Конічні глибоководні ілюмінатори (КГІ) з оргскла широко використовуються в підводній техніці. Із-за специфіки властивостей оргскла, умов експлуатації і складного напружено-деформованого стану (НДС) КГІ важко оцінити їх ресурс роботи і вибрати оптимальні геометричні характеристики. Виконано експерименти та чисельні розрахунки НДС КГІ з оргскла при різних рівнях гідростатичного тиску для розробки методики оптимального проектування КГІ з урахуванням умов експлуатації. КГІ з оргскла піддавались впливу тривалого (до 7 діб) і циклічного (до 2000 циклів) гідростатичного тиску 40, 60, 70 і 80 МПа.

За допомогою датчиків переміщень періодично визначалися деформації КГІ не менше ніж в 20 експериментальних точках. Отримано експериментальні залежності переміщень КГІ при тривалому і циклічному впливі гідростатичного тиску. За методом напружено-часової аналогії здійснений прогноз деформативності КГІ на 10 років.

Виконано прогноз зниження механічних властивостей оргскла за методикою прискореного теплового старіння при температурах 40, 70 і 100 °С. Визначено вимоги до граничних деформацій в КГІ. На основі досліджень теплового старіння органічного скла, випробувань КГІ під дією гідростатичного тиску виконана комплексна оцінка їх працездатності в умовах експлуатації на 10-річний період.

Виконана серія розрахунків КГІ при кутах конусності 60–150° і відносних товщинах 0,35–0,60 за допомогою методу скінчених елементів. Отримані розрахунки збігаються з результатами експериментів, що свідчить про адекватність прийнятої розрахункової схеми КГІ – безвідривному ковзанні світлопрозорого елемента з тертям по опорній поверхні корпусу ілюмінатора. Показано, що збільшення кута конусності зменшує прогин КГІ, а еквівалентні напруження мінімальні при кутах конусності 75–105°. Синтез розрахунків НДС методом скінчених елементів у сукупності з прогнозом на основі нетривалих випробувань дозволяє вибрати оптимальні геометричні характеристики КГІ в залежності від умов експлуатації

Ключові слова: глибоководні ілюмінатори, теплове старіння, органічне скло гідростатичний тиск, прогноз властивостей, ресурс роботи

UDC 629.58
DOI: 10.15587/1729-4061.2020.194584

PREDICTION OF THE SERVICE LIFE OF DEEP-SEA CONICAL ACRYLIC PORTHOLES AT DESIGNING

Ye. Burdun
PhD, Associate Professor*
E-mail: evgeniy.burdun@nuos.edu.ua

V. Kochanov
Scientific Researcher*
E-mail: Kochanov@nuos.edu.ua

T. Yuresko
PhD*
E-mail: tyuresko@gmail.com

*Department of Design and Production of Structures from Composite Materials
Admiral Makarov National University of Shipbuilding
Heroiv Ukrainy ave., 9, Mykolayiv, Ukraine, 54025

Received date 14.11.2019
Accepted date 31.01.2020
Published date 24.02.2020

1. Introduction

Using biological and mineral resources of the World ocean at the modern stage of the civilization development is becoming an objective necessity, therefore, technical means for studying and mastering its depths have gained accelerated development. This implies the improvement of individual structural elements of underwater vehicles, which are used to work on the shelf (depths up to 200 m), continental slope (up to 1,800 m) and the ocean floor – abyssal plains with depths up to 7,000 m.

In studies of the ocean depths, the use of devices equipped with underwater video cameras is considered the most effective and least risky. The main elements of underwater optical systems are deep-sea portholes, in the design of which it is necessary to ensure the strength of translucent elements under the conditions of long-term and cyclic loads of hydrostatic pressure.

Acrylic, due to its high strength and large elastic deformation, is widely used for the manufacture of translucent porthole elements. The mechanical properties of acrylic, like most polymers, greatly diminish over time under the action of the atmosphere, moisture, and ultraviolet radiation. Their influence extends primarily to the surface layers of the material, which causes a decrease in the molecular weight of the polymer, a decrease in toughness and critical strain under tension. The application of protective films on the optical surfaces of portholes almost completely eliminates the negative impact of external influences.

At the same time, the temperature influence extends over the entire volume of the material and leads to its «heat aging». Since the process of heat destruction of polymers is rather long, the problem of predicting the service life of deep-sea portholes, taking into account heat aging and deformation under the hydrostatic pressure action is quite relevant.

The operating conditions of underwater equipment in most cases involve multiple diving-ascents, which are cyclic effects of hydrostatic pressure. As a result of such an impact, a nonhomogeneous stress state arises in the porthole, which leads to the appearance of elastic, viscoelastic, and plastic deformations. When unloading in the porthole there is a relaxation of stresses and strains. While partially or completely (depending on the stress magnitude), the shape of translucent elements is restored. The stress field in the porthole is not uniform and it is extremely difficult to predict its fatigue life. Therefore, in accordance with the recommendations of [1], the workload for long-term operation of portholes is assigned 4–12 times less than the failure hydrostatic pressure during short-term exposure.

