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# CREEP AND LONG-TERM STRENGTH OF HIGH-ENTROPY ALLOYS

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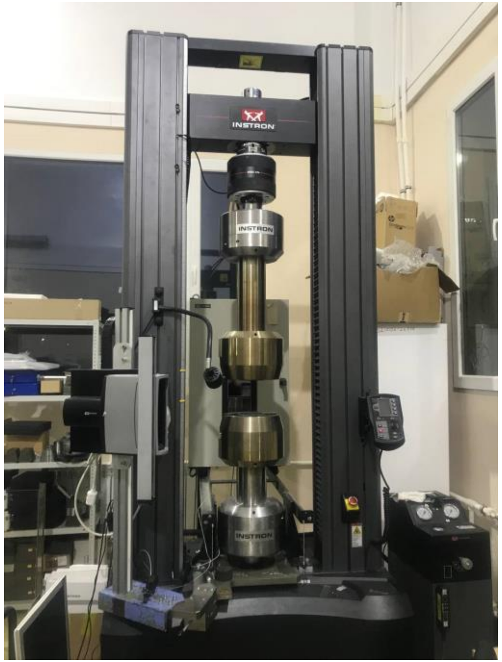



**Laboratory for Mechanics of Advanced Bulk Nanomaterials for Innovative Engineering Applications**

# Relevance of the research topic:

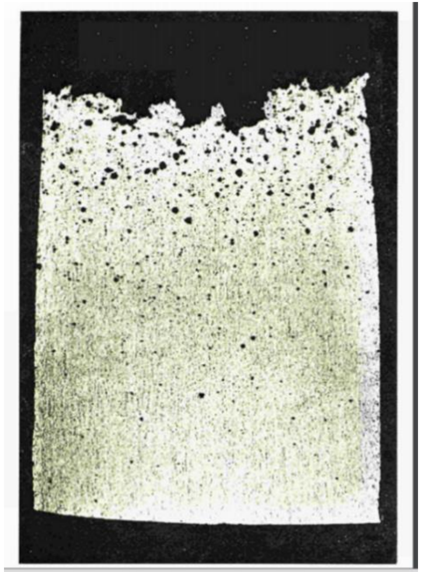


**Fig. 1.** Optical micrograph of a sample of Zircaloy-2, tested for a long time at **creep** (400 °C, more than 10,000 hours) [1]

- Under the long action of high temperatures and relatively small stresses many metallic alloys and pure metals lose plasticity and fractured as brittle with a deformation 1-2% (**the phenomenon of thermal brittleness**).

- The problem of high-temperature creep and long-term strength of metallic materials is relevant in such critical areas of modern mechanical engineering as **thermal and nuclear power plants, aviation and spacecraft, etc.**

- Because these effects are observed in elements of many important engineering objects, in particular, in power and nuclear, the problem of brittle fractures became a subject of numerous theoretical and experimental researches.

[1] Piatti G., Lubek R., Matera R. (1972) Study of microcrack formation and propagation phenomena in creep deformed metals. Euro Spectra. Scientific and technical review of the European communities. **XI** (4), 93-101.

# The development degree of the research topic:

**Continuum Damage Mechanics (CDM)**

This direction was created by two outstanding Soviet mechanical scientists, Professor **L.M. Kachanov** and Academician **Y.N. Rabotnov.**

**At the end of the 1950s,** they introduced into consideration of creep under uniaxial tension a new parameter**: material damage.** Subsequently, significant results in the area under consideration were obtained:

**Russian scientists:** Y. N. Rabotnov, L. M. Kachanov, N. N. Malinin, A. A. Ilyushin, V. S. Namestnikov, S. A. Shesterikov, Yu. K. Petreney, A. A. Chizhik , A. M. Lokoshchenko, O. V. Sosnin, Yu. P. Samarin, A. F. Nikitenko and others.

