DOI: http://dx.doi.org/10.15407/tpwj2019.07.03

MODELLING OF TEMPERATURE FIELDS, STRESSES AND DEFORMATIONS IN CYLINDER SHELLS PRODUCED BY ADDITIVE MANUFACTURING METHOD[*]

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The paper presents the results of modelling of temperature fields, stresses and deformations in formation of additive multilayer structure of aluminum alloy 1561, low-alloy structural steel of 09G2S grade and titanium alloy of Grade 2 grade. Based on the experimental results obtained earlier at the E.O. Paton Electric Welding Institute during application of additive deposits of these materials the computer modelling was carried out for improvement of technology of additive process. In course of calculations there was analyzed an effect of algorithm of sequence of additive layers deposition, namely deposition of cylinder shell on circle and on spiral, on distribution of temperatures in deposition and its resistance to external loads. It is determined that for formation of cylinder shells by additive method it is reasonable to use the spiral deposition technology and apply less heat-conducting structural materials, i.e. structural steels and titanium alloys. 10 Ref., 7 Figures.

Keywords: *additive manufacturing, modelling, spiral deposition, cylinder shells, resistance, residual stresses*

In modern construction, aircraft and space engineering as well as in a series of other branches of commercial manufacturing the large importance is given to application of thin-wall shells of different materials [1]. Such shells can be used as bodies of rocket solid-fuel engines, construction domes, tanks for storage of active and cryogenic liquids, i.e. structures operating under high inner pressures at axisymmetric external loading.

Different structural steels, titanium and aluminum alloys, composite materials based on titanium, aluminum and ceramics are often used as raw materials for their production.

Application of thin-wall shells allows significantly reducing weight of structure at keeping the maximum volume, providing its necessary strength and rigidity, using various complex shapes in design of products of different types.

Traditionally, such shells are obtained by method of tool or magneto-pulse stamping, electrohydraulic stamping or explosion stamping, rotary drawing, bending of roll sheet material and next joining of its edges by welding [2].

In the case of application of shells of variable thickness there is a problem of removal of excess of material. It is realized by means of mechanical milling or chemical etching that significantly increases duration of a process of its manufacture and considerably rises fabrication cost. The mechanical defects, appearing in course of these operations, make it useless for repair restoration.

Renewed interest to investigation of thin-wall structures is caused by appearance of new materials and alloys, rapid development of computer technologies as well as possibility of application of new methods for manufacture of parts and their components using additive manufacturing [3, 4].

Today, many world companies in manufacture of their products started to use additive manufacturing for 3D printing. In the beginning of 2018 the famous American Aerospace Corporation Lockheed Martin presented [5] the first 3D-printed rocket-propellant tank of titanium alloy (Figure 1).

Selection of titanium was caused by its high specific strength, heat and corrosion resistance. When using the traditional technologies of manufacture of cylinder fuel tanks as a rule up to 70–80 % of valuable material is sent in recyclable wastes. A new method of printing from Lockheed Martin allows considerably saving on manufacture of these tanks (on Companies' data up to 87 %).

Cylinder fuel tanks are not a single product of Lockheed Martin being 3D printed. The Company has already used this technology for creation of satellite communication system and components for interplanetary station NASA Juno. The Company also plans to produce external shell for spaceship Orion using 3D-printing technology.

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[*] Based on presentation made at International Conference «Consumables for Welding, Surfacing, Coating Deposition and 3D-Technologies», June 04–05, 2019, Kyiv.

Figure 1. Rocket fuel tank (*a*) and electron beam chamber for 3D printing (*b*) [5]

Additive manufacturing is a new highly-efficient method of development of products and structures based on addition of small portions of material. The products and materials are developed by melting of metallic powder [4], solid wire or flux-cored wire [6] with concentrated heat sources.

Application of metallic wire instead of powder in additive process allows rising efficiency of metallurgical processes, providing higher energy efficiency, increasing material utilization rate, decreasing residual stresses and deformations, providing necessary level of properties. Application of additive method in repair of thin-wall shells can allow restoration of their structural integrity and bearing capacity. At the same time, development of working thin-wall structure requires preliminary laboratory investigations and computer modelling.