When designing conical acrylic portholes, it is necessary to take into account their mass and dimensional characteristics, which directly affect the operational performance of underwater technical equipment. Reducing the weight of the portholes allows you to place additional equipment in the underwater vehicle, which increases its capabilities during research. Therefore, the problems of rational choice of porthole shape and the appointment of a reasonable operating life are relevant and of practical interest.

2. Literature review and problem statement

The author of [1] performed lengthy tests of more than 200 full-scale portholes of various shapes, on the basis of which recommendations for their design were developed. However, such tests were found to be very expensive, which did not allow accumulating a sufficient amount of statistical data.

The work [2] summarized information about the structural types of underwater acrylic portholes, however, algorithms for choosing their optimal shape depending on operating conditions were not proposed.

Most commonly, in the designs of underwater technical means, deep-sea portholes in the form of a truncated cone made of acrylic glass are used (Fig. 1).

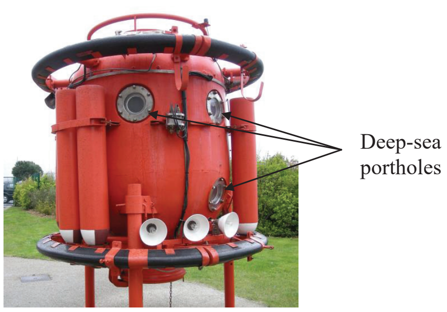


Fig. 1. Diving bell of the «Caley Ocean Systems» company (Glasgow, Great Britain)

In experiments [3], it was found that for the surface layers of the material that had a 10-year service life in the structure of the underwater vehicle «Alvin», reduced strength and deformability during tension and bending reaches 30–50 %.

At the same time, the critical strain ε_{cr}=5.4 % for just made acrylic is reduced to the minimum allowed during service ε_{ser}=3 %, which corresponds to the strains of the conventional yield strength. For the inner layers of the material, and also in compression tests, a decrease in strength was not detected. It should be noted that the material during service was under the action of only compressive stresses; in the case of tensile stresses, the decrease in strength and critical strain would be significantly greater due to the development of microcracks on the surface of the material. It was concluded that for 10-year service only portholes are suitable, in the surface layers of which no tensile deformations occur under hydrostatic pressure load. This requirement is ensured by proper selection of the basic geometric characteristics of the translucent porthole element (Fig. 2), which include the cone angle α and the ratio of thickness to diameter from the low-pressure side h/D.

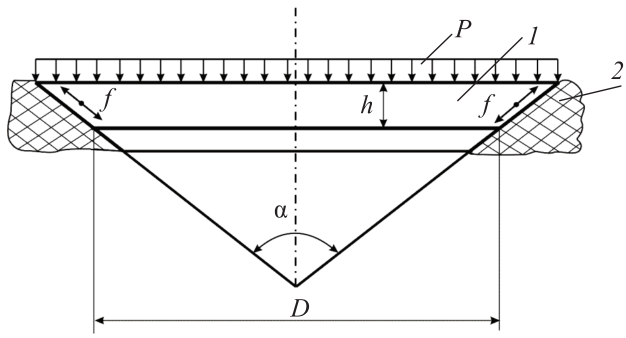


Fig. 2. Design scheme of the deep-sea porthole: P – hydrostatic pressure; f – friction sliding; 1 – translucent element; 2 – porthole body

In [4], considerable attention was paid to the design of the porthole body and ways to ensure sealing, however, optimal engineering solutions were not proposed. The authors of [5] found that for a taper angle α=90° and a relative thickness h/D=0.41, there are no tensile strains in the porthole, however, the influence of design parameters on the creep of the porthole under operating conditions was not evaluated.

An experimental study [6] was carried out, which showed the ability of acrylic to «adapt» to the shape of the porthole body due to a slight creep. It was found that due to the plastic behavior of acrylic glass, the greatest mechanical stresses at dangerous points in the porthole are reduced by 64–71 %. This confirmed the promise of using acrylic in the optical systems of deep-sea equipment, but it was not indicated in [6] which method is used to determine their reliability coefficient.

In situ 10-year research of portholes are not effective, as they are extremely expensive, and information about them is late. At the same time, it is possible to predict the properties of polymeric materials by the method of accelerated heat aging [7].

The methods for calculating conical portholes based on the finite element method (FEM) are considered in [8, 9]. In the calculation models, a translucent element under the influence of hydrostatic pressure slides with friction along the conical supporting surface of the porthole body. Moreover, the elastic-plastic state of the acrylic glass porthole was taken into account in [8], but creep analysis under cyclic loading was not given.