**British scientists:** F. A. Leckie and D. R. Hayhurst

**German scientists:** a group of scientists led by prof. H. Altenbach

**Polish scientists:** M. Chrzanowski and W. Tramczynski

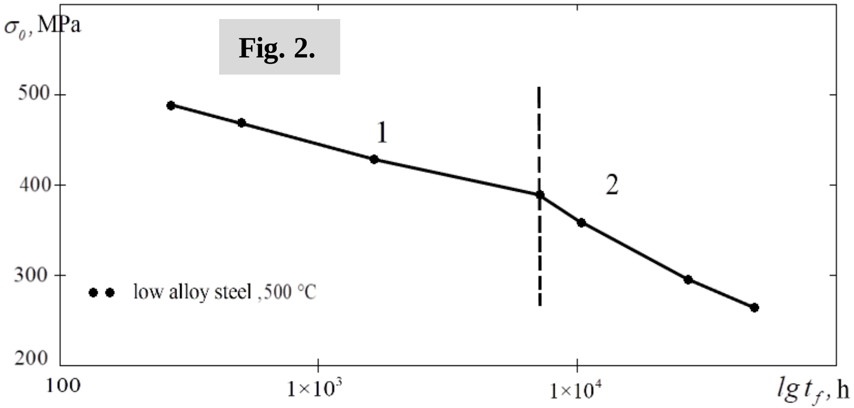
**Japanese scientists**: S. Murakami

**French scientists:** J. Lemaître

**American scientists:** B.F. Dyson, D. Taplin, M.S. Loveday

**Chinese scientists:** Y. Song, B. B. Zhang, Z. Liu, L. Wei

**Fig. 2.**





[1] Oding I.A., Ivanova V.S., Burduksky V.V. and Geminov V.N. Theory of creep and long-term strength of metals. Publishing house "Metallurg-izdat", 1959. (In Russian)

# Materialization of damage parameter:

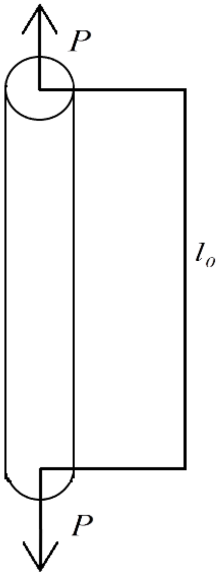
One of **the main problems** in assessing the strength of structures operating at high temperatures is to determine **the duration of operation of these structures before fracture.**

| Scalar damage parameter | Damage vector parameter | Tensor damage parameter |
|---|---|---|
| V.V. Novozhilov<br>O.V. Sosnin and his students<br>F.A. Leckie<br>Q. Xu and D. R. Hayhurst<br>Z. L. Kowalewski<br>A.R. Rzhanitsyn<br>J. Lemaître<br>S.A. Shesterikov<br>M. Chrzanowski and J. Madej<br>S. Murakami and M. Mizuno<br>B. F. Dyson and D. Taplin<br>F. Trivaudey and P. Delobelle<br>V. Tvergaard<br>W. Trąmpczyński and D. R. Hayhurst<br>F. A. Leckie and E. T. Onat<br>Maruyama T. and Nosaka T.<br>A.M. Lokoshchenko<br>V.I. Betekhtin<br>R. A. Arutyunyan | L.M. Kachanov<br>I.V. Namestnikova and S.A. Shesterikov<br>V.A. Peleshko<br>A.M. Lokoshchenko and V.V. Nazarov<br>Lokoshchenko A. M. and Platonov D.<br>S.A. Shesterikov et al.<br>A.A. Chizhik and Yu.K. Petrenya<br>O.K. Morachkovskii<br>M. Chrzanovski and J. Madej<br>G.M. Khazhinsky<br>D. Hayhurst and co-authors | Y.N. Rabotnov<br>E. Johnson<br>V.P. Tamuzh<br>A.Zh. Lagzdynsh<br>H. Altenbach and P. Schieße<br>K. Naumenko et al.<br>A.A. Ilyushin<br>E.B. Zavoychinskaya and I.A. Kiiko<br>B.E. Pobedrya<br>A.A. Lebedev and V.M. Mikhalevich<br>J. Betten<br>C. Chow, J. Wang<br>S. Bodner<br>S. Murakami et al.<br>V.I. Astafiev<br>D. Krajcinovic et al.<br>V.A. Man’kovskii<br>P. Delobelle et al.<br>J. Lemaître<br>A.M. Lokoshchenko<br>K.A. Agakhi and D.V. Georgievsky |

## The aim and objectives of the study:

The purpose of this work is a theoretical and experimental study of high-temperature creep, damage and long-term strength of metallic materials and alloys using the concept of damage based on the relative change of density.

