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DEVELOPMENT OF A STOCHASTIC MODEL OF FAILURE OF STRUCTURAL MATERIALS IN CREEP AT HARDENING STAGE

I. Doyar
Junior Researcher*
E-mail: ivandoyar90@gmail.com
V. Poshyvalov
Doctor of Technical Science,
Professor, Leading Researcher*
E-mail: vposhivalov@gmail.com
*Institute of Technical Mechanics of the National Academy of Sciences of Ukraine and the State Space Agency of Ukraine
Leshko-Popelya str., 15,
Dnipropetrovsk, Ukraine, 49005

Розроблено метод прогнозування довготривалої міцності конструкційних матеріалів при ізотермічній повзучості в умовах одноосного стаціонарного навантаження з урахуванням стадії зміцнення. Запропоновано стохастичну модель руйнування при повзучості і методику ідентифікації констант повзучості матеріалу. Проведено розрахунок параметрів стохастичної моделі, який підтверджує її адекватність експериментальним даним

Ключові слова: руйнування, ізотермічна повзучість, пошкодження матеріалу, час до руйнування, імовірнісний розподіл

Разработан метод прогнозирования длительной прочности конструкционных материалов при изотермической ползучести в условиях одноосного стационарного нагружения с учетом стадии упрочнения. Предложена стохастическая модель разрушения при ползучести и методика идентификации констант ползучести материала. Проведен расчет параметров стохастической модели, который подтверждает её адекватность экспериментальным данным

Ключевые слова: разрушение, изотермическая ползучесть, поврежденность материала, время до разрушения, вероятностное распределение

1. Introduction

Prediction of the durability of structural elements is one of the most important problems of modern mechanical engineering.

Currently, the development of methods of prediction of the long-term strength of various classes of structural materials, operating in a wide range of stresses and temperatures is of particular importance for reasonable assignment of the service life of structures, operating in extreme conditions. At the same time, the defining relations of creep should be on the one hand physically reasonable, and on the other – simple and easy to use in engineering calculations [1–3].

The most natural way to describe the spread of the time to failure of structural materials in creep is to construct a physically adequate stochastic model of failure and use statistical physics methods. This way, as applied to the problem under consideration presents severe difficulties due to the complexity and multiscale heterogeneity of structural elements of solids. Possibilities for obtaining quantitative characteristics of durability of modern structural materials in this way are rather limited.

The use of statistical methods, based on direct experimental data on the time to failure spread and construction of simple probability models of failure in creep is more effective from the practical standpoint [4–10].

This problem is particularly relevant for the determination of the long-term strength characteristics of the long-operated products at constant loads and high temperatures, when the creep effect is manifested.

2. Literature review and problem statement

The damage criteria in the form of the relation of the current value of the controlled parameter to its maximum value in failure are widely used in the calculations of the long-term strength for evaluating durability performance. The mathematical reflection of these processes is cumulative failure models based on the hypothesis of linear and non-linear damage summation.

Prediction of the long-term strength of metallic materials also involves the Larsen-Miller, Manson-Haferd, Orr-Sherby-Dorn parametric methods, which allow taking into account mostly a limited number of factors. To analyze more factors, the base diagram approach should be used.

Since there is a large spread of experimental data on the time to failure for specimens made of a single metal casting in creep tests, even under ideal laboratory conditions, the use of deterministic models is not always reasonable for obtaining long-term strength characteristics.

Hence the need to develop stochastic models of creep and long-term strength, which on the one hand justify the probabilistic nature of the failure, and on the other – allow one to adequately determine the time to failure and its possible spread.

Stochastic models of structural materials in creep are generally built by a generalization of various deterministic models.

The basic approaches to the construction of stochastic models of failure of structural materials in creep were laid in the works [1–3] and are based on the hypothesis that the creep strain rate is determined by the stress, temperature, and some structural parameters. Structural parameters make it possible to more accurately describe the strain processes, and in some cases even to take into account the effect of loading history on the current stress-strain state of the material.