The authors of [9] performed calculations for portholes with h/D=1, α=90° and a friction coefficient on the supporting surface f=0–0.2 under the action of pressure P=70 MPa, which were in good agreement with Stachiv J. D. results of experiments [1]. However, there is no information on the applicability of this calculation procedure to portholes with $h/D \leq 1$, which can be used for operation at depths up to 2,500 m (Black Sea basin).

In accordance with the current standards for the design of portholes [1], deep-sea portholes intended for operation at depths of 6,000 m and more are mainly considered. So, the recommendations for the design of portholes consider this range of depths. At the same time, areas of the coastal shelf, continental slope and inland seas with the greatest depths of up to 2,500 m are the most interesting for research and rich in natural resources.

Therefore, it is necessary to solve the problem of calculating and evaluating the life of portholes precisely for such depths, which is currently insufficiently studied. For that, it is proposed to predict the operational properties of portholes based on physical analogies, which can significantly speed up and simplify the process of their design.

3. The aim and objectives of the study

The aim of the work is to improve the design methodology of deep-sea portholes for technical means for developing the shelf of the World Ocean with a depth of up to 2,500 m.

The following objectives were accomplished to achieve this aim:

– to determine the heat aging effect, the magnitude, duration and number of cycles of hydrostatic pressure on the deflection and the nature of the destruction of acrylic portholes;

– to determine the effect of geometric characteristics (taper angle and relative thickness) on the stress-strain state of conical portholes.

4. Materials and methods of studying the influence of operating conditions on the properties of acrylic portholes

4. 1. Materials and equipment used in the experiment

The studies were carried out on standard specimens for tensile tests and full-scale portholes of a diving bell made of one batch of acrylic grade CO–120. Tensile test specimens and full-scale portholes were made on a lathe from blanks cut from a 50 mm thick plexiglass plate.

Heat aging of plexiglass samples was performed at temperatures of 40; 70 and 100 °C in the SM 30/120–80 TS thermostat. Subsequent tensile testing of the samples was carried out on a universal FP–10 machine.

Tests of the portholes for a long and cyclic exposure to hydrostatic pressure were carried out in a high-pressure chamber (chamber volume – 0.06 m^3, maximum pressure – 150 MPa). Axial displacements were measured with an ICh-10 dial gauge, and pressure with an ECM–2U electrocontact manometer.

The pressure in the chamber was created using the UNGR–2,500R pump station.

The stress-strain state of the conical portholes was calculated using the finite element method (FEM) by means of the ANSYS Workbench program (2014).

4. 2. Method of determining the properties of the material and natural object

The main indicator of heat aging of acrylic was the value of the ultimate deformability ε_{cr}, which decreases over time.

The main controlled indicator when testing full-scale portholes is the dependence of the axial displacement (deflection) w in the center of the unloaded optical surface on the value P, duration τ, and number of cycles N of hydrostatic pressure.

When calculating the FEM, the main indicators are the displacements of the porthole points along the axis of symmetry w and equivalent stresses σ_{eq}.

4. 2. 1. Method of determining the ultimate deformability during heat aging of acrylic

Heat aging of acrylic, as a polymer material, is associated with the process of thermal-oxidative destruction that proceeds at a constant rate at a given temperature. This process is characterized by a change in the concentration of one of the reagents or active radicals of the same type. Under the condition of volume constancy, the reaction rate can be represented by a derivative of the reagent concentration. The appearance of new bonds and free radicals can be determined by the swelling degree of the polymer during its aging, which is directly related to the number of free functional groups. Specific reaction rate can be determined both by changes in the concentration of free radicals and by the Arrhenius equation [10].

The prediction of acrylic properties using the heat aging method suggests that the change in the mechanical properties of the polymer is proportional to the change in the number of functional groups in it.

The aging rate of acrylic increases with increasing temperature, which allows writing a formula for the durability prediction based on extrapolation according to accelerated heat aging data:

$$\ln t_1 = \ln t_2 + \frac{E}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right), \quad (1)$$

where E – energy of activation, J/mol; R – physical constant, J/(mol·K).

This means that during the time t_2 of accelerated heat aging at a temperature T_2, the critical strain of acrylic decreases to the normative value. Thus, the predicted durability is the time t_1 during which the critical strain reaches the normative value at the aging temperature T_1 in normal conditions. The value of permissible critical strain is determined based on the operating conditions of the underwater object. Determination of the critical strain of just made acrylic was carried out on standard samples in accordance with [11].

The essence of the accelerated heat aging method is to expose samples of material for a certain time at elevated temperatures and followed by their testing [7].

Heat aging of acrylic samples was carried out in a thermostat at three temperature levels T: 40; 70 and 100 °C. Holding time t for the samples at each temperature was: 48; 120; 240; 480 and 720 hours. The samples subjected to time-temperature processing were removed from the thermostat and tested no later than 24 hours. In the tensile test of acrylic samples, the values of critical strain ε_{cr} were determined [11], which served as the basis for constructing long-aging curves (Fig. 3) in ε_{cr} – ln$t$ coordinates.

