Journal of Aerospace Technology and Management
ISSN: 1984-9648
editor@jatm.com.br
Instituto de Aeronáutica e Espaço
Brasil

Lobanov, Leonid M.; Volkov, Valentin S.; Yakimkin, Alexander V.; Savitsky, Viktor V.
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Journal of Aerospace Technology and Management, vol. 8, núm. 1, enero-marzo, 2016, pp. 1-8
Instituto de Aeronáutica e Espaço
São Paulo, Brasil

doi: 10.5028/jatm.v8i1.529

Functional Characteristics Improvement of Metal Transformable-Volume Structures for Space Applications

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ABSTRACT: Under conditions of the influence of space environment factors, the thin-walled load-carrying transformable-volume structures are subjected to volumetric deformation and long-time exposure to external loads, close to maximum permissible design values. The required functional properties of transformable-volume structures are ensured on the basis of applying surface engineering methods, whose effectiveness is difficult to confirm as there is no possibility to reproduce the space environment factors complex under the terrestrial conditions. The method for verification of applied technologies regarding the modification of surface properties was described. It was based on the comparison of finite-element and experimental-computational models of displacements in equivalent fragments of the transformable-volume structures surface. Qualitative and quantitative evaluation of methods is given, allowing changing the rigidity-strength characteristics of transformable-volume structures for space applications without alteration of their mass and compactness.

KEYWORDS: Transformable-volume structures, Surface engineering, Non-destructive testing, Electron shearography, Load-carrying shells, Foldable shells.

INTRODUCTION

Deployable structures refer to the actively developing field of space technologies, which allow simplifying the delivery of useful freight to the near-Earth orbit. In the majority of cases the deployable or inflatable space structures represent shells made of elastic soft materials, capable of withstanding multiple non-fracturing bends. Therefore, the main attention of developers of these types of structures is focused on the provision of shell rigidity and its stability after deployment by using different methods of strengthening, which have limited effectiveness (Pellegrino 2015; Underwood *et al.* 2015; Schenk *et al.* 2014).

A separate class of deployable structures are transformable-volume structures (TVS) with a metal shell (Fig. 1c), in which the use of geometric regularities of surface bending allows realizing the volumetric deforming, comparable with the bends of soft materials (Paton *et al.* 2015). One of the applications of such structures is their use as a sliding bearing rod rigidly fixed at one of its ends on the outer surface of the base spacecraft (e.g. the International Space Station — ISS). In the working state after unfolding the metal TVS has higher spatial rigidity compared with the initial metal shell before its transformation to a compact state. In creation of similar structures the main objects for research are the methods of surface engineering, whose application allows providing the required functional properties of the transformable shell with minimum weight and maximum compactness under condition of aggressive space environment factors (SEF) action. Finally, it is necessary to solve the problem of correctness of calculated evaluations at the stage of laboratory and check tests. This problem is predetermined by

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Received: 08/08/2015 | **Accepted:** 11/26/2015

the impossibility of reproduction of all SEF spectrums, under the Earth conditions, and also by complexity and high cost of experiments for their simulation.

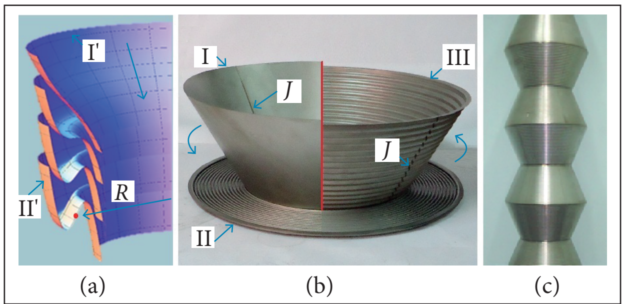

Figure 1. Graphic representation of the mathematical model for: (a) Fragment transformation of the initial conical shell (I′) into a single corrugation (II′); (b) The transformation stages of the metal TVS shell; (c) Design solution for multi-conical TVS. J represents the welded joints of the shells.

