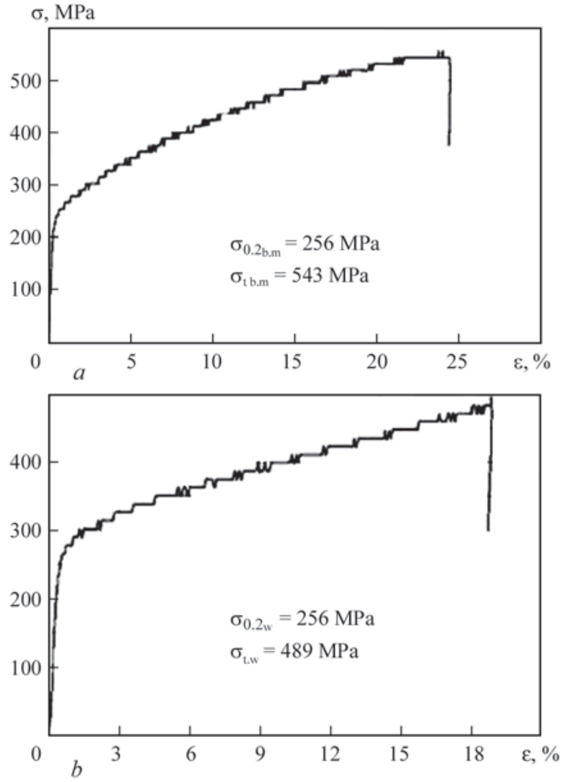

Figure 7. Diagrams of tension of base metal (*a*) and welded joint, produced at a pulsed current frequency of 200 Hz (*b*)

from the mass of PL, which undergoes linear and angular accelerations and is fixed at the ends of the TVS, leads to a decrease in the frequency of the natural oscillations of the structure to ω = 20.45 Hz. For the values $\omega \geq$ ≥ 20 Hz: a_x ±4.5 m/s^2; $a_y = a_z$ = ±6.0 m/s^2; ε_x = ±0.2 rad/s^2; $\varepsilon_y = \varepsilon_z$ = ±0.7 rad/s^2; the directions of accelerations are preset in the right coordinate system *OXYZ*, where axis *Z* coincides with the longitudinal axis (axis of symmetry) of TVS, the axes *Y* and *X* are perpendicular to it. Respectively, a_x is the acceleration in the direction of the axis *X*, a_y and a_z are the accelerations in any transverse plane parallel to the plane *OYZ*, ε_x is the angular acceleration around the axis *X*, and ε_y and ε_z are the angular accelerations around any transverse axis, which lies in the plane parallel to the plane *OYZ* and passes through the axis *X*.

The joint effect of accelerations and temperature loads leads to increase in the values of equivalent stresses, the maximum value of which reaches σ_e = = 226 MPa. It should be noted that insignificant influence of inertial loads on the general character of stress distribution in the shell of TVS is associated with the peculiarity of mutual orientation of vectors of accelerations and temperature gradients, which almost eliminates their superposition. In the area of joining the support conical section with the further elements, the maximum values of equivalent stresses do not exceed the admissible stresses for the applied steel (the yield strength $\sigma_{0.2}$ = 250–260 MPa) and do not cause necessity in correction of the accepted designed scheme. The maximum total values of linear

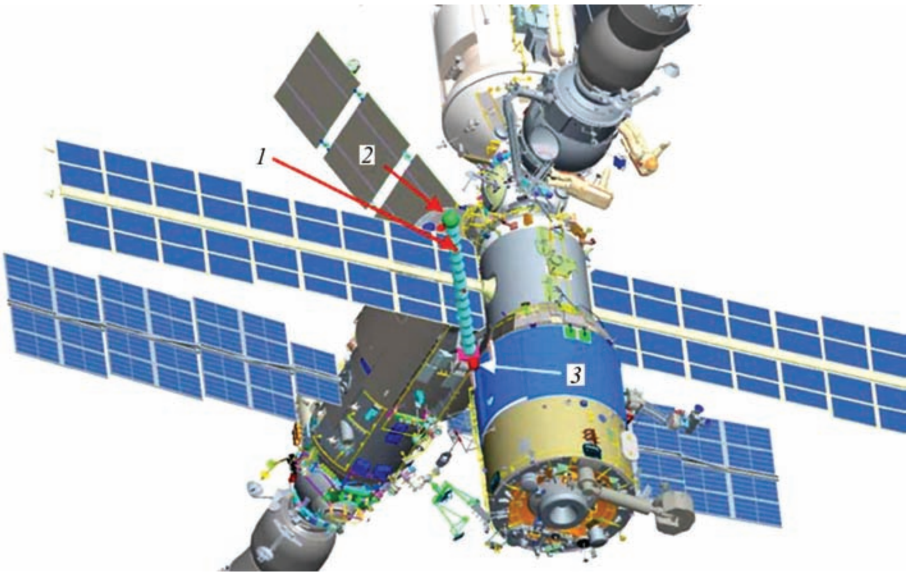

Figure 8. Layout of the TVS (*1*) with the payload (*2*) on the universal working place (*3*) of the ISS service module