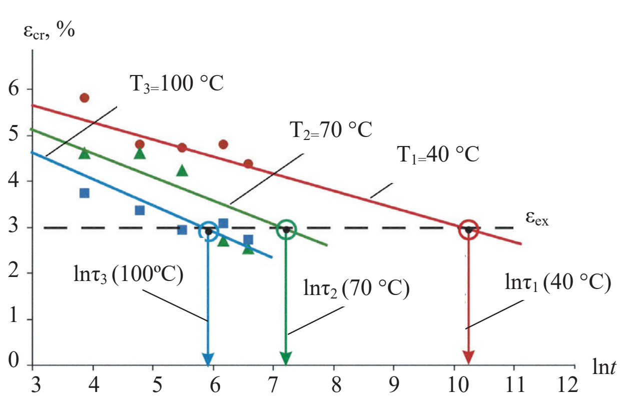


Fig. 3. Curves of accelerated heat aging

According to equation (1), the accelerated heat aging curves in Fig. 3 at each temperature were approximated by straight lines of the form $\varepsilon_{cr}=\varepsilon_0-a\cdot\ln t$.

4 2. 2. Method of determining the deflections of the portholes under the action of hydrostatic pressure

During the hydrostatic tests, the porthole of the diving station with a depth of 500 m was adopted as the main object under study. The translucent porthole element had the following dimensions: thickness h=50 mm; low-pressure side diameter D=116 mm; h/D=0.43 and the cone angle α=90°.

To assign the hydrostatic pressure levels during long and cyclic tests of the porthole, it was initially necessary to determine the value of the breaking pressure during short-term loading. For this, the translucent element of the porthole was fixed in the landing device of the high-pressure chamber, the chamber was closed and its filling was carried out with the working fluid (MS-20 oil). At the same time, the air was completely removed from the chamber through a special valve. Then, using a pumping station, the working fluid was supplied to the chamber, which ensured an increase in pressure in the chamber at a rate of 0.6 MPa/s. From the side of the low-pressure surface, there was access to the translucent element of the porthole, which made it possible to control its axial movement w with the ICh-10 indicator. The destructive hydrostatic pressure during short-term tests of the porthole was P=110 MPa, and plastic deformation became noticeable at 60 MPa and a deflection of 2.70 mm.

Long-term tests of the portholes were carried out under the following conditions: at hydrostatic pressure levels P=70 and 80 MPa the tests lasted 5 hours and at a pressure P=40 and 60 MPa – one week. During long-term tests, the porthole was loaded to the required level of hydrostatic pressure, which was subsequently automatically maintained constant by means of an electrocontact manometer connected to the pump station. During the experiments, the axial movement of the porthole w and the exposure time under pressure τ (at least 20 experimental points) were periodically controlled. According to the results of the experiments, the porthole deformation curves were constructed in the coordinates $w - \ln\tau$.

Tests of the portholes during cyclic exposure of hydrostatic pressure were performed at three levels of test pressure P=80; 70 and 60 MPa. The hydrostatic pressure during the tests increased at a speed of 0.6 MPa/s to a predetermined test level, followed by exposure of the porthole under pressure P for 10 s. Then, the pressure was reduced to zero and the cycle was repeated. The number of cycles N and deflection w of portholes in the center of the low-pressure surface were recorded. The deflections were measured every 5...20 test cycles. In addition, after every 100 cycles, the translucent element was removed from the porthole body for visual inspection to identify damage. According to the results of the experiments, the porthole deformation curves were constructed in the w–ln$N$ coordinates.

4. 2. 3. Method of calculating the stress-strain state of a conical porthole under the influence of hydrostatic pressure

The porthole translucent element under the action of hydrostatic pressure is in a complex nonhomogeneous stress-strain state; therefore the FEM is used for its calculation.

The stress-strain state of the translucent element is determined by its geometrical characteristics α and h/D [1].

At the first stage of research, the computational model (Fig. 2), which corresponded to full-scale specimens of translucent elements of the diving bell was used. This made it possible to compare the results of FEM calculations with experimental data and to estimate the accuracy of the solution.

Considering the radial symmetry of both the porthole and the external load, the calculations did not use a full-size model, but only a sector (the volumetric body of the translucent element was built at the radial section rotation by 6°). At the same time, the number of FEM elements decreases (that is, the time decreases and the accuracy of the calculation increases at the same finite element size).

The mesh for the translucent element of acrylic porthole was selected with the size of the finite element of 5 mm. On the border of the translucent element – porthole body, the size of the finite element is 2.5 mm. This allowed us to more accurately model the interaction of parts. For the finite element of the porthole body, the size of the mesh is equal to 10 mm.

The boundary conditions for the computational model (Fig. 2) are as follows:

– the porthole body is rigidly fixed;

– on the radial planes there are no friction and displacement in the circumferential direction;

– the condition of continuous sliding with the friction coefficient f is fulfilled on the border of the translucent element – porthole body;

– the pressure of 10 MPa acts on the outer optical surface of the porthole;

– the internal optical surface of the porthole is not loaded.