The problem of uniaxial stretching of a metal rod with constant force at high temperature is solved.



## To achieve this aim it is necessary to:

**1.** formulate a system of kinetic equations for the damage parameter and creep strain, based on the concept of damage;

**2.** obtain exact, approximate analytical and numerical solutions of the considered system of kinetic equations, formulate a criterion of long-term strength according to the obtained solutions, plot the damage, creep deformation and long-term strength curves, compare the obtained theoretical curves with the corresponding experimental results;

## Rabotnov's damage theory:

$$\dot{\varepsilon} = b\sigma_0^m (1-\omega)^{-q} \exp(m\varepsilon)$$

$$\dot{\omega} = c\sigma_0^n (1-\omega)^{-r} \exp(n\varepsilon)$$

where $b,c,m,n,q,r$ are constants, $\varepsilon = ln\frac{l}{l_0}$ is deformation, $l_0, l$ are initial and current sample length, $\sigma$ is true stress.

The brittle fracture model of Rabotnov introduces the function $0 \le \omega \le 1$ ( $\omega = 0$ in the initial state and $\omega = 1$ at the fracture moment).

It is believed that $\omega = 1 - \psi$.

**Kachanov's concept of continuity:**

$$\dot{\varepsilon} = \frac{1}{l}\frac{\mathrm{d}l}{\mathrm{d}t} = B\sigma^m = B\sigma_0^m\left(\frac{F_0}{F}\right)^m$$

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = A\left(\frac{\sigma}{1-\omega}\right)^n = A\left(\frac{\sigma_0}{1-\omega}\right)^n\left(\frac{F_0}{F}\right)^n,$$

where $\sigma = \frac{P}{F}$, $\sigma_0 = \frac{P}{F_0}$, $\varepsilon = ln\frac{l}{l_0}$, $l_0$, $F_0$ are initial, $l$, $F$ are current length and cross-sectional area of the rod, $m,n,A,B$ are constants.

In Kachanov's model, damage is described by some scalar $1 \geq \psi \geq 0$.

# Kinetics of damage and deformation accumulation under high-temperature creep conditions:

**Damage parameter** $\omega = 1 - \frac{\rho}{\rho_0} = 1 - \psi$, ($\psi$ is continuity parameter),

where $\rho_0$ is the initial density, $\rho$ is the current density, $\psi = 1 - \omega = \rho / \rho_0$.

$$\psi^{\beta} \frac{\mathrm{d}\varepsilon}{\mathrm{d}t} = B\sigma^{m} \qquad \textbf{(1)}$$

$$\psi^{\alpha} \frac{\mathrm{d}\psi}{\mathrm{d}t} = -A\sigma^{n} \qquad \textbf{(2)}$$

where $B, A, m, n, \alpha, \beta$ are constants, $\varepsilon = ln(l / l_0)$.

## Kinetics of damage and deformation accumulation under high-temperature creep conditions:

Taking into account the mass conservation law $\rho_0 l_0 F_0 = \rho l F$ and the true stress $\sigma = \sigma_0 F_0 / F = \sigma_0 (l / l_0)(\rho / \rho_0) = \sigma_0 (\rho / \rho_0) e^{\varepsilon} = \sigma_0 \psi e^{\varepsilon}$, these equations can be written in the following form:

$$\frac{\mathrm{d}\varepsilon}{\mathrm{d}t} = B\sigma_0^m \psi^{m-\beta} e^{m\varepsilon} \quad \textbf{(3)}$$

$$\frac{\mathrm{d}\psi}{\mathrm{d}t} = -A\sigma_0^n \psi^{n-\alpha} e^{n\varepsilon} \quad \textbf{(4)}$$