displacements of a structure free end at the combined action of accelerations and temperature ranges reach values U_{a+t} = 0.1499 (m). The fields of distribution of equivalent stresses, as well as maximum total values of linear displacements in the structure shell are shown in Figure 9. The obtained result leads to the need in the accurate keeping with the thermal mode of structure, in which the critical values of temperatures are determined at the stage of choosing thermo-optical characteristics of the surface. As the largest contribution to the general deformation scheme of the structure is made by the components of linear displacements, which are predetermined by the cyclic radiation heating of its shell, the search for methods of surface engineering of the TVS for changing its thermo-optical properties, is most relevant to determine the structure deformability in the conditions of orbital flight. Respectively, the methods were developed to modify the surface of thin-walled stainless steel shells, which allow reducing the deformability of the TVS of space purpose without changing their mass and compactness. It is shown that the modification of thermo-optical properties of the surface by depositing multilayer coatings using the method of electron beam deposition reduces the temperature load to the regulated conditions of the space experiment in the range of –43–63 °C, which leads to 1.45 times decrease in the deformability considered in the operation of the multisectional TVS at the 1.17 times reduction in the maximum equivalent stresses [6].

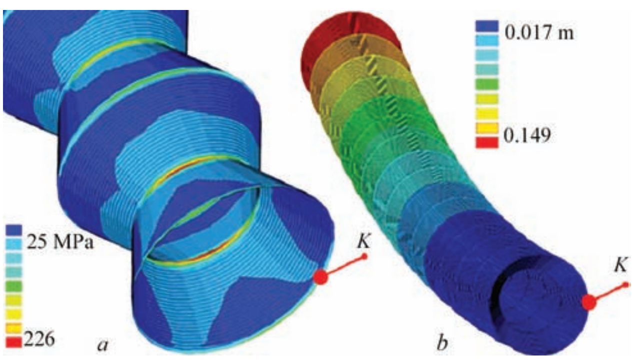

Figure 9. Fields of distribution of equivalent stresses σ_e, (MPa) (*a*) and total values of linear displacements U_{a+t} (m) at the combined action of accelerations and temperatures (*b*) on the neutral surfaces of the TVS in the conditions of acting SEF; *K* — contour of rigid fixation of the TVS (according to Figure 5)

Figure 10 illustrates the dependence of the minimum (T_{min}) and maximum (T_{max}) calculation values of temperatures at the surface of the TVS conical type on the ratio A_S/ε, where A_S is the absorption coefficient of solar radiation; ε is the coefficient of radiation of the optical surface of the TVS, during operation of the structure at an arbitrary operating point of the ISS outer surface. The marked area T_{opt} limits the abovementioned optimal temperature range (–43–63 °C), which allows carrying out the necessary operations in case of open-space spacecraft's activity, and corresponds to the range of ratios A_S/ε = 0.26–0.54. The object of investigation was the correction of the ratio A_S/ε of the definite material of the shell by depositing different combinations of materials and their compounds on its surface, performing the functions of selective-radiating coatings. It should be noted that the coatings known in the space technologies of this purpose do not correspond to the conditions of extreme deformation of the investigated structure either because of the lack of flexibility (enamel), or sufficient strength and compactness (screen-vacuum thermal insulation). Moreover, the selection of the required coating is determined not only by its thermo-optical properties, but also by adhesion to the surface of metallic shell, taking into account the considerable deformations of its surface during deployment, as well as different rates of sublimation of materials under the vacuum conditions of space environment. Preparation of optical surfaces of TVS after correction of roughness can be realized by means of electron beam spraying of thin coatings of metals and their compounds with the necessary ratios of A_S/ε; this method allows providing a sufficient adhesive strength of coatings and effectively control their thickness. The necessary result was obtained applying the aluminum coating of 480 μm thickness on the surface of a shell of steel AISI321 of 0.175 mm thickness, followed by spraying Al_2O_3 layer of 45 μm thickness on aluminum, which imitates the formation of oxide film, significantly increasing the absorption coefficient A_S. The measurement of integral hemispherical thermo-radiation characteristics of the mentioned coatings, carried out using calorimetric methods of investigations, confirmed their conformity with the above-mentioned calculated range of ratios A_S/ε.