METHODOLOGY

The strength and spatial rigidities are referred to the main functional characteristics of TVS, subjected to improvement. They guarantee the mechanical integrity of the transformable shell, its minimum deformability and absence of a local buckling at any combinations of external and operational loads, as well as stability, speed of unfolding and its sequence. The mentioned characteristics depend not only on a general geometric configuration of TVS, properties and thickness of the structural material, type of joining stiffening elements between separate sections, but also on local features of surface geometry (type of surface folding) and on others, first of all, thermal optical properties of the surface.

Selection of design parameters and the task of improvement in the functional characteristics of TVS are reduced to the search for the best combination of strength and rigidity characteristics of the shell and its compactness at minimum possible weight. The thin metal shell of TVS should preserve the mechanical integrity and functional properties under the effect of mechanical loading factors, acting in the process of orbital injection (impact-pulsed loading and acoustic noise) and in the process of operation under space environment conditions. In particular, in case of rigid fixation at the external surface of the ISS, the structure can be subjected to the action of sinusoidal (harmonic) vibration in the range of frequencies from 5 up to 20 Hz and wide-band random vibration in the range of frequencies from 20 up to 2,000 Hz, linear and angular inertial loads. It is also subjected to cyclic temperature influence in solar terminator transition with a maximum admissible temperature difference from −150 up to +125 °C. The decrease in a given range provides the decrease in temperature gradients in the shell structure at cyclic heating and, consequently, leads to the decrease in deformations, in which the maximum values are almost always regulated for definite conditions of service and application of TVS. In addition, the working temperatures of optical surfaces also predetermine other parameters, whose range is limited by the requirements of structures for space applications — for example, the rate of precipitation of volatile condensing substances and duration of a possible contact of an operator in a space suit during the work beyond the ISS (for conical TVS it is more than 5s at temperatures from −43 up to +63 °C). The combination of the above-mentioned requirements allows selecting in most cases stainless steel as the optimum material for a TVS shell, providing also the lower deformability of structure under service conditions due to the value of Young's modulus, which is 1.5/2.0 times higher than that of titanium and aluminium.

The use of a complex approach to the surface engineering allows providing the optimum combination of factors which, to a larger extent, determine the strength and stability of the structure under the SEF effect at the best mass-dimensional characteristics. The design configuration of multisectional conical TVS, which is given by the authors as a main example, is defined by their definite functional application and can vary by changing the geometric sizes of separate sections and thickness of their structural material. On the other hand, the compactness, or coefficient of transformation K_T, is related to geometric parameters of conical sections of given thin-walled TVS with a stainless steel shell by the dependence:

$$K_T = 2 \times n = \frac{S \times \sin\alpha}{14 \times \delta} \quad (1)$$

where: n is the number of folds (circumferential corrugations) in the shell transformed into a flat disc (Fig. 1b, II); S is the slant height of initial cone (Fig. 1b, I); α is the angle of conicity of initial cone; δ is the thickness of structural material of the TVS shell.

The tendency to maximum values of K_T, attainable at δ → min, at unchanged preset design configuration of TVS, requires the correction of flat disks manufacture technology and, finally, the decrease in radius of bending in apexes of circumferential corrugations. The volume deforming of the initial steel shell with the formation of surface folds allows changing its space rigidity after deployment (Fig. 1b, III) at δ = constant and at different variants of meridian profile (Fig. 1a). In our case, not only the operation of shape formation is achieved by plastic deformations of the steel shell, but also the required complex of properties of the structural material is attained.

Further, the application of surface engineering methods applied to metal TVS is of current importance for changing their thermal optical properties. The temperature of TVS surface (T_S), whose material has a high coefficient of thermal expansion, defines mainly its deformation mode. The value T_S under other equal conditions is determined only by the A_S/ε ratio, where A_S is the coefficient of solar radiation absorption and **ε** is the emissivity coefficient of TVS optical surface. The possibility to influence this ratio allows changing within wide ranges the structure deformability under conditions of the orbital flight.