Aim of the present work was improvement of the technologies for development of thin-wall shells by additive method based on selection of geometry of their deposition.

Experiment procedure. Due to the fact that thin-wall structures are widely used in aerospace engineering, shipbuilding and commercial construction, initially, for investigations two types of materials, namely titanium alloy Grade 2 and structural low-alloy steels of 09G2S grade, were selected.

The peculiarities of formation of structures of titanium alloys (high power of heat source, presence of high vacuum in deposition chamber) required application of a special system of additive manufacturing xBeam 3D Metal Printing [7]. The system is based on application of a hollow conical electron beam as a heat source and application of wire as a consumable. This creates favorable conditions for melting of consumable material and its layer-by-layer controlled deposition.

Arc system for development of additive structures was used [8] to deposit the products of structural steel. It is based on application of welding robot ABB IRB-1600.

E.O. Paton Electric Welding Institute has developed a software for creation of 3D model based on scanning of additive coating, planning the trajectory of welding torch movement considering correction of data of laser-TV and videopyrometric probes.

Thin-wall products from researched materials are shown in Figure 2. Welding wires of corresponding composition and thickness were used as a consumable for additive manufacturing of 3D products.

Computer modelling was carried out in order to improve a technology of development of thin-wall shells by additive method and increase their mechanical properties.

Titanium alloy of Grade 2 grade (VT1-0), containing wt.%: 0.03 N; 0.1 C; 0.25 O; 0.3 Fe was used for modelling. A yield limit of alloy made 275 MPa, strength limit was 345 MPa. Steel of 09G2S grade, used for welded structures and containing, wt.%: 0.12 C; 0.6 Si; 1.5 Mn; 0.3 Cu; 0.04 S; 0.003 P was selected as low-alloy steel. Steel yield limit made 345 MPa, strength limit was 490 MPa, relative elongation 21 %.

Application of high-strength aluminum alloys is wide spread in practice of development of cylinder shells for aero- and rocket-space engineering. Therefore, it was reasonable to use developed approaches to analysis of development of additive shells for these alloys.

Due to limitation of access to experimental results in this branch, a modelling of electric arc wire surfacing of thin-wall product of wrought aluminum alloy of 1561 (AMg61) grade in shielding argon medium was carried out as a predicted variant. Alloy of 1561 grade contains, wt.%: 6.1 Mg; 0.9 Mn; 0.4 Si; 0.4 Fe; 0.003 Be, 0.12 Zr. This alloy is widely used in manufacture of thin-wall elements of aerospace engineering. Aluminum alloy has a yield limit not less than 250 MPa and strength limit not less than 360 MPa.

Calculated cylinder shells are the layers of material of 2 mm width and 2 mm thickness in sequence deposited on a substrate by circle with 20 mm radius. Number of deposited layers shall satisfy the condition of thin wall, i.e. shell is supposed as thin, if $h/R \leq 1/10–1/20$. Following from selected parameters this condition was fulfilled when number of layers exceeds 10.