The challenging tasks of using multiconical TVS as telescopic-type systems and hull structures of orbital space modules are related with the need in their recycling, which requires the development of a reverse transformation mechanism with the preservation of an original geometry. The ability of rigid shells of a transformable volume to multiple reproduction of stable geometric parameters is coordinated with the principles of a regular isometric transformation method. However, the full-scale metallic shell after the first repeated cycle of transformation acquires wavy deformations in the intercorrugated gaps, which indicate a local loss of stability. The analysis of the mathematical model of movement and the results of the carried out experiments on the transformation of TVS elements allowed concluding about the causes for the loss of stability of conical shells subjected to reverse transformation by creating a vacuum in the interior space. Therefore, the direct transformation of the shell takes place gradually, starting from the circumferential corrugation of the largest diameter, which undergoes the greatest load under the condition of the constant transformation pressure during the whole process. On the contrary, during reverse transformation, any of the elements of the surface of the deployed shell of TVS undergoes a load which is approximately equal to normal atmospheric pressure, moreover, all the elements of the surface begin to move simultaneously. During the process of transformation, local deformations in the vicinity of the apexes of the circumferential corrugations are increasing, the areas of their localization are united, which leads to a general loss of structure stability and significant distortions of its surface.

The conclusion on the local nature of bending deformation at the boundary of buckling and the appropriate deformations of the middle surface for the test thin shell is confirmed by finite element modeling of

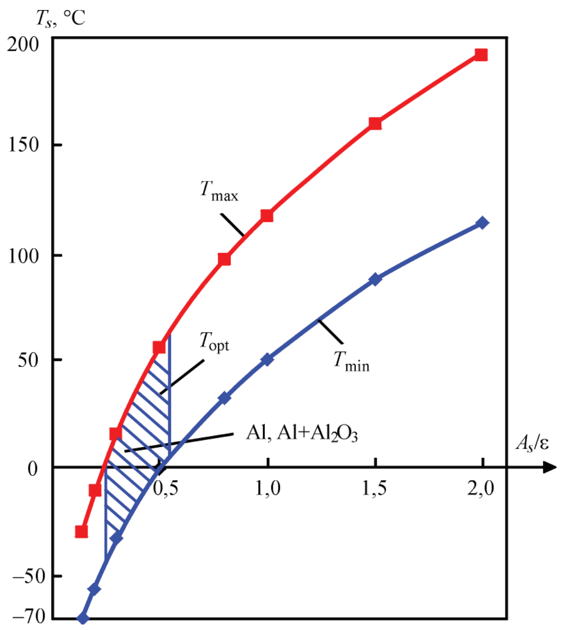

Figure 10. Dependence of minimum (T_{min}) and maximum (T_{max}) calculated values of temperatures on the surface of the TVS of conical type on the ratio A_S/ε

stresses and deformations in the process of volumetric deformation. Thus, the equivalent stresses on the face surfaces are located in the near-boundary elastic-plastic zone, and on the neutral surface of the corrugation their values do not exceed 10–20 MPa. On the basis of the mentioned considerations it can be assumed that one of the possible variants of the transformation technology change for realization of multiple shaping of the shell may be the decrease in the radius of rounding at the apexes of the matrix fins. Moreover, the areas of maximum elastic-plastic deformations are localized in the vicinity of the corrugation apexes, the number of transition zones of equivalent stresses decreases, and the sinusoidal profile of the conical generatrix approaches to the form of a piecewise broken curve, corresponding to the respective mathematical model of mirror reflection of the truncated conical surface (see Figure 1, *c*).

For experimental investigation of behavior of the TVS shell of $D = 400$ mm, $d = 250$ mm diameters, the angle of conicity $\alpha = 25°$ and the steel AISI321 shell thickness of $\delta = 0.175$ mm at the reverse transformation, a test specimen of the structure with the length $L = 1190$ mm of 7 sections with a ratio of $r_c/\delta = 3.0$ was manufactured. At the same time, the basic criterion of approaching to the isometric transformation, which consists in the equality of the length of the initial and the transformed area of the conic shell meridian, as well as the ratio of the thickness of its material δ to the step size b, did not change.