[1] Arutyunyan R.A. High-Temperature Embrittlement and Long-Term Strength of Metallic Materials // Mech. Solids. 2015. V. 50. I. 2. P. 191-197.
[2] Arutyunyan R.A. The problem of strain aging and long-term fracture in the mechanics of materials. St. Petersburg: Publishing House of St. Petersburg State University, 2004. 252 p. (in Russian)

## The exact solution in the form $\psi(\varepsilon)$

$$\frac{d\psi}{d\varepsilon} = -\frac{A}{B}\sigma_0^{n-m}\psi^{n-\alpha-m+\beta}e^{(n-m)\varepsilon}, \qquad (5)$$

$$\psi = \left[1 + \frac{A\sigma_0^{n-m}(1-n+\alpha+m-\beta)}{B(n-m)}(1-e^{(n-m)\varepsilon})\right]^{\frac{1}{1-n+\alpha+m-\beta}} \qquad (6)$$

## The case of purely brittle fracture and small deformations at $e^{m\varepsilon} \approx 1,\ e^{n\varepsilon} \approx 1$

$$\frac{\mathrm{d}\varepsilon}{\mathrm{d}t} = B\sigma_0^m \psi^{m-\beta} \qquad \textbf{(7)}$$

$$\frac{\mathrm{d}\psi}{\mathrm{d}t} = -A\sigma_0^n \psi^{n-\alpha} \qquad \textbf{(8)}$$

## The case of purely brittle fracture and small deformations at $e^{m\varepsilon} \approx 1,\ e^{n\varepsilon} \approx 1$

$$\psi = \left[1-(\alpha-n+1)A\sigma_0^n t\right]^{\frac{1}{\alpha-n+1}} \qquad (9)$$

$$\varepsilon = \frac{B\sigma_0^{m-n}}{A(m-\beta+\alpha-n+1)}\left\{1-\left[1-(\alpha-n+1)A\sigma_0^n t\right]^{\frac{m-\beta}{\alpha-n+1}+1}\right\} \qquad (10)$$

$$\psi = \left[-\frac{A}{B}(-n+m+\alpha-\beta+1)\sigma_0^{n-m}\varepsilon+1\right]^{\frac{1}{-n+m+\alpha-\beta+1}} \qquad (11)$$

## The case of purely brittle fracture and small deformations at $e^{m\varepsilon} \approx 1,\ e^{n\varepsilon} \approx 1$

**Our creep curves according to formula (10):** $\alpha = 6$ **—curve 1,** $\alpha = 4$ **—curve 2, and** $\alpha = 2$ **—curve 3.**

$$\varepsilon = \frac{B\sigma_0^{m-n}}{A(m-\beta+\alpha-n+1)}\left\{1-\left[1-(\alpha-n+1)A\sigma_0^n t\right]^{\frac{m-\beta}{\alpha-n+1}+1}\right\}$$

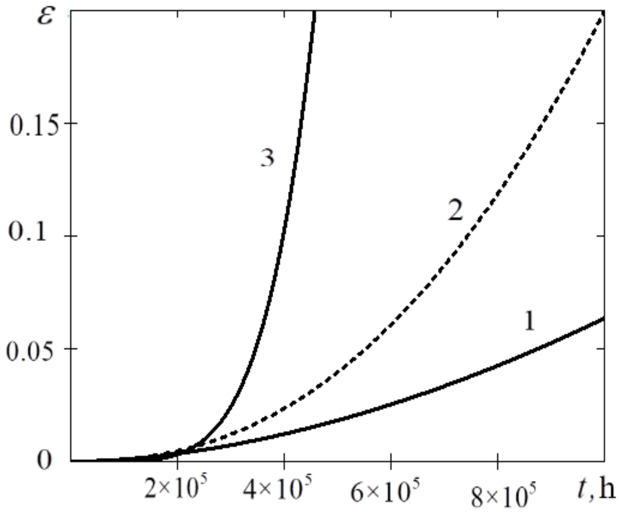
**Kachanov-Rabotnov's model**

**(curve 2** at $\alpha = 2n$ and $\beta = 0$**):**

$$\varepsilon = \frac{B\sigma_0^{m-n}}{A(m+n+1)}\left[1-\left(1-A(n+1)\sigma_0^n t\right)^{\frac{m+n+1}{n+1}}\right]$$