Figure 2 illustrates the dependence of minimum (T_{Smin}) and maximum (T_{Smax}) calculated values of temperatures on the TVS surface of a conical type (material: steel AISI 321) on the $A_S/\boldsymbol{\varepsilon}$ ratio in service of the structure in random working point of the ISS's external surface. The selected zone (T_{Sopt}) limits the selected optimum range of temperatures (−43 to +63 °C), corresponding to the ratio $A_S/\boldsymbol{\varepsilon}$ = 0.26/0.54.

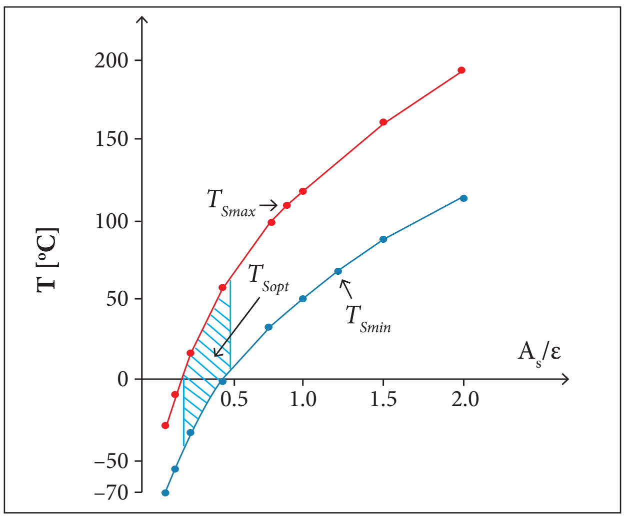

Figure 2. Dependence of minimum and maximum calculated temperature values on the surface of conical-type TVS on the A_S/ε ratio.

The precise selection of temperature range and the determination of required thermal optical characteristics of the surface can be made after the solution to the problem of stability and strength analysis of a definite structure and the estimation of optimum combination of methods for strengthening and for optical surfaces treatment, which allows deformability reduction. At this stage it is necessary to implement the effective methods of monitoring, which could confirm the correctness of calculations by using numerical methods and reduce as much as possible the cycle of complex and expensive on-land stand tests of the structure at the stage of manufacture. In creating a TVS (Fig. 1c) the verification of a finite-element computational model of the structure has been implemented by the method of electronic shearography. At the same time, the effectiveness of the discussed methods below for surface property modification was confirmed in the modelling of radiation heating under vacuum conditions on separate segments of the conical structure. For these segments the boundary conditions on the circular mating contours corresponding to a multi-sectional shell have been reproduced.

RESULTS AND DISCUSSION

ALTERATION IN SPATIAL RIGIDITY OF A TVS SHELL

The transformation of a circumferential fragment of the conical shell surface into a fold corrugation with width **AB** (Fig. 1a) should be maximally approached to the equality condition of cone fragment meridian length before and after the transformation that allows producing the shell folding in a compact shape without tension and compression of the material. It is evident that this condition can be fulfilled at different flatnesses of the fold meridian's profile. The formation of fold meridian can be described, in particular, by the deformation of the function $f(x) = (x - R)^3$:

$$y = t \times (x - R)^3 + k \times (x - R) \times (1 - t) \tag{2}$$

where: $t \in [0; 1 + \gamma]$, $\gamma \geq 0$, $k = \text{tg}\alpha$; R is the equivalent radius of a fold (Fig. 1a).

So, the shape of the meridian profile, present in the process of volumetric deformation of the shell, greatly influences the space rigidity of the structure and the parameters of its stability under the SEF conditions. The residual plastic deformations in the apexes of the folds lead to the formation of circular corrugations (Fig. 1b, III), which fulfil the function of stiffeners in a TVS shell after deployment. To determine the critical values of external loads of single shells, for example, under the influence of the axial compressive force, there are known analytic solutions. Nevertheless, such solutions are absent for the stability problems of conical shells with a complex shape of generatrix in the configuration of the folding multi-layered systems at a random direction of the loads application. In modern studies, considering the problems of non-linear mechanics of multilayered structures, the numerical methods of calculation, based on the principle of minimum potential energy of the system, are applied for the solution to stability problems (determination of bifurcation points, critical loads and forms of stability losses, accompanied by snap-through behaviour (Ario and Watson 2009, 2010). In particular, in the study of Ario and Watson (2009), the equilibrium equation, as applied to the bar system, is written by using the mentioned principle:

$$F_i(\ldots,\upsilon_i,\ldots) \equiv \frac{\partial \Pi}{\partial \upsilon_i} = \frac{\partial \Pi}{\partial \overline{\upsilon}_i}\frac{\partial \overline{\upsilon}_i}{\partial \upsilon_i} = 0, \quad for \quad i = 1,\ldots,n \qquad (3)$$

where: F_i is the critical force; $\overline{\upsilon}_i$ and υ_i are the angular and linear displacement; Π is the total potential energy of model; n is the number of bars in the model.

It is assumed that a stability criterion of the system is the non-equality to zero of a determinant of rigidity matrix R (Jacobian for $J \in R^{n\times n}$), which is presented in the form:

$$J \equiv (J_{ij}) = \left(\frac{\partial^2 \Pi}{\partial \upsilon_i \partial \upsilon_j}\right) = \left(\frac{\partial^2 \Pi}{\partial \overline{\upsilon}_i \partial \overline{\upsilon}_j}\frac{\partial \overline{\upsilon}_i \partial \overline{\upsilon}_j}{\partial \upsilon_i \partial \upsilon_j}\right) = \left(\frac{\partial F_i}{\partial \overline{\upsilon}_j}\frac{\partial \overline{\upsilon}_j}{\partial \upsilon_j}\right), \quad for \quad i, j = 1,\ldots,n \qquad (4)$$

Similarly to Ario and Watson (2009), at the first stage, the neutral surface of the multifolding TVS is approximated by a set of discrete elements, where, for each of them, an expression of potential energy Π_e is formed taking into account the rigid characteristics and mutual links. The general view of this expression can be written in the form:

$$\Pi_e = 1/2\ [D]^T\ [K][D] - [D]^T\ [R] \qquad (5)$$

where: $[D]$ is the matrix of nodal displacements; $[D]^T$ is the transposed matrix D; $[K]$ is the stiffness matrix; $[R]$ is the matrix of external load.

By summing up the expression Π_e for all n elements of the model, we shall obtain the expression of the potential energy for all the calculated regions:

$$\Pi = \sum_i^n \Pi_{ei}, \qquad for\ i = 1\ldots n \qquad (6)$$

The equilibrium of the system is determined by the principle of minimum total potential energy:

$$\delta\Pi = \frac{\partial \Pi}{\partial u_1}\delta u_1 + \frac{\partial \Pi}{\partial \upsilon_1}\delta \upsilon_1 + \frac{\partial \Pi}{\partial w_1}\delta w_1 + \ldots \frac{\partial \Pi}{\partial \beta_i}\delta \beta_i + \frac{\partial \Pi}{\partial \vartheta_i}\delta \vartheta_i + \frac{\partial \Pi}{\partial \theta_i}\delta \theta_i = 0, \ for \ \ i = 1,\ldots,m \quad or \ \frac{\partial \Pi}{\partial [D]} = 0 \qquad (7)$$

where: u, υ and w are linear displacements; β, ∂ and θ are angular displacements; m is the number of nodes in the model.

The equilibrium stability of TVS is determined similarly to Eq. 4 by double differentiation of Eq. 6: $J = \partial^2\Pi / \partial[D]^2$. Under the condition $J > 0$, the structure is at the stable equilibrium and, at $J = 0$, it is at a non-stable one. In the second case, the critical load leads to the appearance of the bifurcation point, i.e. to the probability of formation of several stability losses forms.

At the equivalency of approach to the solution, the calculation of TVS is more complicated than that of the bar systems. This is caused by the degree of approximating polynoms, determining the number of nodes in a finite element and by a number of degrees of freedom (angular and linear displacements) in its nodes. In addition, the segments of multifolding TVS are characterized by a more complicated three-dimensional work, while the structural elements of bar hinged systems experience single-axis loading.