5. Results of the studies of the influence of operating conditions on the properties of acrylic portholes

According to the tests results of acrylic samples under heat aging, accelerated heat aging curves were constructed (Fig. 3). If you normalize the minimum acceptable critical strain at service time of acrylic ε_{ser}=3 % (deformation of the conventional yield strength), then in Fig. 3 you can determine the service time of material for each temperature T_1, T_2 and T_3 of accelerated aging. For this in Fig. 3, a horizontal curve ε_{ser}=3 % is drawn and the coordinates $\ln\tau_1$, $\ln\tau_2$, $\ln\tau_3$ of the intersection points with the aging curve are marked at temperatures T_1, T_2 and T_3, respectively, in the coordinates $\ln\tau - 1/T$, according to (1), the allowable service life curve should be a straight line (Fig. 4).

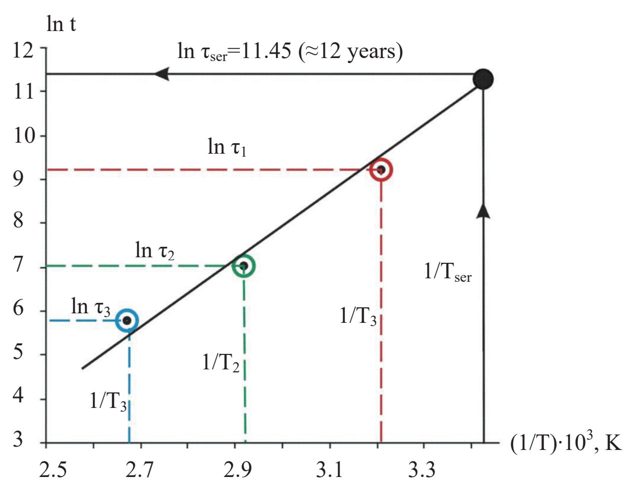


Fig. 4. Prediction of the service life of the acrylic deep-sea porthole

For the Black Sea basin, the average annual operating temperature of deep-sea portholes can be accepted as

T_{ser}=20 °C (293 K). By constructing a vertical straight line $1/T_{ser}$=const before the intersection with the durability curve, it is possible to determine the allowable period of service time ($\tau_{ser}\approx$12 years).

Thus, it is possible to predict the service time of deep-sea acrylic portholes.

Fig. 5, in the w–lnτ coordinates (w is the deflection of the porthole, mm; τ is the exposure time under load, min), shows the deformation curves of the portholes at different levels of hydrostatic pressure. The deformation curves are the source data for predicting the deformability of translucent elements by the method of stress-time analogy, which is as follows.

Acrylic, as most thermoplastic polymers, has a continuous spectrum of relaxation time in a highly elastic state, so compliance curves $J(\ln\tau)=w(\ln\tau)/P$ for different pressure levels are similar and transform into each other with parallel transfer along the time scale.

This allows, by a parallel transfer of compliance curves to the right to align with the «base» curve, corresponding to the lowest pressure during testing, constructing a generalized curve (Fig. 6), that is, performing a prediction of compliance. The stress-time analogy method is described in more detail in [12, 13].

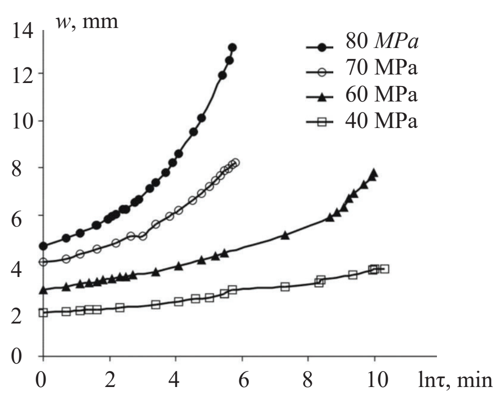


Fig. 5. Material deformation curves under load at different levels of hydrostatic pressure

Detailed analysis of compliance curves (Fig. 6) of the porthole shows that under a load less than 40 MPa, the porthole has the properties of linear viscous-elasticity. This means that the compliance curve at a working pressure of 5 MPa (diving depth of 500 m) is similar to the control curve for 40 MPa (Fig. 6).

At the level of external pressure of 80 MPa, the translucent elements were destroyed on average during 320 test cycles – the central part was separated from the peripheral one (Fig. 7, *a*). At 70 MPa after 2,000 cycles, annular cracks and crumpling zones on the edge of the low-pressure surface (Fig. 7, *b*) were observed; at 60 MPa and the same test base showed no visible damage.

The dependence of deflections w of the portholes on the level of hydrostatic pressure and the number of cycles N during testing is shown in Fig. 8.

