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STUDY OF CREEPING IN HERMETICALLY SEALING ELEMENTS

Abstract

Stress-strain creeping state of elastic elements made of rubber material used as a seal with symmetric and eccentric holes depending on the effort, pressure and temperature is studied in the paper. Obtained analytic expressions for the creeping on the basis of quasistatic similarity theory describes the creeping better than the expressions obtained on the basis of energetic theory. Obtained by long-time experiments.

Elastic elements made of rubber materials are used to create packing in hermetically sealing systems. In these elements the creeping causes elastic contagious promoting the loading of the seal up to flow

The creeping in elastic elements with symmetrically and eccentrically arranged holes depending on applied efforts, pressure and temperature field is studied in the paper.

The study of elastic elements made of rubber materials proves that under stress-strain state their general deformation is combined of three deformations [2]:

$$\varepsilon_i^* = \varepsilon_{эл} + \varepsilon_{пл} + \varepsilon_s, \tag{1}$$

where $\varepsilon_{эл}$ is high elastic deformation of the seal; $\varepsilon_{пл}$ is a plastic deformation; ε_s is a deformation accompanying the flow of the seal stipulating the loss of construction completeness.

We must note that in known references [2, 3, 5 and etc.] only the investigation of creeping of small volume "□" and "O" forms of seals with symmetrically arranged holes are considered. A seal with eccentrically arranged holes and large volume creeping in these elements have not been studied.

To this end, a quasistatic problem of elastic analogy [3] has been used

$$U = U^*(t)U(\bar{x}); \quad \sigma = \sigma(t)\sigma(\bar{x}), \tag{2}$$

where $U(\bar{x})$, $\sigma(\bar{x})$ are coordinate functions; $U(t)$, $\sigma(t)$ are time functions [3].

Write a differential equilibrium equation [3]:

$$\frac{\partial\sigma_r}{\partial r} + \frac{\sigma_r - \sigma_\theta}{r} = 0. \tag{3}$$

Assume that the seal under the action of external pressure P and of internal pressure q is in equilibrium state. Adopt the following denotations:

$$P = \frac{Q\Delta h}{2V_p}; \quad q = \sigma_{op}, \tag{4}$$

where $\frac{Q\Delta h}{2V_p}$ is the external deformation energy, applied to the seal; $\sigma_{op} = \frac{M_Q S_c}{2V_p}$ is the deformation energy accumulated in the seal; M_Q is the measure of the effort Q applied to the seal; S_c is the square depending on $Q = f(\Delta h)$ contained between the curve and from the axis abscissa determined experimentally; Δh is an axial deformation of the seal; E_c is an elasticity module of the seal under compression.

We can write for a radial and tangential deformation

$$\varepsilon_r = \frac{\partial U}{\partial r}; \quad \varepsilon_\theta = \frac{U}{r}. \tag{5}$$

We adopt that, permutation in direction r of the seal at achieving it a seal housing is absent, then $\varepsilon_r = 0$; here the compressibility condition for the seal will be:

$$\varepsilon_r + \varepsilon_\theta = 0 \tag{6}$$

or

$$\frac{\partial U}{\partial r} + \frac{U}{r} = 0. \tag{7}$$

The solution of (7) is found in the following form:

$$U = \frac{C(t)}{r}. \tag{8}$$

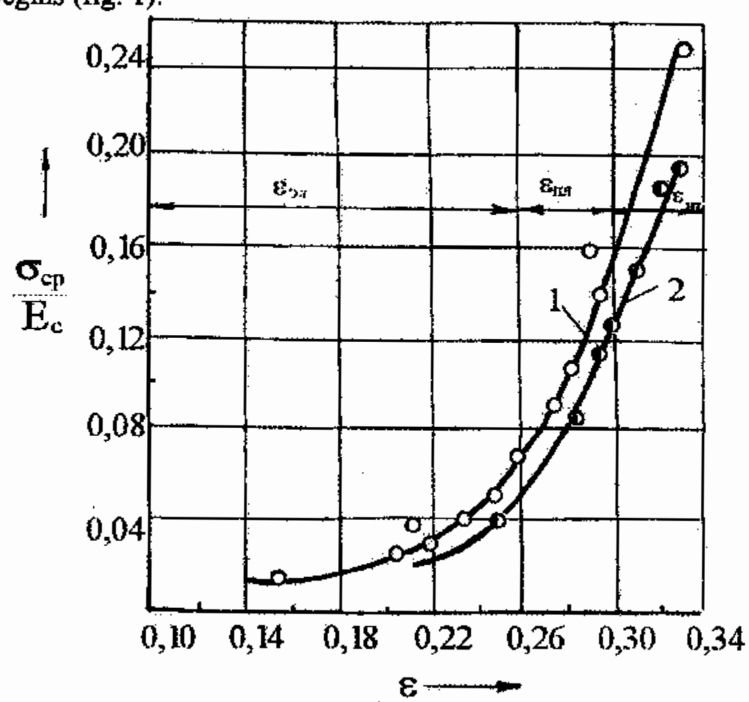
The intensity of deformation under the creeping will be [4]:

$$\varepsilon_i = \frac{2}{\sqrt{3}} \frac{C(t)}{r^2}. \tag{9}$$

Boundary conditions at internal and external radiuses of the seal correspondingly will be:

$$r = r_0; \quad \sigma_r = -\frac{Q\Delta h}{2V_p}; \qquad r = R_p; \quad \sigma_r = -\sigma_{op}^k. \tag{10}$$

Experimentally we have obtained that transient of process to self-sealing corresponds to elastic deformation; then plastic deformation takes place, and then flow phenomena begins (fig. 1).



$\varepsilon_{эл}$ -elastic deformation

$\varepsilon_{пл}$ -plastic deformation

$\varepsilon_т$ - flow deformation

Fig.1. Dependence of dimensionless elastic deformation energy on relative deformation of seals

Denote a conversion radius r_{11} of the seal from the self-sealing deformation to the plastic deformation:

$$\text{for } r_k = r_n \qquad \begin{matrix} \sigma_r^k = \sigma_r^n \\ \sigma_i^k = \sigma_i^n \end{matrix} \tag{11}$$

where σ_r^k, σ_r^n are radial stresses to self-sealed and plastic states of the seal; σ_i^k, σ_i^n are the stress intensity corresponding to these states.

Use the expression for the intensity of creeping deformation in the following form [4]:

$$\varepsilon_i^c = \frac{At}{1+Bt}, \tag{12}$$

where A are linear stress functions; B is the coefficient characterizing the properties of the material.

On the premises of the test on elastic elements with symmetric and eccentric holes of creeping deformation by equation (12) we choose in the following form [1]:

$$\varepsilon_i^c = \frac{\dfrac{\sigma_{op}}{E_c} \dfrac{t}{h_0\sqrt{\dfrac{\rho}{E_c}}}}{1 + k_{gT}\dfrac{t}{h_0\sqrt{\dfrac{\rho}{E_c}}}}, \tag{13}$$

where t is the time; ρ is the density of the seal material; h_0 is the initial height of the seal; k_{gT} is the filling coefficient of the seal with regard to temperature of the medium [1]. The filling coefficient may be estimated by the coefficient of temperature volume extension [5]:

$$æ = \frac{1}{V}\left(\frac{dV}{dT}\right)_p. \tag{14}$$

For the seal $P = const$ and $æ = 3\alpha_{Л}$; $\alpha_{Л}$ is the linear extension coefficient:

$$æ\, dT = \frac{dV_p}{V_p}. \tag{15}$$

Hence

$$V_{pT} = V_p e^{æ\Delta T}, \tag{16}$$

$$\frac{V_{PT}}{V_k} = \frac{V_P}{V_k} e^{æ\Delta T}, \tag{17}$$

where V_{pT} is the extended volume of the seal because the temperature influence; V_k is the volume of the sealed space.