The modelling of the TVS unfolding process with different initial shapes of the meridian profile by applying the dynamic finite-element model (FEM) (Mayes *et al*. 2009; Silver and Warren 2010), carried out by using standard finite-element analysis, allows determining the final shapes of profile, taking into account the physical and mechanical properties of the real structural material. Figure 3 presents the shells in unfolded state with two maximum different shapes of initial profile of the meridian: at $\gamma = 1.5$(a) and at $\gamma = 0.5$ (b) (see Eq. 2).

In the computational model of the structure variant, the thickness of shell structural material (stainless steel AISI 321, proof stress $R_{p0.2} = 205$ MPa) is taken as $\delta = 0.15$ mm. The number of truncated conical elements with diameters of bottoms $D = 400$ mm, $d = 250$ mm and height $h = 160$ mm is equal to 11. Figure 3 illustrates the calculated maximum values of equivalent stresses in the joining zone of structure's support

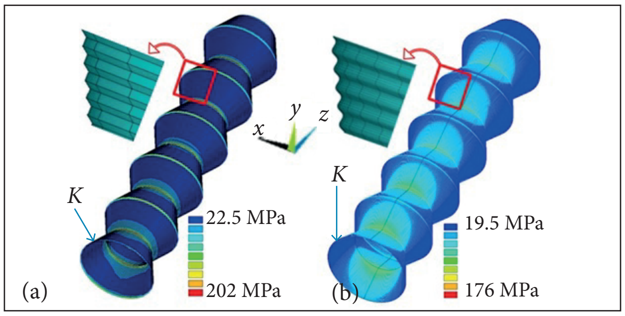

Figure 3. Equivalent stresses σ_e in TVS with a piecewise smooth (a) and sinusoidal (b) profiles of the shell meridian subjected to the effect of maximum SEF values.

conical sections, rigidly fixed on the circular base *K*, under the effect of typical combination of mechanical loads. They include linear ($a_X = +12$ m/s², $a_Y = +12$ m/s², $a_Z = +9$ m/s²) and angular ($\varepsilon_X = +1.4$ rad/s², $\varepsilon_Y = +1.4$ rad/s², $\varepsilon_Z = +0.4$ rad/s²) accelerations of the structure's centre of mass in combination with admissible values of temperature effects (from −150 up to +125 °C). As a main criterion of structure strength, the following condition is taken:

$$R_{p0.2} > \sigma_e \qquad (8)$$

where: σ_e are the equivalent stresses in the TVS shell, determined in accordance with the von Mises-Hencky theory given as:

$$\sigma_e = \{[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2]/2\}^{1/2} \qquad (9)$$

where: σ_1, σ_2 and σ_3 are the principal stresses.

At equivalent combinations of maximum external effects, the values of maximum equivalent stresses in a supporting part of the structure with a sinusoidal profile (Fig. 3b) are 1.15 times lower than in the structure with a profile of corrugations close to the piecewise smooth one (Fig. 3a). TVS with a piecewise smooth profile are characterized by the formation of clearly expressed stress raisers at the broken regions of corrugations and, as a consequence, by less uniform distribution of stresses over the surface; the maximum values of stresses $\sigma_{eMAX} = 202$ MPa practically correspond to the $R_{p0.2}$ value.

Figure 4 shows an experiment on TVS unfolding consisting of 11 sections (according to Fig. 3) with a different fold profile of structural elements (Fig. 4a) and the result of dynamic FEM of the unfolding process of the equivalent structure (Fig. 4b). In the isofields scales, the equivalent stresses σ_e (MPa) in the neutral surface of the structure shell are shown; *a* and *b* are conical sections with the shape of a meridian profile, corresponding to Fig. 3a and 3b. It can be seen that the integration into a multisectional TVS of structural elements with a different shape of a meridian profile also allows the process of the controlled unfolding, where the transformation of structural elements can start, for example, on the side of a free edge, and finish with an element, rigidly fixed on the support contour. This approach gives an opportunity to greatly decrease the deformability of TVS in the unfolding process, caused by non-uniform heating of its surface with the flux of solar radiation, and also to reduce the values of stresses in the zone of a supporting conical section fixation and in the zones of conical sections joining.