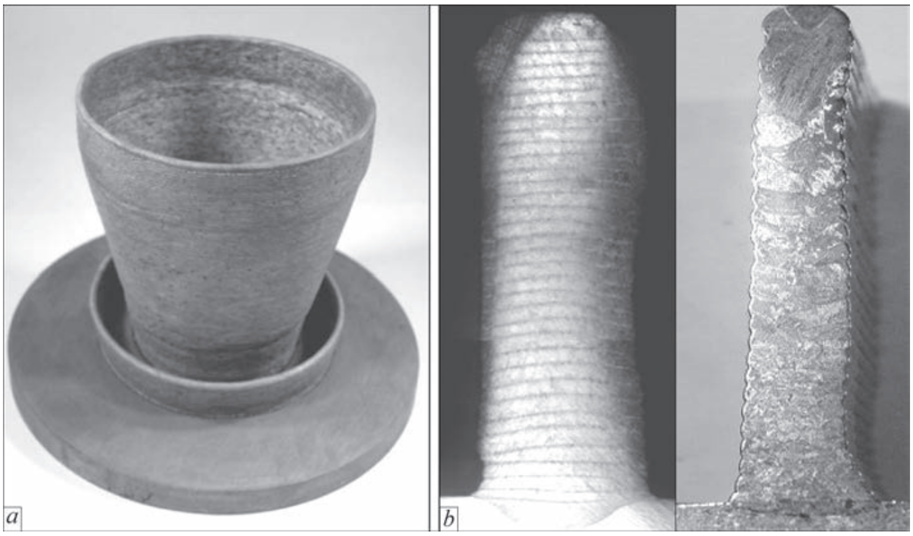

Figure 2. Deposits of investigated materials produced by additive method: *a* — low-alloy steel of 09G2S grade; *b* — titanium alloy Grade 2

Technological parameters of additive manufacturing

Power of heat source (Al/Fe/Ti), kW	0.6/1/5
Plate thickness, mm	5
Thickness of deposited layer, mm	2
Deposition width, mm	2
Deposition radius, mm	20
Deposition height , mm	40
Number of layers	20
Arc movement rate, rps	0.1; 0.2; 1
Number of deposited layers	20–30

Selection of power of arc heat source was determined by typical modes of welding for this type of material, namely electron beam welding of titanium alloys (5 kW), gas-shielded arc welding of low-alloy steels (1 kW) and consumable electrode arc welding of aluminum alloy (0.6 kW).

Two methods of deposition of additive layers were investigated, i.e. on circle and on spiral. Angular rate of deposition of one layer was determined by technological possibilities of units and made 0.1; 0.5 and 1 rps.

Computational model. To model the effect of deposit application on its properties the temperature fields and stress-strain state of cylinder products in process of their formation were calculated. Computational package COMSOL Multiphysics® was used for calculations. A mathematical model of additive process was presented in works [9, 10]. It was assumed based on experimental results that in the initial moment of time the precipitated material was in a solid-liquid state between temperatures of liquid and solid body. Therefore, the liquid phase can be neglected in the calculations.

For numerical analysis of the kinetics of temperature field change in the deposited shell a 3D nonstationary heat-conduction equation was solved:

$$\rho C_p\left(\frac{\partial T}{\partial t}+u\nabla T\right)=\nabla\left[k(T)\nabla T\right], \tag{1}$$

where ρC_p is the specific heat capacity; k is the coefficient of heat conduction of the material.

Boundary conditions, necessary for solution of equation (1), are determined by a balance of heat input and heat sink from the surface of part being precipitated. Heat transfer in the area of contact of deposited product with a substrate can be described by Newton's law, whereas a heat radiation on a free surface is regulated by Stefan–Boltzmann law. The boundary conditions for solution of heat-conduction equation (1) have the following form (2):

$$-k(T)\frac{\partial T}{\partial n}=\begin{cases} h(T-T_{ext}), \\ \text{in contact area} \\ h(T-T_{ext})+\varepsilon\sigma_0(T^4-T_{ext}^4)-q_{arc}-q_{wire}, \\ \text{on free surface} \end{cases} \tag{2}$$

where n is the normal line to surface; $h = 10$ (W/m^{2}K) is the coefficient of convective heat conduction; $\varepsilon =$ $= 0.8$ is the coefficient of material radiation; σ_0 is the Stefan–Boltzmann constant ($5.6\cdot10^{-8}$ J·s^{-1}m^{-2}·K^{-4}); $T_{ext} = 293$ K is the environment temperature; q_{arc} is the density of heat flux developed by arc heat source (W/m^2); q_{wire} is the density of heat flux developed by molten wire (W/m^2).

The work used the model of joint energy transfer from two simultaneously operating heat sources, namely from arc source and molten wire. The arc coordinates, moving on the surface, are set by equation (3):

$$X = X_g + R\cos(2\pi\omega t);\ Y = Y_g + R\sin(2\pi\omega t) \tag{3}$$

where X_g, Y_g are the initial arc position; ω is the angular rate; *R* is the trajectory radius; *t* is the time.