Starting from the fact for $T = T_0$ for the seal $\dfrac{V_p}{V_k} = k_{oд}$ [1], then for $T = \Delta T$ we can write:

$$k_{gT} = k_{og} e^{æ\Delta T}. \tag{18}$$

We see from (18) that because of temperature influence, volume of the seal increases $e^{æ\Delta T}$ times.

If we write equation (1) on the basis of the experiment (fig. 1), we obtain [1]:

$$\varepsilon_i^0 = \frac{\sigma_{op}^k}{E_c} + \frac{\sigma_i - \sigma_{op}^n}{E_c} + \frac{\dfrac{\sigma_{op}^{ax}}{E_c}\dfrac{t}{h_0\sqrt{\dfrac{\rho}{E_c}}}}{1 + k_{gT}\dfrac{t}{h_0\sqrt{\dfrac{\rho}{E_c}}}}. \tag{19}$$

If we consider (9) and (13) in (19), we get

$$\frac{2}{\sqrt{3}}\frac{C(t)}{r^2} = \frac{\sigma_{op}^k}{E_c} + \frac{\sigma_i - \sigma_{op}^n}{E_c} + \frac{\dfrac{\sigma_{op}^{ax}}{E_c}\dfrac{t}{h_0\sqrt{\dfrac{\rho}{E_c}}}}{1 + k_{gT}\dfrac{t}{h_0\sqrt{\dfrac{\rho}{E_c}}}}. \tag{20}$$

The stress intensity is defined from (20)

$$\sigma_i = \frac{2}{\sqrt{3}}\frac{E_c C(t)}{r^2} - \frac{\sigma_{op}^{ax} t}{k_{gT} t + h_0\sqrt{\dfrac{\rho}{E_c}}} + \sigma_{op}^n - \sigma_{op}^k \tag{21}$$

or

$$\sigma_i = \sigma_{op}^n - \sigma_{op}^k - \frac{\sigma_{op}^{ax} t}{k_{gT} t + h_0\sqrt{\dfrac{\rho}{E_c}}} + \frac{2}{\sqrt{3}}\frac{E_c C(t)}{r^2}. \tag{22}$$

It is known that the stress intensity is defined by the following way [4]:

$$\sigma_i \frac{\sqrt{3}}{2}(\sigma_\theta - \sigma_r). \tag{23}$$

If we consider (23) in (3) we get

$$\frac{\partial \sigma_r}{\partial r} = \frac{2}{\sqrt{3}}\frac{\sigma_i}{r}. \tag{24}$$

By integrating (24) we find

$$\sigma_r = \frac{2}{\sqrt{3}}\int_{r0}^{R}\frac{\sigma_i}{r}dr + C_1. \tag{25}$$

Substituting the boundary condition (10) in (25) we get:

$$\frac{Q\Delta h}{2V_p} - \sigma_{op}^k = \frac{2}{\sqrt{3}}\int_{r_0}^{R_p}\frac{\sigma_i}{r}dr. \tag{26}$$

If we consider (22) in (26) we get:

$$\frac{Q\Delta h}{2V_p} - \sigma_{op}^k = \frac{2}{\sqrt{3}}\ln\frac{R_p}{r_0}\left(\sigma_{op}^n - \sigma_{op}^k - \frac{\sigma_{op}^{ax} t}{k_{gT} t + h_0\sqrt{\dfrac{\rho}{E_c}}} + \frac{2}{3}\frac{E_c\left(r_0^2 - R_p^2\right)}{R_p^2 - r_0^2}C(t)\right) \tag{27}$$

Hence we find

$$C(t)=\frac{3}{2}\frac{r_0^2R_p^2}{R_p^2-r_0^2}\frac{\sigma_{op}^k}{E_c}-\frac{3}{2}\frac{r_0^2R_0^2}{R_p^2-r_0^2}\frac{Q\Delta h}{2V_pE_c}+$$

$$+\frac{1}{\sqrt{3}}\frac{r_0^2R_p^2}{R_p^2-r_0^2}\ln\frac{R_p}{r_0}\left(\sigma_{op}^n-\sigma_{op}^k-\frac{\sigma_{op}^{ax}t}{k_{gT}t+h_0\sqrt{\frac{\rho}{E_c}}}\right). \quad (28)$$