The work [4] notes that the main problems of the theory of creep are physical and stochastic nonlinearity of the problem. The method of reliability assessment of structural elements in creep, implemented on a model example for a thin-walled pipe under internal pressure was developed. However, this method does not allow a reliable prediction of the durability of structural elements in creep in terms of service life, which is several orders of magnitude greater than the experimental data.

Probabilistic damage and failure models are considered in [5], where the methods for determining the probability characteristics of strength reliability of engineering products were developed. However, all the proposed hypotheses of damage summation are of limited use. Each hypothesis is based on assumptions that are not entirely valid. The statistics are often not enough to confirm this or that theory, and the materials are different in damage accumulation patterns.

The work [6] provides a unified description of the patterns of instantaneous and short-term strain, creep, stress relaxation, and long-term strength of heat-resistant materials. It should be noted that in some cases this approach gives worse results, than some parametric methods in the stress calculations for the specified durability, not exceeding one order in relation to the available experimental data.

The work [7] presents an approach to the prediction of the time to failure of polypropylene. It is shown that the critical value of the cumulative creep strain does not depend on the level of the applied load. The strain criterion is used as the failure criterion. The proposed approach to creep prediction can be applied to other materials.

The work [8] gives the results of numerical modeling of the size effect in creep. The time to failure spread obtained using the proposed model, correlates well with the experimental data.

To study the size effect in creep, a series of long-term strength tests for the thin tin alloy wires was carried out in the work [9]. The influence of the size effect on the time to failure is shown.

In the work [10], the Box-Wilson method was used to quantify the effect of the loading parameters on the test results. This method allows you to define the criteria for finding optimum loading parameters.

The approach to the prediction of the time to failure of polymers and polymer composites, proposed in the paper [11] leads to a conclusion: when the cumulative creep strain reaches a high value, the creep strain rate reaches its minimum value with respect to time. The model was tested for various types of polymer materials, as well as polymer composites and showed good results.

The numerical model, presented in the work [12] is designed to simulate the strain of rocks in creep. The key parameter that affects the time to failure is the applied load. This model allows us to simulate changes in the basic characteristics of the material in creep.

The work [13] describes the basic problems of durability prediction of structural materials and the influencing factors. The probabilistic model was constructed, and the time to failure the spread was determined. The proposed model allows one to properly plan the processes of design, testing, operation and maintenance of structural materials.

The work [14] investigates the crack growth patterns under quasi-static tension on the basis of defining relations of creep, postulating a power law of damage accumulation.

Evaluation of the bearing capacity of structural elements based on the continuum mechanics of damage is considered in [15]. It should be noted that such an approach requires further improvement and better definition of application areas.

Among stochastic models, those that are based on statistical analysis of failures are widely used. In accordance with these models, it is necessary to have a large amount of statistical material for the experimental evaluation of durability performance with a satisfactory level of probability.

To estimate the unknown parameters of stochastic models of long-term strength, it is possible to use the known methods: least squares, maximum likelihood, correlation and regression analysis, minimizing functions of several variables.

The literature review showed that conventional approaches to solving long-term strength problems present great difficulties associated with the need for complete information on the rheological characteristics of the material and the stochastic and physical nonlinearity, defining the creep equation. It is impossible to fully apply numerical methods to solve the relevant problems. The volume of long laboratory tests is usually insufficient.

3. Research goal and objectives

The goal of the research is to construct a stochastic model of long-term strength of structural materials based on parametric, strain and mixed criteria of failure.

The problems solved in order to achieve the goal of the research:

– development of the stochastic isothermal creep model, considering the hardening and damage of the material;

– development of a method that allows identifying the unknown constants of the model, based on the analysis of experimental data on creep curves;

– evaluation of the adequacy of the constructed stochastic model of long-term strength according to the results of pilot studies of failure of structural materials in creep.