As a result of FEM calculations, the displacements in the porthole were determined (axial displacement in the center of the low-pressure surface was 0.455 mm). During short-term testing of full-size portholes, axial displacement at a pressure of 10 MPa also amounted to 0.455 mm. This indicates that the computational model corresponds well enough to the real object. The calculated displacements of the translucent element at points on the border of contact with the porthole body are about the same; that is, the translucent element really slips along the conical support surface as a solid body. This phenomenon was observed also in full-scale tests. The displacements and equivalent stresses in the porthole are shown in Fig. 9, *a*, *b*.

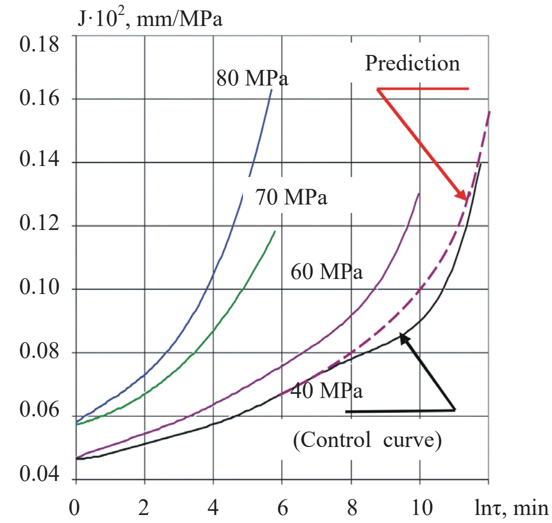
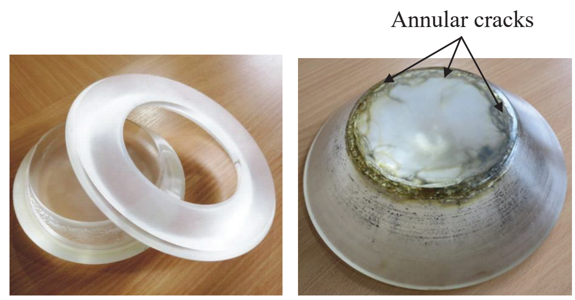


Fig. 6. Compliance curves of the translucent element and prediction of their deformability



a *b*

Fig. 7. Types of destruction of the translucent elements of the porthole: *a* – central part separated from the peripheral at 80 MPa; *b* – annular cracks and crumpling zones on the edge of the low-pressure surface at 70 MPa

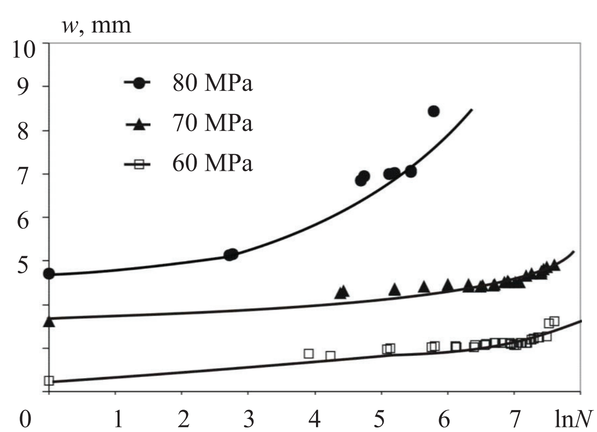


Fig. 8. Axial deflections w of the translucent element under cyclic loading of hydrostatic pressure P

The equivalent stresses in the porthole were determined according to the energy-strength (Huber-Mises-Hencky) theory. The rib on the low-pressure surface of the porthole is the most dangerous point w (Fig. 9, *b*); the equivalent stress σ_{eq} at this place was 32.5 MPa.

After confirmation of the correctness of the computational algorithm, the numerical optimization of the geometric characteristics of the porthole was made; which was carried out by the parameter h/D and the cone angle α (Fig. 2). The value D is assumed to be equal to the corresponding size of the experimental samples, that is, 116 mm. The value h varied from 40 to 70 mm with a step of 10 mm, and the value of α from 60° to 150° with a step of 15°.

The stress-strain state of the models was determined according to an algorithm that was tested to calculate the full-scale porthole.

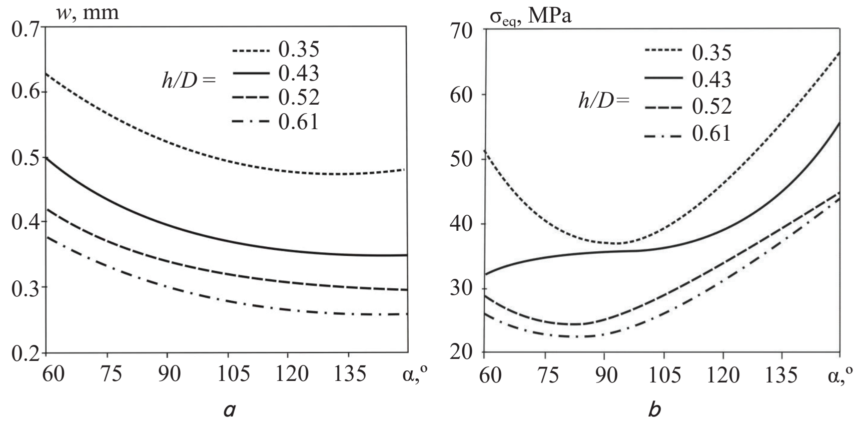


Fig. 10. Dependences of the stress-strain state on the porthole parameters h/D and α: *a* – deflections w in the center of the low-pressure surface; *b* – maximum equivalent stresses σ_{eq} in the dangerous point