By passing from elastic state to plastic one, i.e. $r=r_n$ with regard to (11), (22), (23) and (28) we find

$$\sigma_i=\sigma_{op}^n-\sigma_{op}^k-\frac{\sigma_{op}^{ax}t}{k_{gT}t+h_0\sqrt{\frac{\rho}{E_c}}}+\frac{2}{\sqrt{3}}\frac{E_c}{r^2}\left\{\frac{3}{2}\frac{r_0^2R_p^2}{R_p^2-r_0^2}\frac{\sigma_{op}^k}{E_c}-\right.$$

$$\left.-\frac{3}{2}\frac{r_0^2R_p^2}{R_p^2-r_0^2}\frac{Q\Delta h}{2V_pE_c}+\frac{1}{\sqrt{3}}\frac{r_0^2R_p^2}{R_p^2-r_0^2}\ln\frac{R_p}{r0}\left(\sigma_{op}^n-\sigma_{op}^k-\frac{\sigma_{op}^{ax}t}{k_{gT}t+h_0\sqrt{\frac{\rho}{E_c}}}\right)\right\}. \quad (29)$$

With regard to (29) in (26) we can find a radial stress stipulated by the creeping of the seal:

$$\sigma_r=\frac{2}{\sqrt{3}}\int_{r_0}^{r_n}\sigma_i\frac{dr}{r}\frac{Q\Delta h}{2V_p}=\frac{2}{\sqrt{3}}\left\{\int_{r0}^{r_n}\left(\sigma_{op}^n-\sigma_{op}^k-\frac{\sigma_{op}^{ax}t}{k_{gT}t+h_0\sqrt{\frac{\rho}{E_c}}}\right)\frac{dr}{r}+\right.$$

$$+\frac{2Ec}{\sqrt{3}}\frac{3}{2}\frac{r_0^2R_p^2}{R_p^2-r_0^2}\frac{\sigma_{op}^k}{Ec}\int_{r_0}^{r_n}\frac{dr}{r^3}-\frac{3}{2}\frac{r_0^2R_p^2}{R_p^2-r_0^2}\frac{Q\Delta h}{2V_pE_c}\int_{r_0}^{r_n}\frac{dr}{r^3}+\frac{1}{\sqrt{3}}\frac{r_0^2R_p^2}{R_p^2-r_0^2}\ln\frac{R_p}{r_0}\times$$

$$\left.\times\left(\sigma_{op}^n-\sigma_{op}^k-\frac{\sigma_{op}^{ax}t}{kgT+h_0\sqrt{\frac{\rho}{E_c}}}\right)\right\} \quad (30)$$

or

$$\sigma_r=\frac{2}{\sqrt{3}}\ln\frac{r^n}{r_0}\left(\sigma_{op}^n-\sigma_{op}^k-\frac{\sigma_{op}^{ax}t}{k_{gT}t+h_0\sqrt{\frac{\rho}{E_c}}}\right)+\frac{2}{3}\frac{r_0^2R_p^2}{R_p^2-r_0^2}\ln\frac{R_p}{r_0}\times$$

$$\times\left(\sigma_{op}^n-\sigma_{op}^k-\frac{\sigma_{op}^{ax}t}{k_{gT}t+h_0\sqrt{\frac{\rho}{E_c}}}\frac{r^{n^2}-r_0^2}{r_0^2r^{n^2}}\right)-\frac{3}{\sqrt{3}}\frac{r_0^2R_p^2}{R_p^2-r_0^2}\frac{Q\Delta h}{2V_pE_c}\frac{r^{n^2}-r_0^2}{r_0^2r^{n^2}}. \quad (31)$$

It is experimentally shown, that if we cut 8-10% volume from the body of the seal made of rubber material, the creeping time, i.e. the elastic contagion is increased. By being the seal in a compressed state under the action of constant effort and under pressure (transformer oil is taken as a medium to avoid swelling of the rubber) about three years, the axial deformation composed 4 mm (fig.2). The results obtained from the test are estimated by the expression (31) and we get $\sigma_r = (0.15 - 0.35)E_c$, i.e. the sealing is in elastic bound (fig. 3a) and the seal preserves its stable state and air-tightness sealing is provided (fig. 4).