4. Research materials and methods

The objects of the research were experimental data of the long-term strength test of PA6 aluminum alloy at different levels of stress and temperature [16].

The methods of the probability theory and mathematical statistics, numerical integration methods and the method of random outliers elimination from experimental data were used [17]. Creep and damage of the material are described by the system of kinetic equations [1].

$$\dot{\varepsilon} = \dot{\varepsilon}(t, \sigma, T, \omega, \varepsilon), \ \dot{\omega} = \dot{\omega}(t, \sigma, T, \omega), \tag{1}$$

where t is time; ε is creep strain; σ is stress; T is temperature; ω is metal damage $(0 \le \omega \le 1)$.

5. The results of the research of failure prediction of structural materials in creep

The paper proposes an approach that allows predicting the durability performance of structural materials in isothermal creep under uniaxial steady loading, which considers three stages of creep: transient, steady-state, and accelerated, prior to failure.

We assume the kinetic equations describing the creep process in the following form [18]:

$$\dot{\varepsilon} = \frac{a \cdot \exp\left(-\frac{h}{T}\right) \cdot \sigma^n \cdot \left[1 + c \cdot \exp(-\varepsilon / g)\right]}{(1-\omega)^n}, \tag{2}$$

$$\dot{\omega} = \frac{b \cdot \exp\left(-\frac{p}{T}\right) \cdot \sigma^m}{(1-\omega)^l}, \tag{3}$$

where a, b, n, m, l, p, h, c, g are constants of creep and damage of the material. The parameters c, g describe the strain hardening characteristic of the transient creep stage.

We consider the parameters n, m, l, p, h, c, g as deterministic values, and the parameters a, b – normally distributed random variables.

By integrating the relations (2) and (3), we obtain the expressions for the creep curve and damage parameter:

$$\varepsilon(t) = g \ln\left[(c+1) \cdot \exp\left(\frac{I_2(t)}{g}\right) - c\right], \tag{4}$$

$$\omega(t) = 1 - \left[1 - (l+1) \cdot b \cdot \exp\left(-\frac{p}{T}\right) \cdot \sigma^m \cdot t\right]^{\frac{1}{l+1}}, \tag{5}$$

where

$$I_2(t) = \frac{a \cdot \exp\left(\frac{p-h}{T}\right) \cdot \sigma^{n-m}}{b \cdot (n-l-1)} \times$$
$$\times \left\{\left[1 - (l+1) \cdot b \cdot \exp\left(-\frac{p}{T}\right) \cdot \sigma^m \cdot t\right]^{\frac{l-n+1}{l+1}} - 1\right\}. \tag{6}$$

The proposed probabilistic model of long-term strength is based on the use of the three criteria of failure in creep: parametric, strain and mixed.

5. 1. Parametric failure criterion

Parametric criterion assumes that failure occurs when the damage parameter ω reaches the value 1.

In this case, the time to failure t_p is determined by the relation (5) as a solution of the equation $\omega(t) = 1$:

$$t_p = \frac{1}{\left[(l+1) \cdot b \cdot \exp\left(-\frac{p}{T}\right) \cdot \sigma^m\right]}. \tag{7}$$

On the basis of the relation (6), we find the distribution function of the time to failure:

$$F_{t_p}(x) = \begin{cases} 0, \ x \le 0, \\ 1 - \int\limits_0^{\frac{1}{x \cdot (l+1) \cdot \sigma^m \cdot \exp\left(-\frac{p}{T}\right)}} f_b(t) dt, \ x > 0, \end{cases} \tag{8}$$

where $f_b(t)$ is the distribution density of the random variable b.

5. 2. Strain failure criterion

Strain failure criterion assumes the occurrence of failure when the creep strain ε reaches a maximum permissible value ε^*.

We consider the random process $\varepsilon(t)$ as normal.