Distribution of density of heat flux of moving arc $q_{arc}(X, Y, t)$ was set by equation (4):

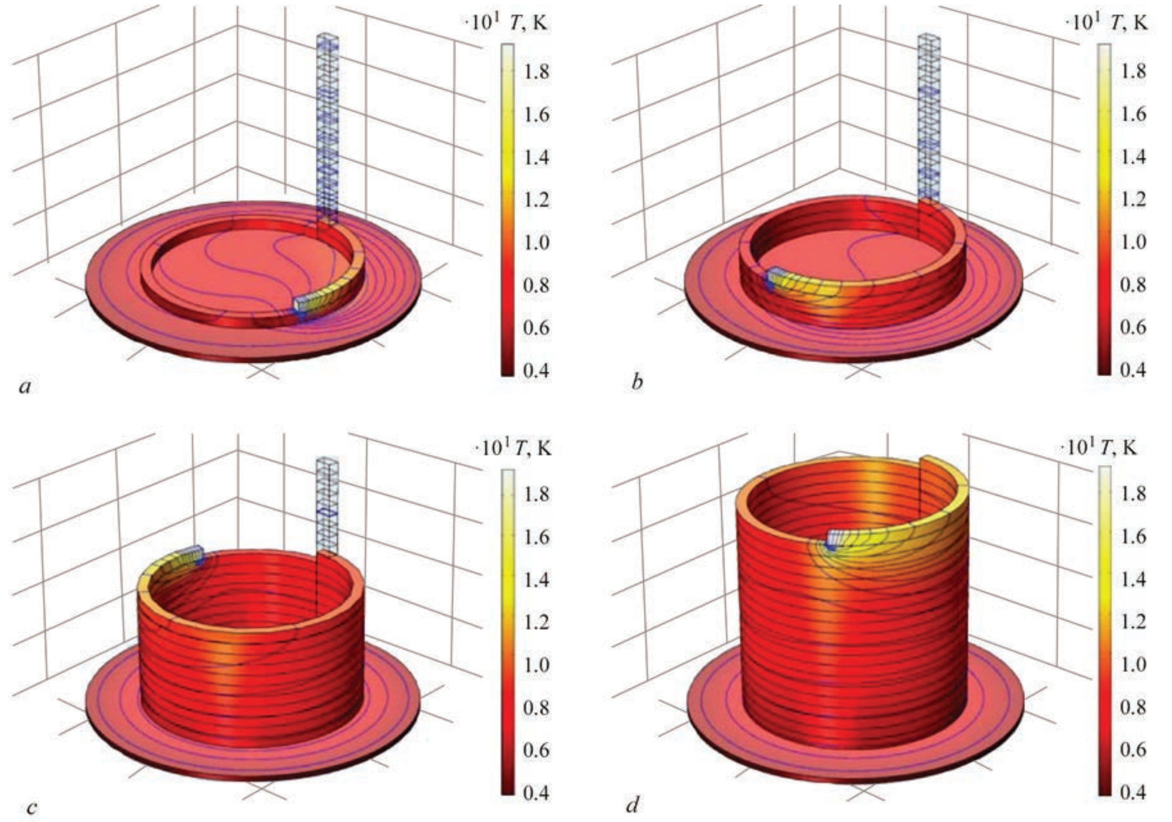

Figure 3. Distribution of temperature in cylinder shell of titanium alloy Grade 2 obtained at 0.1 rps rate by time: *a* — 13; *b* — 35; *c* — 108; *d* — 194 s

$$q_{arc}(x,y,t) = \\ = q_{\max} \exp\left[-K_x \left(\frac{X - X_g}{R} \right)^2 - K_y \left(\frac{Y - Y_g}{R} \right)^2 \right], \tag{4}$$

where X, Y are the coordinates of heat source; $q_{max} = \eta U_a I_w$ is the arc power; η is the coefficient of efficiency (0.9–0.95) of source; U_a is the arc voltage; I_w is the arc current; K_x, K_y are the coefficients of concentration of specific heat source.

Distribution of density of heat flux from molten wire q_{wire} (X, Y, t) was set by movement of edge of forming layer with angular rate omega at constant temperature $T_{wire} = T_{melt}$. In researched materials T_{melt} made 625, 1504 and 1716 °C for aluminum alloy 1561, steel grade 09G2S and titanium Grade 2, respectively.