Creeping deformation is compensated by a cut out volume stipulated at the seal body, and on the contrary, if this volume is not stipulated at the seal, during an hour because of creeping deformation its air-tightness (fig. 3b) is broken.

Conclusion: obtained expression (31) for creeping deformation describes well temporary factors in seals and connects the characteristics of the material (ρ, E_c) with its geometrical parameters and force characteristics- energy deformation with creeping time.

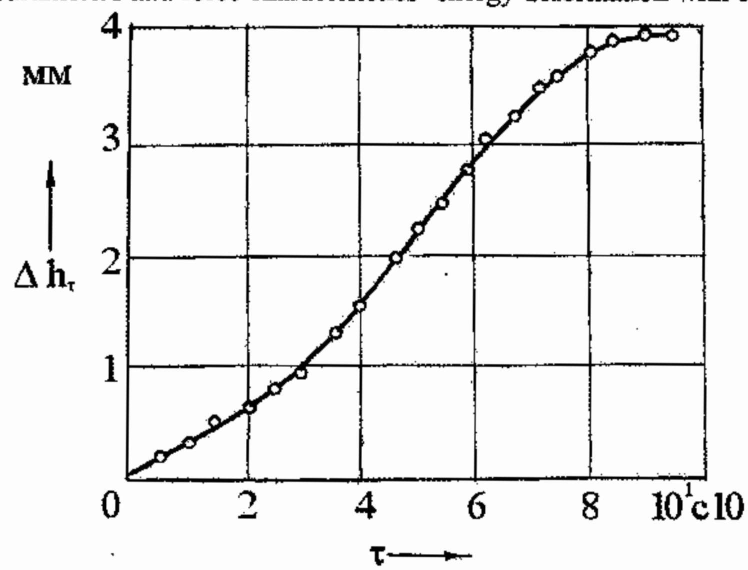
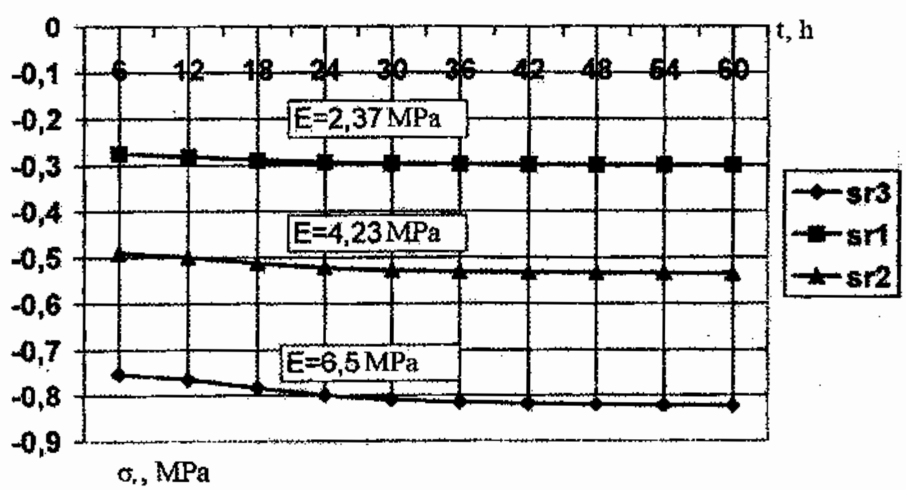


Fig. 2. Axial creeping deformation of the seal.

Radial creeping stress of the seal.



E is an elasticity module of the seal

Fig. 3a.