$A = 1\times10^{-9}\,[MPa]^{-2}\times[h]^{-1}$, $B = 5\times10^{-17}\,[MPa]^{-4}\times[h]^{-1}$,

$\sigma_0 = 100\,\text{MPa}$, $n = 2$, $m = 4$, $\beta = 0$.



## The case of purely brittle fracture and small deformations at $e^{m\varepsilon} \approx 1 + m\varepsilon,\ e^{n\varepsilon} \approx 1 + n\varepsilon$

$$\frac{\mathrm{d}\varepsilon}{\mathrm{d}t} = B\sigma_0^m \psi^{m-\beta}(1 + m\varepsilon) \qquad \textbf{(12)}$$

$$\frac{\mathrm{d}\psi}{\mathrm{d}t} = -A\sigma_0^n \psi^{n-\alpha}(1 + n\varepsilon) \qquad \textbf{(13)}$$

# The case of purely brittle fracture and small deformations at $e^{m\varepsilon} \approx 1 + m\varepsilon,\; e^{n\varepsilon} \approx 1 + n\varepsilon$

$$\psi = \left[1 - \frac{A}{B} \cdot \sigma_0^{n-m} \cdot (m - \beta - n + \alpha + 1) \cdot \left[\frac{(m-n) \cdot ln(m\varepsilon + 1)}{m^2} + \frac{n\varepsilon}{m}\right]\right]^{\frac{1}{m-\beta-n+\alpha+1}} \qquad \textbf{(14)}$$

$$\psi = e^{\left[\frac{A\sigma_0^{n-m}(m-n)}{Bm^2}\left(e^{mB\sigma_0^m t} - 1\right) - \frac{A\sigma_0^n (m-n)}{m} t\right]} \qquad \textbf{(15)}$$

$$\varepsilon = \frac{e^{Bm\sigma_0^m t} - 1}{m} \qquad \textbf{(16)}$$

## Long-term strength criterion from (9)

From **(9),** taking the fracture conditions in the form $t = t_f$ , $\psi = \psi_*$, obtain:

$$t_f = \frac{1 - \psi_*^{\alpha - n + 1}}{A(\alpha - n + 1)\sigma_0^n} \qquad \mathbf{(17)}$$

# Long-term strength criterion from (9)

From **(9),** taking the fracture conditions in the form $t = t_f$ , $\psi = 0$, obtain:

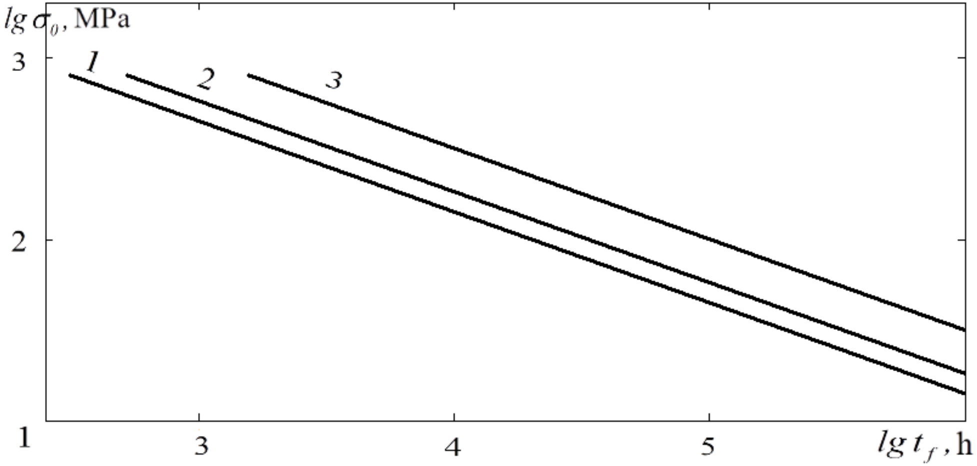
**Our criterion (curve 1 and curve 3):**