As a result of calculations for 28 different variants of the geometric characteristics of the portholes, dependency graphs were obtained; displacement values in the center of the low-pressure surface w (Fig. 10, *a*) and the value of the maximum equivalent stress σ_{eq} at a dangerous point (Fig. 10, *b*) depends on the parameters h/D and α.

The results of FEM calculations of the stress-strain state, presented in Fig. 10, at the initial stages of design, allow selecting the optimal geometric parameters of the porthole. The optimal values of the relative thickness h/D and the taper angle α correspond to the minimum values of the axial displacement w and the equivalent stress σ_{eq}.

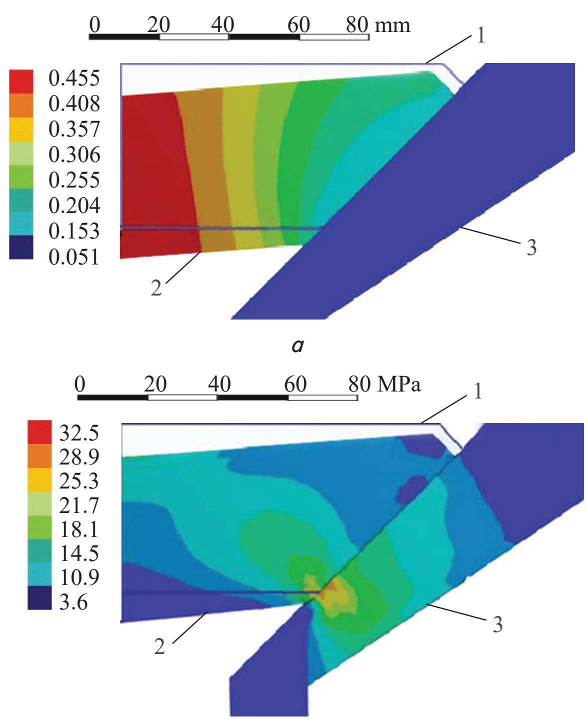


Fig. 9. Elements of the stress-strain state of the porthole: *a* – distribution of displacements; *b* – distribution of equivalent stresses; 1 – starting position of the translucent element; 2 – translucent element after deformation; 3 – porthole body

6. Discussion of the results of the study and prediction of the service life of conical acrylic portholes

The result of predicting the service life of the porthole by the method of heat aging is determined primarily by the assignment of the values of the allowable critical strain ε_{ser} and operating temperature T_{ser}. For acrylic, as the material of the translucent element of the porthole, ε_{ser}=3 % was chosen, which approximately corresponds to the value of elastic strain. Reducing the allowable value of ε_{ser} (that is, lower requirements for brittle fracture) will lead to an increase in service life.

The prediction, which was made on the basis of 7 days of portholes testing under hydrostatic pressure of different levels (Fig. 6), coincides well with the control (experimental) compliance curve for 3 months at a pressure of 40 MPa. This allows determining the deflection of translucent elements over a 10-year period by extrapolating a generalized curve. The compliance of translucent elements at a pressure of 5 MPa will be J=0.28 mm/MPa, and the deflection will reach w=1.4 mm, which is significantly less than the elastic deflection w_e=2.70 mm. It is possible to use such portholes even at depths of up to 900 m. At the same time, it is not possible to make the translucent element thinner for depths of up to 500 m, as this will cause tensile stresses on the low-pressure surface.

The tests series of conical portholes under the cyclic action of hydrostatic pressure was limited by the number of translucent elements and the duration of the experiments. However, the portholes survived 2,000 cycles of hydrostatic pressure of 60 MPa (at an operating pressure of 5 MPa) without visible damage, which indicates high fatigue life.

According to the recommendations of [1], for deep-sea portholes, the service life at operational loads should be at least 100,000 hours of prolonged and 10,000 cycles of hydrostatic pressure. Such a service life seems to be excessively high, since it corresponds to a daily dive of 10 hours for 27 years. It is proposed to revise the recommendations [1] in the direction of reducing the requirements for reliability [14].

The analysis of the influence of portholes geometric characteristics on the stress-strain state showed that an increase of the cone angle at a constant relative thickness of the translucent element in all cases reduces its axial displacement. Equivalent stresses acquire a minimum value when the cone angle is in the range of 75–105° (with an increase in the relative thickness h/D, the optimum cone angle is decreased).