It should be noted that the flatter profile of a corrugation greatly complicates the technology of the volumetric deformation of the shell and, as shown above, it has no decisive effect on the structure stability during its service after unfolding. Hence, the tendency to simplify the technology of TVS manufacture and its improvement causes the need for changing the thermal optical properties of the shell surface.

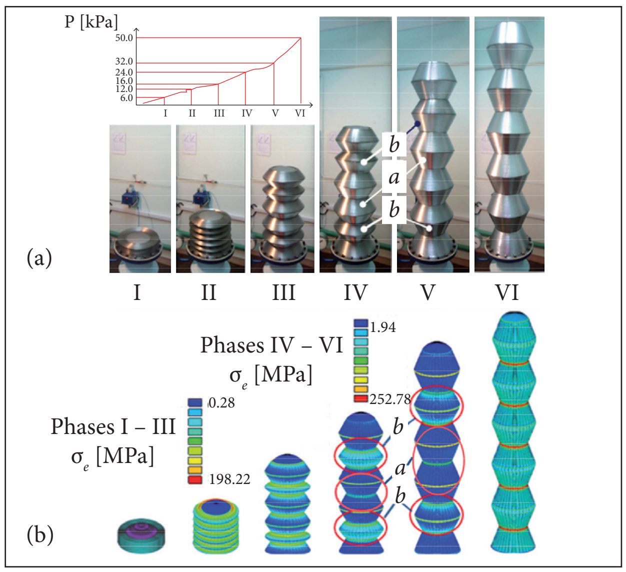

Figure 4. (a) The experiment on TVS unfolding and the growth curve of the excessive unfolding pressure (*P*) in the inner cavity of the shell; (b) The result of dynamic FEM of the process.

THE MODIFICATION OF TVS SURFACE PROPERTIES

The surface of the metal shell, absorbing the solar radiation mainly in the visible part of the spectrum, should possess a low absorbing capacity A_S and a high radiating capacity ε under conditions of heating and, respectively, high A_S in the spectrum's infrared part. In the definite range the change of the mentioned value is attainable with mechanical and chemical treatment of the surface. Thus, the increase in roughness leads to the simultaneous reduction of A_S and ε and does not allow reducing greatly the maximum temperatures on the TVS surface neither under conditions of heating by the solar radiation flux, nor during the heat emission by radiation in the shade side of the orbit. For this reason, during the TVS development, the object of investigation was the A_S/ε ratio correction of definite shell material by deposition of different combinations of materials and their compounds on TVS surface, which performed functions of selective-coatings. The option of the necessary coating was determined not only by its thermal optical properties, but also by adhesion to the surface of the metal shell taking into account the large deformations of its surface during unfolding, as well as by different rates of sublimation of materials under vacuum space conditions.

Unique functional characteristics of the transformable shells, capable of changing one of their dimensions by 40 and more times, do not allow applying the known materials with preset thermal optical properties for their passive heat protection, for example, enamels, screen-vacuum heat insulation etc. The preparation of TVS optical surfaces after roughness correction was carried out by using electron beam spraying of thin coatings of metals and their compounds with required A_S/ε ratios. At the same time, it is evident that the result of this modification in the shell, expressed in values of displacement of random parts of its surface at different temperature values, requires a valid experimental confirmation even at the intermediate stages of large-sized transformable structures manufacture.

At the stage of laboratory testing, the efficiency of coatings with different values of ε and A_S was determined on the transformed conical section parts, which were fixed on the rigid frame and, within equal time, were subjected to a vacuum test while heating with an imitation of the spectrum and intensity of the radiation flux close to sunlight. Caused by plates heating, the surface deformation was recorded by a non-contact method of electronic shearography (Lobanov and Pivtorak 2014).

Since the experiments were conducted under the same mechanics and thermal optical conditions, the data on the maximum observed number of fringes N were used to simplify circuit calculations and comparative assessment.