The process of direct and also reverse transformation, realized during creating vacuum in the inner volume of the experimental structure, is presented in

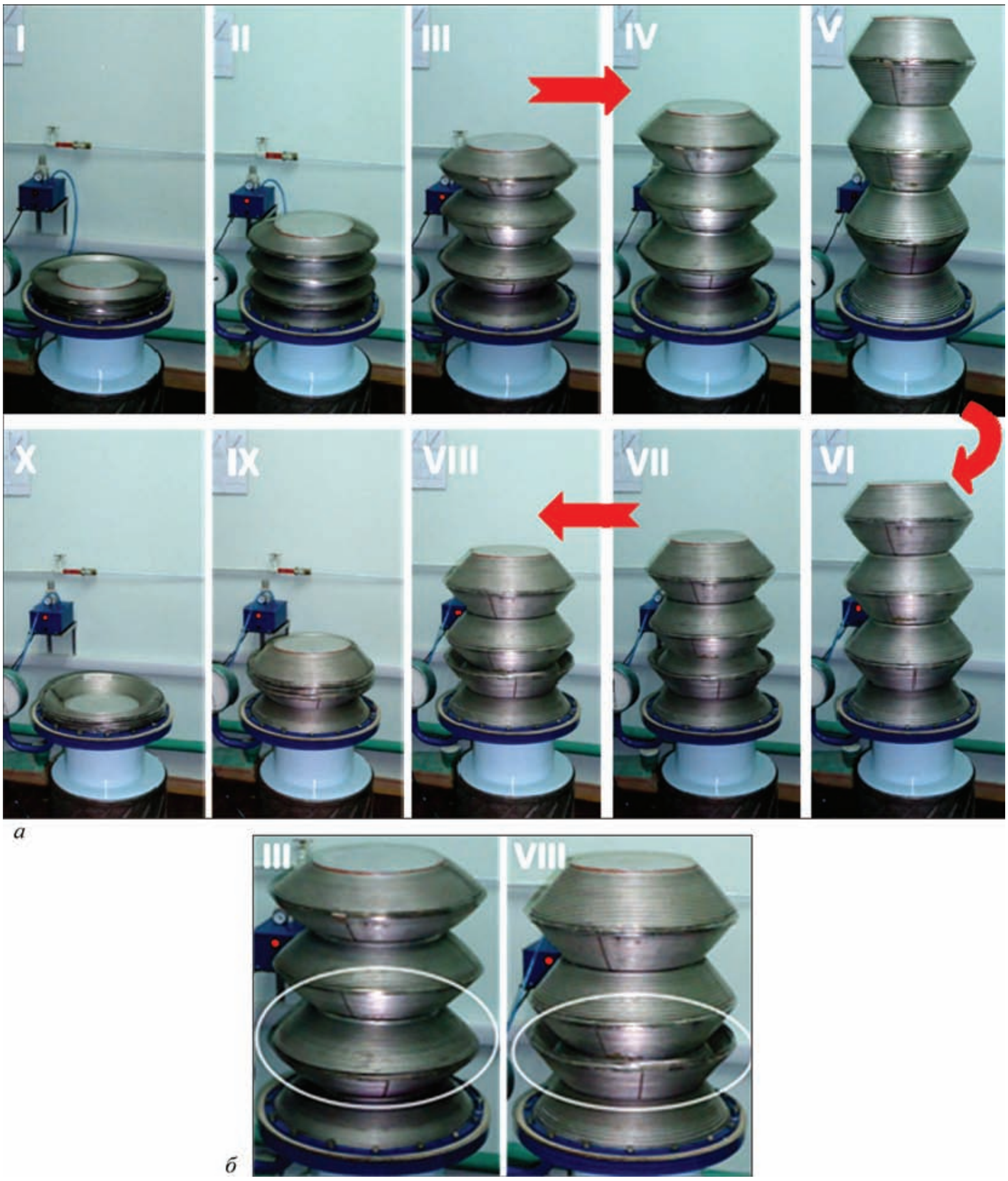

Figure 11. Experiment of direct and reverse transformation of the TVS with the length $L = 1190$ mm and diameter $D = 400$ mm (*a*) and magnified stages III and VIII (*b*)

Figure 11, the pressure curve for the stages (I–X) is in Figure 12. The experiment confirmed the possibility of repeated coaxial folding of the multisectional TVS to the state, which allows performing its necessary disassembly and recycling after termination of its exposure period in the near-earth orbit. At the same time, it was noted that the increased circumferential rigidity of corrugations of a larger radius in the area of the rigid fixation contour leads to the effect of «snap buckling» of the shell (see the stage of deploying «III» and the folding stage «VIII» corresponding to it, Figure 11, *b*) at which the reverse transformation can occur not always successively, starting with the fold of a larger radius, but from some arbitrary corrugation with the smallest circumferential rigidity, which can be predetermined by the initial geometric imperfections of the initial conical semi-product or deviations of the technological process of corrugation. As a result, the shell fragment between the largest and the first «folded» corrugation remains untransformed, which has some negative effect on the