Since the creep strain is a non-decreasing function of time, for the non-failure probability we can write:

$$P(t, \varepsilon^*) = P\{t_p > t\} = P\{\varepsilon(t) \in (0, \varepsilon^*)\} =$$
$$= \frac{1}{\sqrt{2\pi D[\varepsilon(t)]}} \int\limits_0^{\varepsilon^*} \exp\left\{-\frac{(x - M[\varepsilon(t)])^2}{2D[\varepsilon(t)]}\right\} dx. \tag{9}$$

Creep strain at the time of failure is determined from the relation (4), provided that $\omega(t) = 1$:

$$\varepsilon_{t_p} =$$
$$= g \ln\left[(c+1) \cdot \exp\left(\frac{(l+1)}{g \cdot (l+1-n)} \cdot a \cdot \exp\left(-\frac{h}{T}\right) \cdot \sigma^n t_p\right) - c\right]. \tag{10}$$

The maximum permissible value of cumulative creep strain is found from the equation:

$$P\{\varepsilon_{t_p} > \varepsilon^*\} = \alpha, \tag{11}$$

where α is the confidence level.

For this criterion, the time to failure distribution function is as follows:

$$F_{t_p}(t, \varepsilon^*) = 1 - P(t, \varepsilon^*). \tag{12}$$

5. 3. Mixed failure criterion

Mixed failure criterion assumes the occurrence of failure upon the execution of the first event:

– achievement of a maximum permissible value ε^* by creep strain;

– achievement of the value 1 by damage ω.

The time to failure t_p in this case is defined as:

$$t_p = \min\{t_{p1}, t_{p2}\}, \tag{13}$$

where

$$t_{p1} = \min_{t:\ \varepsilon(t) \ge \varepsilon^*} t, \tag{14}$$

$$t_{p2} = \min_{t:\ \omega(t) \ge 1} t. \tag{15}$$

For this criterion, the time to failure distribution function can be written as:

$$F_{t_p}(x)=1-\left\{1-F_{t_{p1}}(x)\right\}\left\{1-F_{t_{p2}}(x)\right\}, \tag{16}$$

where $F_{t_{p1}}(x)$, $F_{t_{p2}}(x)$ are the time to failure distribution functions, defined by the parametric and strain failure criteria respectively.

5. 4. Definition of creep constants

According to the results of N tests for the long-term strength at various

levels of stress σ_e and temperatures T_e, let us define the values:

$\dot{\varepsilon}_{0e}$ – steady-state creep rate at the initial time;

t_{1e} – duration of the first creep stage;

t_{pe} – time to failure;

$\varepsilon_{t_{pe}}$ – creep strain at the time of failure.

Let us examine the approach that allows determining the creep constants in view of the probabilistic nature of the failure.

Estimates of the constants of the transient creep region are located after determination of the corresponding parameters for the steady-state region and prior to failure region.

5. 4. 1. Stage of steady-state creep

For the second creep stage we have:

$$c=0,\quad g=1, \tag{17}$$

$$\dot{\varepsilon}_0=a\cdot\exp\left(-\frac{h}{T}\right)\cdot\sigma^n. \tag{18}$$

Using the relation (18), we determine the estimates (MLR-estimates) $\hat{n}$, $\hat{h}$ of parameters n, h by the multiple linear regression method.

Hereinafter, the sign «^» (lid) over the parameters indicate the estimates of the corresponding value.

The sample vector $\tilde{a}$ is determined as:

$$\tilde{a}=\left\{\frac{\dot{\varepsilon}_{0e_i}}{\sigma_{ei}^n\cdot\exp\left(-\frac{h}{T_{ei}}\right)},\ i=\overline{1,N}\right\}. \tag{19}$$

Estimates for the mathematical expectation and variance of the random variable a for given values of stress σ and temperature T can be written as:

$$\hat{\mu}_a=\frac{1}{M}\sum_{i=1}^{M}\tilde{a}_i, \tag{20}$$

$$\hat{d}_a=\frac{1}{M-1}\sum_{i=1}^{M}\left(\tilde{a}_i-\hat{\mu}_a\right)^2, \tag{21}$$

where M is the number of sample units $\tilde{a}$ corresponding to the specified parameters σ, T.