Modelling results. The fields of temperatures, stresses, deformations and displacements in formation of cylinder shells by additive method were calculated as a result of modelling.

Figure 3 shows the temperature fields of titanium alloy Grade 2 in time. The analysis demonstrated virtually uniform distribution of temperature over the thickness of deposited layer. Temperature distribution on shell height showed that it does not change in process of deposition of 9–10 layers. Substrate temperature does not exceed 200–230 °C, and, respectively, its structural-phase state does not change.

The calculations show that the quickest stabilizing of shell temperature is observed in welding with wire

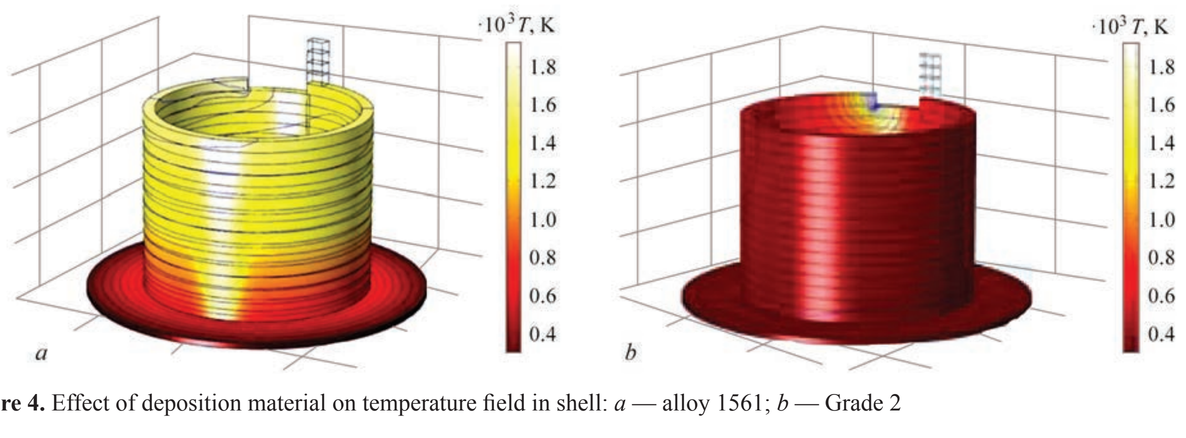

Figure 4. Effect of deposition material on temperature field in shell: *a* — alloy 1561; *b* — Grade 2

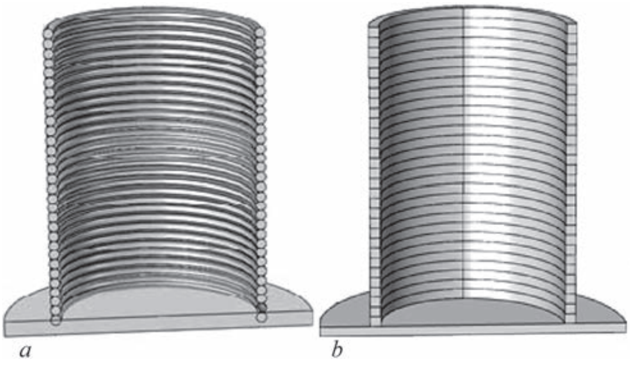

Figure 5. Nature of deposition of additive layers: *a* — on spiral; *b* — on circle

of 09G2S steel after 35–40 s. For aluminum alloy 1561 this time makes 65–70 s, whereas for titanium alloy Grade 2 there is no stabilizing.

The calculations show that depending on composition of used wire the maximum temperature of deposition exceeded the melting temperature of given alloy by 50–75 °C(for aluminum alloy 1561), by 100–150 °C (for steel 09G2S) and by 200 °C (for titanium alloy Grade 2).