$$t_f = \frac{1}{A(\alpha - n + 1)\sigma_0^n}$$

**Kachanov-Rabotnov's criterion**

**(curve 2** at $\alpha = 2n$**):**

$$t_f = \frac{1}{A(n+1)\sigma_0^n}$$



# Comparison of exact and approximate solutions:

$A = 10^{-12}[MPa]^{-2} \cdot [h]^{-1}$, $B = 5\times10^{-17}[MPa]^{-4} \cdot [h]^{-1}$, $\sigma_0 = 100\,MPa$,

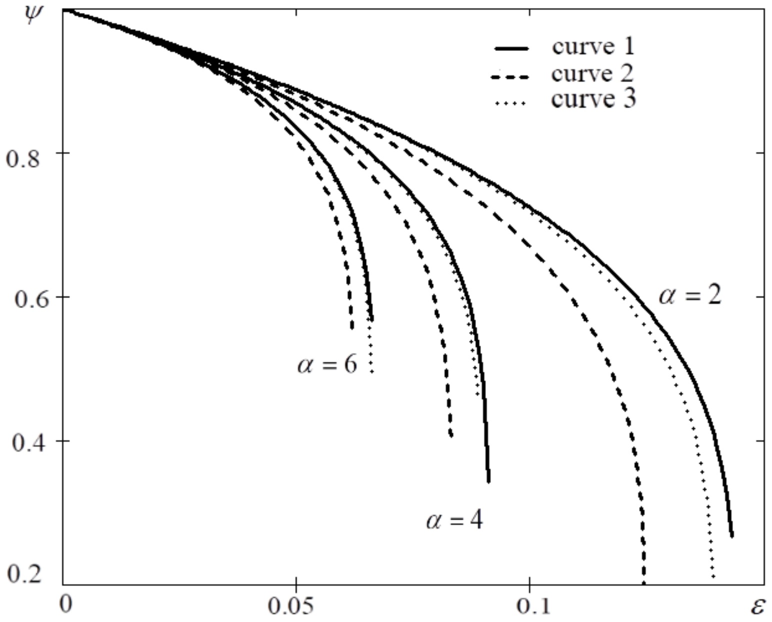
$n = 2$, $m = 4$, $\beta = 1$.

**Curve 1**- the exact solution of the modified system of equations **(6)**

**Curve 2** - the case of purely brittle fracture and small deformations of the modified system of equations $e^{m\varepsilon} \approx 1$, $e^{n\varepsilon} \approx 1$ **(11)**

**Curve 3** - the case of purely brittle fracture and small deformations of the modified system of equations

$e^{m\varepsilon} \approx 1 + m\varepsilon$, $e^{n\varepsilon} \approx 1 + n\varepsilon$ **(14)**