5. 4. 2. Stage of accelerated creep

For the third creep stage:

$$c=0,\quad g=1, \tag{22}$$

and the creep strain at the time of failure ε_{t_p} is determined as:

$$\varepsilon_{t_p}=\frac{(l+1)}{(l+1-n)}\cdot a\cdot\exp\left(-\frac{h}{T}\right)\cdot\sigma^n t_p. \tag{23}$$

For the parameter l we have the expression:

$$l=n-1+\frac{n}{\dfrac{\varepsilon_{t_p}}{a\cdot\exp\left(-\frac{h}{T}\right)\cdot\sigma^n\cdot t_p}-1}. \tag{24}$$

The estimate of the parameter l is as follows:

$$\hat{l}=\sum_{i=1}^{n}l_i, \tag{25}$$

where l_i is the value of the parameter l in the i experiment.

The time to failure is determined as:

$$t_p=\frac{1}{\left[(l+1)\cdot b\cdot\exp\left(-\frac{p}{T}\right)\cdot\sigma^m\right]}. \tag{26}$$

From the relation (26) we find the MLR-estimates $\hat{m}$, $\hat{p}$.

The relation for the sample vector b has the form:

$$\tilde{b}=\left\{\frac{1}{(l+1)\cdot t_{pei}\cdot\exp\left(-\frac{p}{T_{ei}}\right)\cdot\sigma_{ei}^m},\ i=\overline{1,N}\right\}. \tag{27}$$

Estimates of the basic probabilistic characteristics of the random variable b for given values of stress σ and temperature T can be written as:

$$\hat{\mu}_b=\frac{1}{K}\sum_{i=1}^{K}\tilde{b}_i, \tag{28}$$

$$\hat{d}_b=\frac{1}{K-1}\sum_{i=1}^{K}\left(\tilde{b}_i-\hat{\mu}_b\right)^2, \tag{29}$$

where K is the number of sample units $\tilde{b}$ corresponding to the specified parameters σ, T.

5. 4. 3. Stage of transient creep

For the first stage, creep strain $\varepsilon(t)$ at $t=t_{1e}$ is determined from the expression [19]:

$$\dot{\varepsilon}_{0e}\cdot t_{1e}=g\ln\left[(c+1)\cdot\exp\left(\frac{I_2(t_{1e})}{g}\right)-c\right]. \tag{30}$$

From the relation (30) we find the MLR-estimates for given values of stress σ and temperature T.

5. 5. Determination of dependencies of distribution parameters of random variables a, b and parameters c, g on stress σ and temperature T

Let us consider the quadratic dependencies of the distribution parameters μ_b and d_b of the random variable b on stress σ and temperature T:

$$\mu_b = a_{0\mu}\cdot\sigma^2 + a_{1\mu}\cdot\sigma\cdot T + a_{2\mu}\times$$
$$\times T^2 + a_{3\mu}\cdot\sigma + a_{4\mu}\cdot T + a_{5\mu}, \qquad (31)$$

$$d_b = a_{0d}\cdot\sigma^2 + a_{1d}\cdot\sigma\cdot T + a_{2d}\times$$
$$\times T^2 + a_{3d}\cdot\sigma + a_{4d}\cdot T + a_{5d}, \qquad (32)$$

where $a_{i\mu}, a_{jd}$, $i=\overline{0,5}$, $j=\overline{0,5}$ are unknown coefficients.

Estimates $\hat{\mu}_b$, $\hat{d}_b$ for given values of stress y and temperature T are determined by the equations (28), (29).