The number of fringes N, which is recorded by the method of electron shearography using the shearographic system during the object deformation, is connected with values $\partial V/\partial X$ by the following expression (Lobanov and Pivtorak 2014):

$$\frac{\partial V}{\partial X} = \frac{N\lambda}{2\Delta x} \quad \text{(light interference fringes)} \qquad (10)$$

where: λ is the wave length of the laser radiation source; Δx is the value of a shear (shift) in the direction of OX axis in the optical scheme of the interferometer; V is the component of displacement vector, directed normally to the surface. The higher deformations of the surface at thermal loading of the object correspond to the larger number of fringes, observed in the shearographic pattern.

Figure 5 shows the results of the experiment on the determination of the fringes of order N in the TVS shell part with different thermal optical coatings at radiation heating, simulating the conditions of heating at the near-Earth orbit. The temperature drop during heating is $\Delta T = 2\,°C$. At the stage of heating three surfaces were examined: (1) the TVS surface of stainless steel AISI 321 without coatings after chemical etching (Fig. 5, I); (2) the same surface after the deposition by the method of electron beam spraying of aluminium coating of 480 nm thickness (Fig. 5, III); (3) the antecedent surface with spraying of Al_2O_3 of 45 nm thickness on the aluminium layer, simulating the formation of the oxide film, greatly increasing the absorption coefficient A_S (Fig. 5, II). It should be noted that, at applied thicknesses of coatings, the surface's thermal and optical properties depend also on the properties of the coated metal, and small thicknesses of the coated layer were used for the accuracy evaluation of the experimental part of the procedure. The dependence of N values (see Eq. 10) for different variants of surfaces on the heating time t is given in Fig. 5.

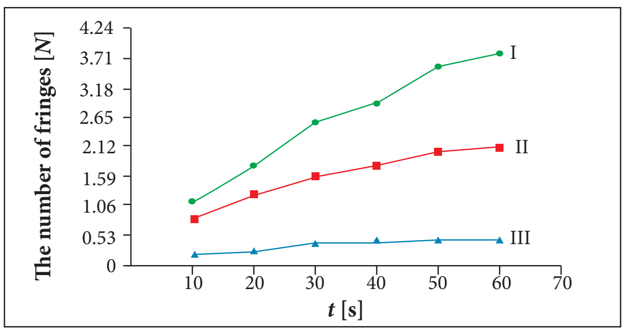

Figure 5. The number of fringes N in a shearographic interferogram depending on the time of radiation heating t in a TVS shell part.

As the coatings, sprayed on the object's surface, have a small thickness and cannot significantly change the thermo-mechanical properties of plates, the deformation $\partial V/\partial X$ and, consequently, the number of observed fringes N in the shearographic interferogram are proportional to the temperature attained on the surface due to the radiation heating. Thus, as to the data of the diagram in Fig. 5, it is possible to obtain the quantitative evaluation of effectiveness of sprayed layer reflecting properties.

In TVS development the experimental-computational method was used, which consists in the verification of a FEM of temperature deformations in a random part of the structure shell. The method was performed by applying standard finite-element analysis. The FEM is compared with a three-dimensional surface of function $\partial V/\partial X$ of the examined part of the metal shell with different surface's thermal and optical properties.

At radiation heating of the shell under the conditions, simulating with a maximum validity the regular service conditions in space vacuum, the interference patterns (shearographic interferograms) were formed (Fig. 6a, II). These patterns were obtained by comparison of two speckle-patterns corresponding to different stages of heating (Fig. 6a, I) at the reflection of the dissipated laser radiation from TVS surface part (Fig. 6a). The further processing of interference patterns using a special software allows plotting a three-dimensional pattern of deformations at thermal loading in the part being examined (Fig. 6a, III).

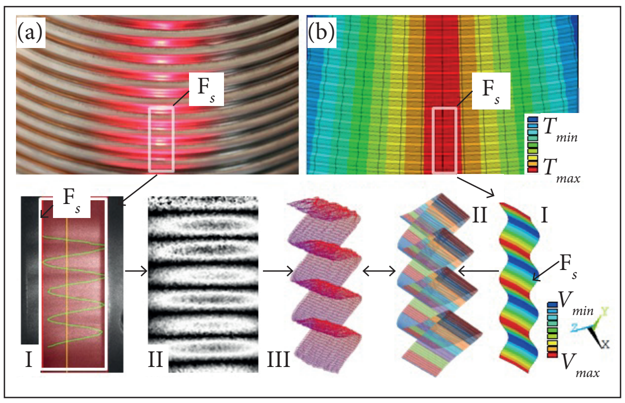

Figure 6. The use of the method of electronic shearography (a) for verification of the FEM (b) of temperature deformations of the random TVS shell fragment F_S.