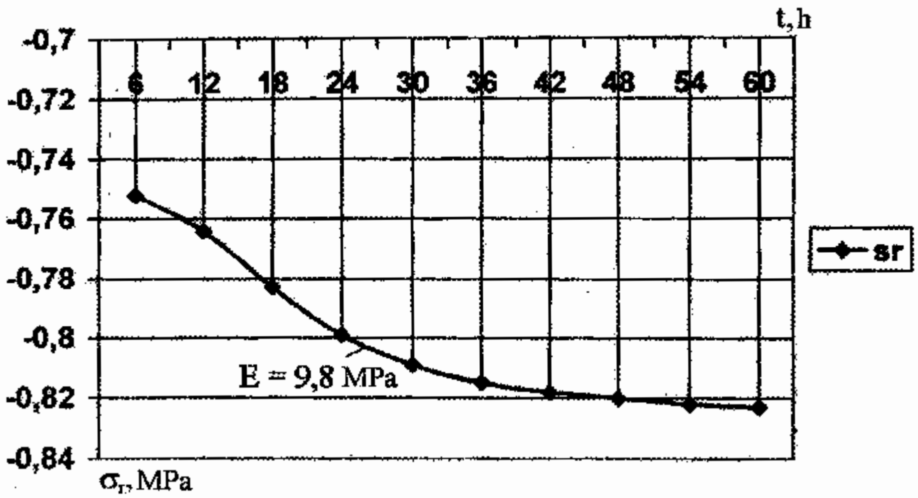
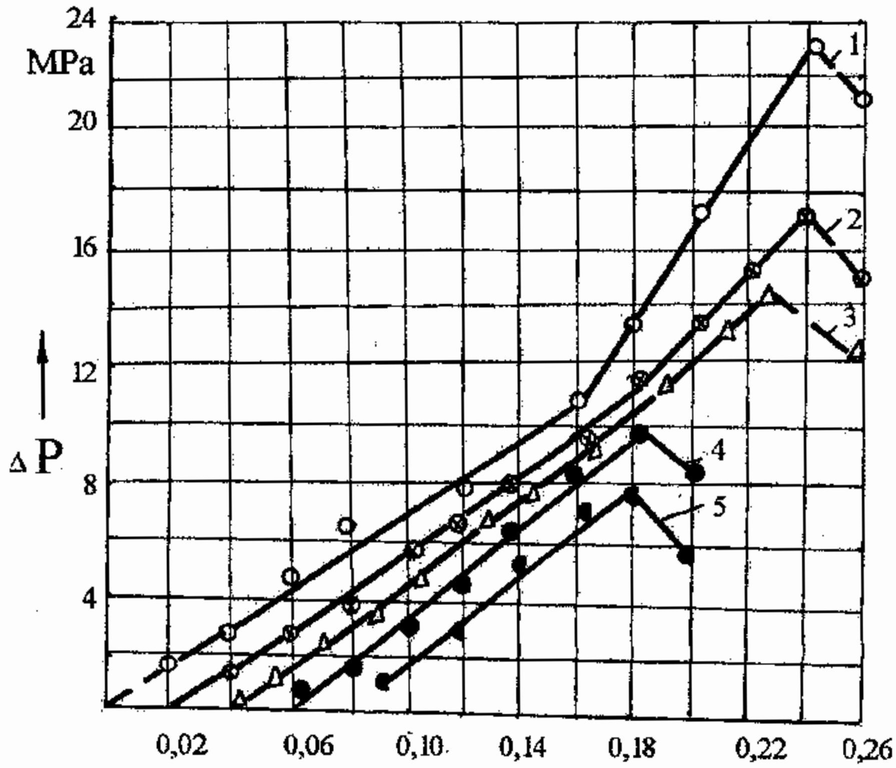


Fig. 3b.



1-with a symmetric of the seal;
2-with three holes
3- with four holes;
4- with two eccentric holes;
5- with an eccentric holes.

Fig. 4. Range of the pressure of air-tightness sealing of the seal under creeping.

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