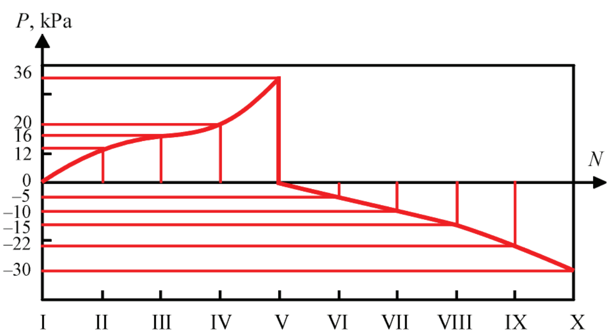

Figure 12. Curve of pressure for stages *N* (I–X) (as is shown in Figure 11)

finite compactness of the TVS (see Figure 11, stages «I» and «X»). It is possible to avoid arising of the similar effect by a successive changing the radius of generatrix of corrugations in slight ranges by reducing their total radius. The determination of correlations between geometric, strength and rigid characteristics of TVS, which arise in this case, can be a subject of challenging investigations.

To determine critical values of external loads of single shells, in particular, under the action of axial compressive forces, there are some well-known analytical solutions. However, for the problems of stability of conical shells with a complex shape of generatrix in the composition of multilevel systems at an arbitrary direction of applying loads, such solutions are absent. In the modern works dealing with the problems of nonlinear mechanics of multifolded structures, the numerical methods of calculation are used based on the principle of minimizing the potential energy of the system for solving the stability problems (determination of bifurcation points, critical loads, and forms of stability loss, accompanied by the so-called snap-through buckling [7], Similarly, the stability of the TVS equilibrium can be determined as $J \equiv (\partial^2\Pi)/(\partial[D]^2)$, where J is the determinant of the Jacobi matrix (Jacobian), Π is the general potential energy of the model, $[D]$ is the matrix of assembly displacements [6]. At the condition of $J > 0$, the structure is in a stable equilibrium, and at $J = 0$ it is unstable. In the latter case, the critical loading results in the appearance of a bifurcation point, i.e., to the possibility of forming several forms of stability loss. As for the investigated TVS, during repeated bending of a piecewise-broken profile, the possibility of creating new forms of stability loss is much lower than in the shell with a sinusoidal profile. This is explained by the fact that appearance of a local stability loss during folding takes place in the areas of thinning the shell material at the apexes of corrugations, which have a more local character at a smaller bending radius.

The mentioned results of the development illustrate the possibility of creating metallic load-carrying shell structures, which can be delivered to the near-earth orbit in a compact state and transformed to the designed dimensions with a minimal energy losses. The use of the described structures in space technologies allows transferring to a new qualitative level by carrying out the scientific experiments related to the open-space spacecraft activities, during manufacture of hull structures of orbital stations, and in future, it can be applied in the creation of long-term erections on the Moon surface.

Conclusions

1. An algorithm for calculating the designing scheme of a welded multisectional TVS of a space purpose is presented, which allows determining its geometric parameters. A calculation-analytical evaluation of the correlation between the physicomechanical characteristics of the TVS material and corrugation parameters was carried out and the conclusion about the advantage of using stainless steel AISI321 was obtained.

2.The parameters of the process of pulsed microplasma welding of conical shells of stainless steel (energy input $Q_c = 17.5$ J/mm, pulsed current frequency $f_{pc} = 200$ Hz and the ratio of the current pulse duration to the cycle duration 0.75) were determined, which allow providing the strength of welds at the level of 0.9 of the strength of the base metal ensuring their vacuum tightness.

3. It is shown, that modification of the surface of thin-walled shells of stainless steel allows increasing the stability of the TVS of space purpose without changing their mass and compactness. The modification of the thermo-optical properties of the surface by applying multilayer coatings $Al/A1_2O_3$ with a total thickness of 525 nm by the method of electron beam deposition allows 1.45 times reducing the deformability of the multisectional TVS from radiation heating.

4. The possibility of a complete reverse transformation of the multisectional TVS without a local stability loss was confirmed.

5. The developed technologies can be used for creation of load-carrying rod and shell structures of space purpose.

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