The obtained three-dimensional pattern (Fig. 6a, III) is compared with three-dimensional distribution of values of the $\partial V/\partial X$ function (Fig. 6b, II), obtained by differentiation of the displacement field V in the direction OX of the FEM of the examined part (Fig. 6b, I). For the examined part, the temperature experimental values of the structure's optical surfaces are taken, which are determined in the experiment process on the radiation heating of TVS surface. Thus, the sufficient coincidence degree of two models (Fig. 6a and b) can confirm both the effectiveness of surface engineering methods and the validity of the accepted computational model (correctness of calculation of structure using numerical methods) without applying full-scale stand tests. The advantage of the experimental calculation method is the possibility to obtain the interference patterns during vacuum tests with simulation of a solar spectrum and density of radiation flux applied to a TVS part. It can be a single conical segment of the multisectional structure, subjected to proportional deformations at orientation of solar radiation flux, normal to the TVS symmetry axis or to the pair of adjacent segments at any other orientation of the flux.

Thus, Fig. 5 illustrates the effectiveness of the applied method of surface modifying. To verify the calculated results of its application, expressed in the deformation pattern, the described experimental-calculation method (Fig. 6), also including differentiation of displacement field V in the directions OY ($\partial V/\partial Y$) and OZ ($\partial V/\partial Z$), can be used.

With respect to the structure in Fig. 3b, as a result of its calculation using standard finite-element analysis, it was determined that taking into account both the effect of maximum values of temperature loads (−150 to +125 °C) and accelerations on optical surfaces without protective coating leads to 2.32 times increase in maximum displacements in the TVS shell and 1.23 times growth of equivalent stresses. Further, the change in shape of a corrugation profile (Fig. 3) allows reducing the maximum values of stresses in the structure by 15% (from 202 to 176 MPa). The application of coatings, decreasing the temperature load to the range of −43 to +63 °C, leads to the deformability decrease of the multisectional shell by 1.45 times and to the reduction of maximum values of equivalent stresses by 1.17 times (from 175 to 150 MPa). Thus, the surface modification in combination with a profile shape variation of shell folds can reduce the deformability and increase the stability of the studied TVS type to values which require the increase in the structure mass by more than 30% at simultaneous reduction of its compactness using standard design approaches (in particular, 2 times increase in material thickness of four conical sections at the attachment side). The results of calculations and their experimental verification demonstrate the possibility to use these types of thin metal shells as the load-bearing elements under SEF conditions. It should be added that the examined example of the conical TVS can be described as the most complicated structural and technological embodiment of this type, which has a small ratio of the diameter of the supporting contour to the overall length and is subjected to direct radiation heating influence on the vacuum of space environment. The determination of optimum ratio of the used surface engineering methods, as well as qualitative and quantitative evaluation of the effectiveness examined in this paper, depends, in each case, on a number of factors — primarily, on the specific functionality of the TVS and the duration of its exposure under SEF.

CONCLUSIONS

The development of new shell structures, with unique functional characteristics and their adaptation to extreme service conditions, predetermines the need to verify the results of superposition modelling of complex stress-strain states, subjected to significant changes in the long-time exposure process. The integrated approach, suggested by the authors, allows evaluating the equivalency of fields of TVS surface displacements, obtained in contactless diagnostics and in the databasis of numerical modelling. It also determines the optimum relation of methods used for modification of its rigidity-strength characteristics. It is shown the possibility of improving the functional characteristics of the examined structure by means of profile adjustment of circular folds of its separate shell elements and spraying on them thin coatings with required thermal and optical properties. The result of this study demonstrates the possibility of effectiveness evaluation of the applied surface engineering methods under the terrestrial conditions, excluding the valid experimental confirmation of computational model results.

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