Using the relations set by the equations (31), (32), we find the MLR-estimates of the parameters $a_{i\mu}, a_{jd}$, $i=\overline{0,5}$, $j=\overline{0,5}$, and dependencies $\mu_b(\sigma,T)$, $d_b(\sigma,T)$ of the distribution parameters of the random variable b on stress σ and temperature T.

The dependencies of the distribution parameters of the random variable a and parameters c, g on stress σ and temperature T are determined in a similar way.

Table 1 presents the estimates of the parameters n, m, l, p, h of the model, set by the relations (2), (3) obtained from the experimental data for PA6 aluminum alloy [16].

Table 1

Estimates of parameters of the model, set by the relations (2), (3) obtained from the experimental data [16]

Model parameter	Model parameter estimate
n	2,89
l	–7,34
m	5,45
p	$17{,}93\cdot10^3$
h	$10{,}01\cdot10^3$

Let $N(\mu_a,\sigma_a^2)$, $N(\mu_b,\sigma_b^2)$ be the distributions of the random variables a, b, respectively.

The dependencies of distribution parameters of the random variables a, b and parameters c, g on stress and temperature take the form:

$$\mu_a(\sigma,T) = -1{,}51\cdot10^{-6}\cdot\sigma^2 + 3{,}76\cdot10^{-6}\cdot T^2 +$$
$$+6{,}79\cdot10^{-6}\cdot\sigma\cdot T + 9{,}58\cdot10^{-9}\cdot\sigma +$$
$$+4{,}1\cdot10^{-5}\cdot T + 0{,}39, \qquad (33)$$

$$\sigma_a(\sigma,T) = -1{,}02\cdot10^{-5}\cdot\sigma^2 + 2{,}01\cdot10^{-6}\cdot T^2 +$$
$$+1{,}32\cdot10^{-5}\cdot\sigma\cdot T + 1{,}28\cdot10^{-8}\cdot\sigma +$$
$$+4{,}73\cdot10^{-9}\cdot T - 0{,}95, \qquad (34)$$

$$\mu_b(\sigma,T) = -1{,}51\cdot10^{-6}\cdot\sigma^2 + 3{,}76\cdot10^{-6}\cdot T^2 +$$
$$+6{,}79\cdot10^{-6}\cdot\sigma\cdot T + 9{,}58\cdot10^{-9}\cdot\sigma +$$
$$+4{,}1\cdot10^{-5}\cdot T + 0{,}39, \qquad (35)$$

$$\sigma_b(\sigma,T) = -1{,}02\cdot10^{-5}\cdot\sigma^2 + 2{,}01\cdot10^{-6}\cdot T^2 +$$
$$+1{,}32\cdot10^{-5}\cdot\sigma\cdot T + 1{,}28\cdot10^{-8}\cdot\sigma +$$
$$+4{,}73\cdot10^{-9}\cdot T - 0{,}95, \qquad (36)$$

$$c(\sigma,T) = 1{,}05\cdot10^{-6}\cdot\sigma^2 - 1{,}25\cdot10^{-6}\cdot T^2 +$$
$$+2{,}29\cdot10^{-6}\cdot\sigma\cdot T - 2{,}78\cdot10^{-9}\cdot\sigma -$$
$$-1{,}49\cdot10^{-9}\cdot T + 0{,}48, \qquad (37)$$

$$g(\sigma,T) = -5{,}51\cdot10^{-3}\cdot\sigma^2 - 1{,}46\cdot10^{-2}\cdot T^2 -$$
$$-1{,}68\cdot10^{-2}\cdot\sigma\cdot T - 3{,}11\cdot10^{-5}\cdot\sigma -$$
$$-1{,}29\cdot10^{-5}\cdot T + 5236{,}17. \qquad (38)$$

Table 2 gives the experimental and calculated values of the basic probabilistic characteristics of the time to failure t_p for PA6 aluminum alloy [16].

Fig. 1, 2 present the graphs of the function and density of distribution of the time to failure t_p respectively.