The analysis of temperature distribution on deposit height shows (Figure 4) that depending on type of used material there is different effect of molten wire on already deposited layers. Thus, the most significant effect as a result of effect of previous layers is achieved in deposition of aluminum alloy 1561, which propagates on underlying 8–10 layers (Figure 4, *a*). In deposition of molten wire of steel 09G2S or titanium alloy Grade 2 this effect is considerably lower. For steel it makes 3–4 layers, for titanium alloy 1–2 layers (Figure 4, *b*). Obtained results can be explained by noticeably higher heat conduction of aluminum alloy (100–150 W/(m·K)) in comparison with steel (23–28 W/(m·K)) or titanium alloy (17–25 W/(m·K)).

A cylinder structure of aluminum alloy 1561 cools down visibly quicker and reheating reaches deeper layers that results in grain growth and decrease of mechanical properties of these alloys. Application of 09G2S steel and titanium alloy Grade 2 in the additive process results in formation of more homogeneous structure of the deposit and reduces residual stresses, forming in cylinder shell formation.

Effect of algorithm of performance of additive cylinder deposit, namely deposition on circle or spiral, on temperature of deposition and parameters of stability of additive shell to external loads (Figure 5) was analyzed in course of calculations.

Majority of works on modelling of additive manufacturing do not consider effect of deposit shape. This is related with the fact that in this case it is necessary to take into account drop hydrodynamics, solidification processes, interaction of drops between themselves, etc. In order to eliminate these difficulties and approach to real deposit geometry a shape of deposited layer on section was set in advance. In the most cases a view of side surface of the shell has wavelike «ribbed» nature, moreover it depends on layer thickness and deposition rate.

In course of work it was accepted that the spiral deposition forms wavelike geometry of side wall, whereas in deposition on circle it is flat. This assumption grounds on the fact that a real deposition is carried out continuously over the whole height of products and this provokes formation of «ribbed» surface, whereas deposition on circle is more idealized variant, which is used for calculations.

The analysis of obtained data showed that spiral deposit is heated to higher temperatures in comparison with circular one. This, apparently, is related with reduced heat transfer between the layers. At that, a deposited layer cools down quicker, that is determined by larger area of cooled surface.

The parameters of cooling of cylinder shell of less heat-conducting titanium alloy Grade 2 in comparison with shell of steel 09G2S provide higher temperature levels. As a consequence, rise of overheating of liquid pool and coming out of range of temperatures of solid-liquid state for this alloy (T_{sol}/T_{liq}) is possible. Thus,

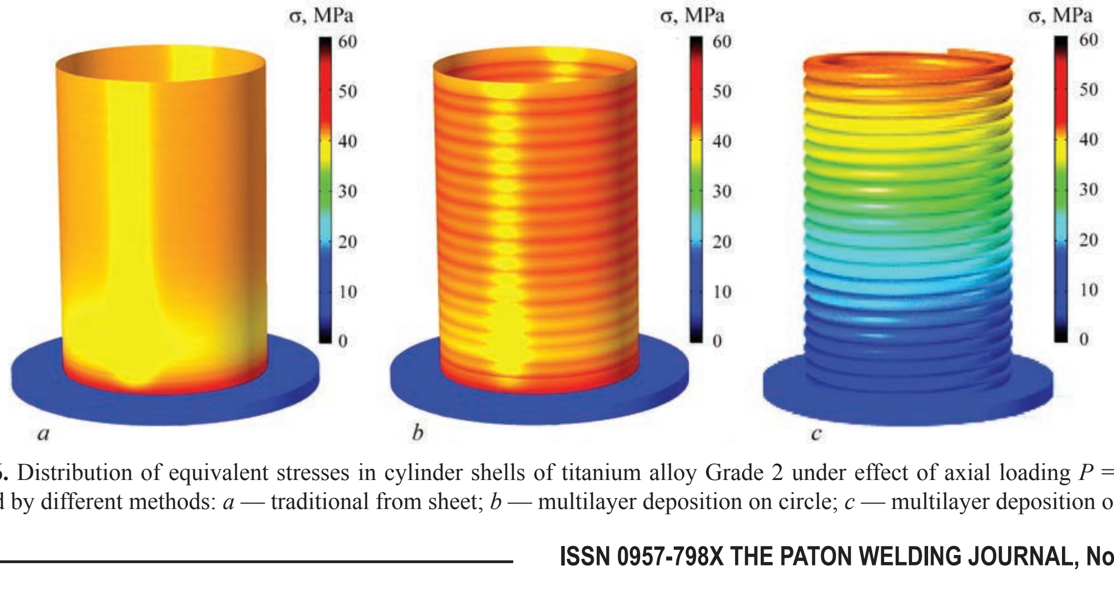

Figure 6. Distribution of equivalent stresses in cylinder shells of titanium alloy Grade 2 under effect of axial loading $P = 50$ MPa produced by different methods: *a* — traditional from sheet; *b* — multilayer deposition on circle; *c* — multilayer deposition on spiral

there is increase of a risk of «leaking» of liquid melt on side surface of the cylinder shell.