The advantage of the study is the adaptation of accelerated test methods based on the use of physical analogies to predicting the service life of acrylic portholes. However, in the experiments, portholes of only one configuration were used with a relative thickness h/D=0.41 and a taper angle α=90°, which does not allow generalizing the research results. Nevertheless, the development of methods for predicting the properties of polymeric materials and their structures are of practical interest to mechanical engineers.

Further research in this field can be directed at improving the design, in particular, the methods of fixing a translucent element in the porthole body.

7. Conclusions

1. The possibility of deformability prediction of the translucent elements of deep-sea portholes based on short-term creep tests at elevated (relative to operating) load levels of 40–80 MPa was confirmed. The test results confirm the reliability of the translucent elements of the deep-sea portholes of the diving station with a relative thickness h/D=0.41 and a taper angle α=90°. When exposed to prolonged and cyclic hydrostatic pressure up to 9 MPa, taking into account thermal aging at a temperature of 20°, reliable operation of the portholes for 10 years is ensured.

2. The appointment of safety strength and deformability factors of deep-sea portholes must be coordinated with actual operating conditions. The design operating conditions are diving depth, loading duration, cyclical effects of hydrostatic pressure, the period between repeated diving, the relaxation time of deformations in the material. Under real operating conditions of underwater technical equipment for 10 years, the value of the safety factors of acrylic portholes for strength and allowable deflection, apparently, should not exceed $k_z \leq 4$. The developed algorithm of FEM calculation allows one choosing the optimal geometric parameters of portholes, if operating conditions are known, and improving the mass-dimensional (reduction in the mass of a translucent element to 15–20 %) characteristics of deep-sea portholes.

References

1. ASME PVHO-1. 2012. Safety standard for pressure vessels for human occupancy. New York (NY): American Society of Mechanical Engineers.
2. Stachiw, J. D. (2003). Handbook of Acrylics for Submersibles Hyperbaric Chambers and Aquaria. Best Publishing Co., 1080.
3. Stechiv, Dzh., Dolan, R. (1982). Vliyanie atmosfernyh usloviy dlitel'nosti ekspluatatsii i tsiklicheskogo nagruzheniya gidrostaticheskim davleniem na rabotosposobnost' sfericheskih korpusov iz akrilovoy plastmassy pri nagruzhenii vneshnim davleniem. Konstruirovanie i tehnologiya mashinostroeniya, 104 (2), 227–244.
4. Trudel, T., Stanley, K. (2019). Window Seat Weight Reduction Exploration With Nontraditional Seat Geometry. Marine Technology Society Journal, 53 (1), 107–116. doi: https://doi.org/10.4031/mtsj.53.1.2
5. Tian, C. L., Hu, Y., Liu, D. Q., Cui, W. C. (2010). Creep analysis on deepsea structure's viewport windows. J. Ship Mechanics, 14 (5), 526–532.
6. Pranesh, S. B. et. al. (2018). Structural analysis of spherical pressure hull viewport for manned submersibles using biological growth method. Ships and Offshore Structures, 13 (6), 601–616. doi: https://doi.org/10.1080/17445302.2018.1440885
7. Wang, F., Wang, W., Zhang, Y., Du, Q., Jiang, Z., Cui, W. (2019). Effect of Temperature and Nonlinearity of PMMA Material in the Design of Observation Windows for a Full Ocean Depth Manned Submersible. Marine Technology Society Journal, 53 (1), 27–36. doi: https://doi.org/10.4031/mtsj.53.1.4
8. Kemper, B. (2016). Use of finite element analysis in designing acrylic structures for fatigue and stress. Proceedings of the 13th Annual Manned Underwater Vehicles Symposium (Marine Technology Society); New Orleans, LA. doi: http://doi.org/10.13140/RG.2.2.26146.12482/2
9. Du, Q., Hu, Y., Cui, W. (2016). Safety assessment of the acrylic conical frustum viewport structure for a deep-sea manned submersible. Ships and Offshore Structures, 12 (sup1), S221–S229. doi: https://doi.org/10.1080/17445302.2016.1261390
10. Bartenev, G. M. (1983). Fizika i mehanika polimerov. Moscow: Vyssh. shkola, 391.
11. Shah, V.; Malkina, A. Ya. (Ed.) (2009). Spravochnoe rukovodstvo po ispytaniyam plastmass i analizu prichin ih razrusheniya. Sankt-Peterburg: NOT, 732.
12. Urzhumtsev, Yu. S., Maksimov, R. D. (1975). Prognostika deformativnosti polimernyh materialov. Riga: Zinatne, 415.
13. Gol'dman, A. Ya. (1988). Prognozirovanie deformatsionno – prochnostnyh svoystv polimernyh kompozitsionnyh materialov. Leningrad: Himiya, 272.
14. Kemper, B. (2012). Advances in acrylics and expansion of PVHO window cyclic life. Conference: Underwater Intervention 2012, At New Orleans, Louisiana USA.