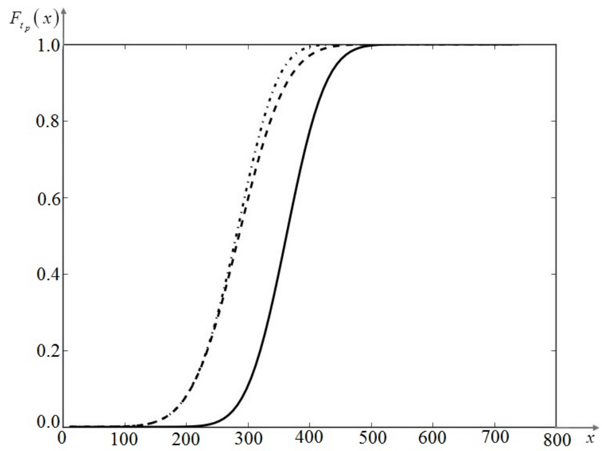

Fig. 1. The distribution function of the time to failure t_p at a stress σ=300 MPa and temperature T=423 ºC for PA6 aluminum alloy

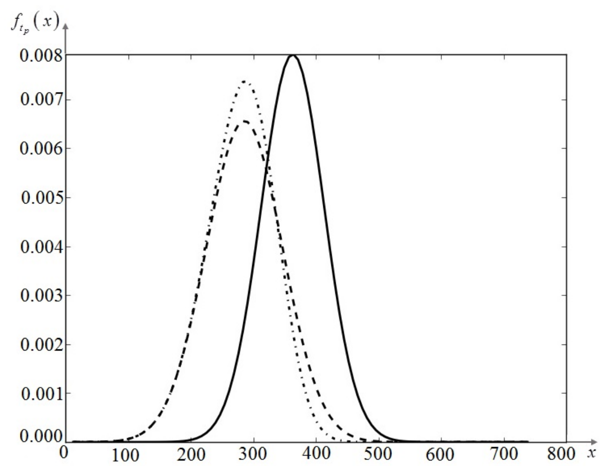

Fig. 2. The distribution density of the time to failure t_p at a stress σ=300 MPa and temperature T=423 ºC for PA6 aluminum alloy

Table 2

The experimental and calculated values of the basic probabilistic characteristics of t_p for PA6 aluminum alloy

Stress σ, MPa	Temperature T, ºC	TM t_p (PFC)	TCO t_p (PFC)	TM t_p (SFC)	TCO t_p (SFC)	TM t_p (MFC)	TCO t_p (MFC)	OM	OSD
300	423	361,38	48,85	286,69	61,13	280,44	53,87	363,29	51,21
200	473	38,03	9,79	48,16	11,44	31,5	10,27	35,33	7,72

Note: PFC – parametric failure criterion; SFC – strain failure criterion; MFC – mixed failure criterion; TM – theoretical mean; TSD – theoretical standard deviation; OM – observed mean; OSD – observed standard deviation

Fig. 1, 2 indicate: x – time, $F_{t_p}(x)$ – distribution function of the time to failure, $f_{t_p}(x)$ – distribution density of the time to failure. Here, the solid line corresponds to PFC, dashed line – SFC, dash-dot line – MFC.

Fig. 1, 2 illustrate the difference in the values of failure probability, calculated according to different criteria for the same period of time t. In particular, from Fig. 1, 2 it follows that PFC predicts the lowest failure probability, and MFC – the highest failure probability.

6. Discussion of the results of research to construct the stochastic model of long-term strength of structural materials

According to the research, it is enough to use the quadratic dependencies as dependencies of distribution parameters of the random variables a and , as well as the parameters c and g on the stress and temperature. The choice of the type of dependencies of higher degrees has little impact on calculation results.

The parametric criterion gives a more accurate prediction of the time to failure and its use does not require the identification of the hardening parameters, but it does not take into account the specifics of the material strain, considered by the strain and mixed criteria of failure.