Difference in mechanical stability of cylinder additive shells produced by different methods was analyzed in the work.

Analyzing the stability of cylinder shells, produced by additive method, it is necessary to take into account presence of residual stresses, which are formed on a boundary of deposited layers. In the case of deposition of layers on circle the residual stresses on the boundaries make 40–50 MPa, at the same time in deposition of layers on spiral the residual stresses are somewhat lower and make 10–30 MPa. At that, as it was shown by previous investigations [10] the highest level of stresses was observed on a boundary of the additive layers and substrate. In this case the level of stresses makes 100–150 MPa.

A nature of distribution of stresses in the cylinder shells, produced by different methods, under effect of axial compressive load *P* = 50 MPa is given in Figure 6. As can be seen from given results, presence of stresses, forming in process of additive manufacturing, changes in whole nature of distribution of stresses in shells under effect of axial compression load.

Analysis of obtained results (Figure 6) shows that a nature of forming stresses significantly depends on method of shell formation. The differences, first of all, lie in a level of stresses forming in them. The highest stresses (55–60 MPa) are formed in a shell produced by circular layers, whereas the lowest (35–40 MPa) are formed in a multilayer deposit made on spiral. This result is, probably, explained by some damping of external axisymmetric loads by layers of deposited on spiral.

Analysis of shell stability, produced by different methods, to effect of axial compressive load is presented in Figure 7. Loss of shape structure under effect of external forces was meant under stability loss. The van Mises yield criterion (5) was used for determination of start of plastic deformations:

$$g(\sigma) = \\ = \sqrt{\frac{1}{2}\left(\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_2)^2+(\sigma_1-\sigma_3)^2}{\sigma_y^2}\right)} - 1 \geq 0, \quad (5)$$

where σ_1, σ_2, σ_3 are the main normal stresses; σ_y is the yield limit.

Investigation of cylinder shells, produced by different methods, showed that multilayer deposition on spiral provides the highest level of critical stresses (180–200 MPa), at which it loses stability in comparison with shells produced from solid sheet (150–165 MPa) and multilayer deposition on circle (145–150 MPa).

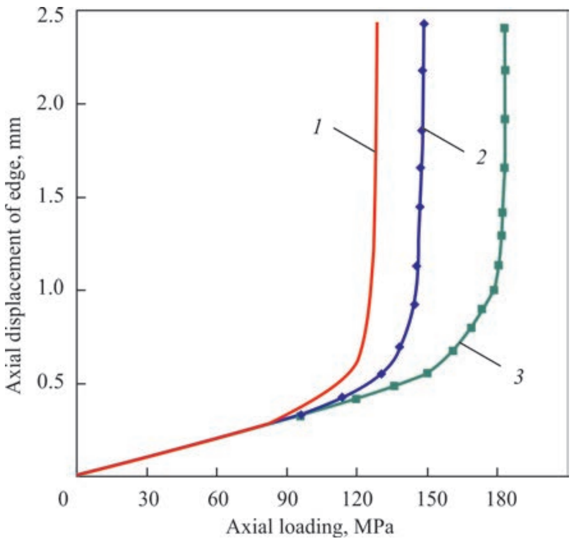

Figure 7. Stability of cylinder shells produced by different methods to effect of axial compression loads: *1* — from solid sheet; *2* — from multilayer circle deposit; *3* — from multilayer spiral deposit

Thus, it can be concluded based on carried work that formation of the cylinder shells by additive method is reasonable using technology of additive manufacturing on spiral.

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Received 08.04.2019