The proposed method of identification of creep constants is based on the research carried out in the works [18, 20] and can be used for prediction of the characteristics of long-term strength of various structural materials, operating at high stresses and temperatures, as well as the development of standards, guidelines and other documents in the field of reliability and durability assessment of structural materials.

The shortcomings of the model:

– it does not consider the kinetics of the structural state of the material under prolonged exposure to load;

– the volume of the experimental data does not allow to check the accuracy of durability prediction of structural materials for periods that are more than an order of magnitude greater than the duration of the experiments.

Further research suggests the use of stochastic methods for the development of extrapolation techniques, allowing to predict the durability of structural materials for two orders of magnitude or more.

7. Conclusions

1. The approach to prediction of the long-term strength characteristics of structural materials in isothermal creep under uniaxial steady load was proposed. It allows determining the probability distribution of the time to failure using the specified values of stress and temperature. This approach is original in the probabilistic interpretation of kinetic equations describing the creep, as well as a variety of failure criteria and their relative characteristics.

2. The method of identification of unknown constants of the model, based on the statistical processing of the family of experimental creep curves by regression analysis methods was developed.

3. It is shown that the theoretical calculations carried out by the developed method are in good agreement with the experimental data on the long-term strength of PA6 aluminum alloy in terms of the time to failure (error of about 7 % for PFC, 30 % for SFC, 20 % for MFC) and the standard deviation (error of about 25 % for PFC, 40 % for SFC, 30 % for MFC).

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RESEARCH OF STRUCTURE AND FORMATION OF NODULAR GRAPHITE INCLUSIONS IN DUCTILE CAST IRON

V. Ivanov
PhD, Associate Professor*
E-mail: ivanov@zntu.edu.ua
V. Pirozhkova
PhD, Senior Research Fellow*
E-mail: pirozhkova29@mail.ua
V. Lunev
Doctor of Technical Sciences, Professor*
E-mail: mitlv@ukr.net
*Department of Machinery and Technology foundry
Zaporozhye National Technical University
Zhukovskoho str., 64, Zaporizhzhia, Ukraine, 69063

На підставі металографічних, петрографічних і рентгеноспектральних досліджень представлено нові дані про будову та формування включень графіту кулястої форми у високоміцному чавуні. Виявлено нестехіометричні з'єднання заліза, магнію та інших елементів (субокісли), які беруть активну участь у формуванні включень графіту кулястої форми у високоміцних чавунах. Також встановлено три морфологічні різновиди графіту, з яких складаються включення у високоміцних чавунах

Ключові слова: кулястий графіт, газова бульбашка, окис магнію, металографія, петрографія, мікрорентгеноспектральний аналіз

На основании металлографических, петрографических и рентгеноспектральных исследований представлены новые данные о строении и образовании включений графита шаровидной формы в высокопрочном чугуне. Выявлены нестехиометрические соединения железа, магния и других элементов (субокислы), которые принимают активное участие в формировании включений графита шаровидной формы в высокопрочных чугунах. Также установлены три морфологические разновидности графита, из которых состоят включения в высокопрочных чугунах

Ключевые слова: шаровидный графит, газовый пузырек, окись магния, металлография, петрография, микрорентгеноспектральный анализ

1. Introduction

The mechanism of formation of nodular graphite in cast irons remains the most debatable issue of materials science. Competition of several dozen hypotheses of the formation of nodular graphite and modern technologies of computer simulation have not designed a single universally accepted theory up to now. This is probably due to a large number of factors that affect this process: the nature of the charge materials, the presence of impurities, melting conditions, inoculation, etc.

Detection of the mechanism of formation of nodular graphite will contribute to the development of the general theory of inoculation of cast iron, it will open vast opportunities for the control of its structure and properties, and will make it possible to design effective technological processes for obtaining castings for various purposes from ductile cast iron.

Attaining new data on the structure of the inclusions of nodular shaped graphite, obtained by new modern research methods and laboratory equipment, is an urgent task to solve this problem.