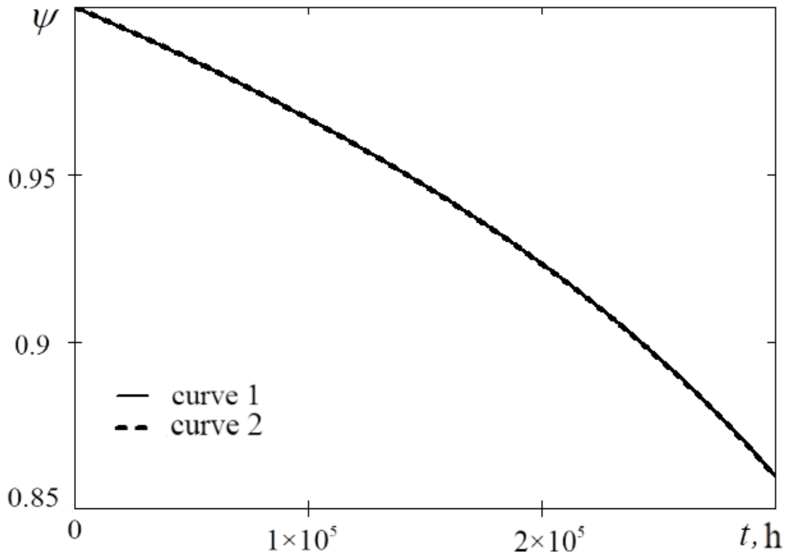


# Numerical solution of the system of equations (1)-(2)

$A = 2.99\times10^{-11}\left[MPa\right]^{-2}\cdot\left[h\right]^{-1}$, $n = 2$, $\sigma_0 = 100\,MPa$, $\alpha = 8.634$.

**Curve 1 -** the case of purely brittle fracture and small deformations at **(9)** $e^{m\,\varepsilon} \approx 1$, $e^{n\,\varepsilon} \approx 1$

**Curve 2** –Numerical solution of the system of equations (1)-(2)



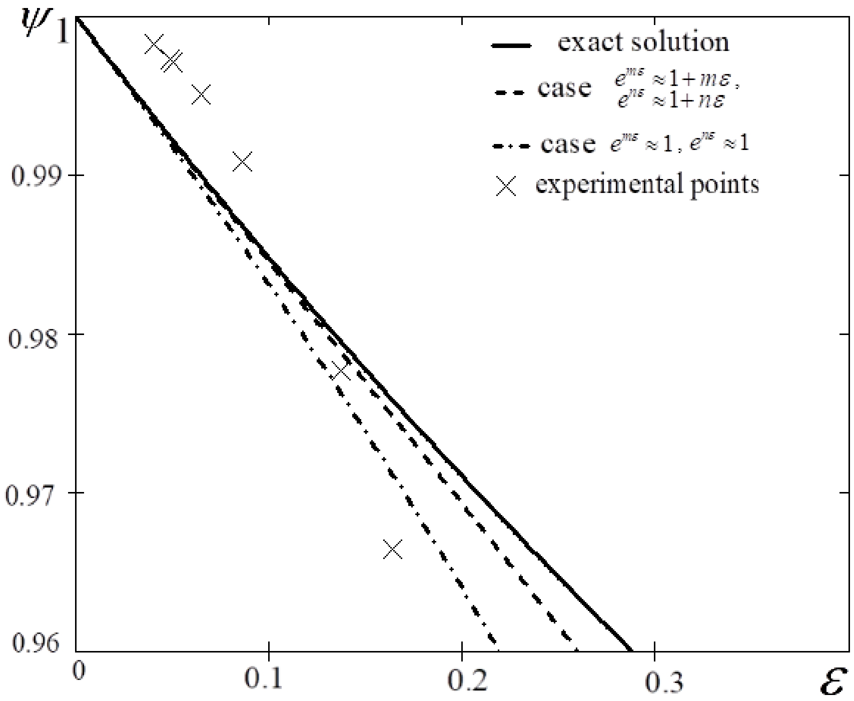
# Comparison of the obtained solutions with experimental results on density variation:

**Creep**, oxygen-free copper, 500°C [1].

$A = 1.7 \cdot 10^{-10} [MPa]^{-2} \cdot [h]^{-1}$,

$B = 2.5 \cdot 10^{-12} [MPa]^{-4} \cdot [h]^{-1}$, $\sigma_0 = 20.68\, MPa$, $n = 2$,

$m = 4$, $\beta = 1$, $\alpha = 6$.





[1] Boettner R.C, Robertson W.D. A study of the growth of voids in copper during the creep process by measurement of the accompanying change in density // Trans. of the Metallurg. Society of AIME. 1961. vol. 221. № 3. P. 613-622.

# Comparison of the obtained solutions with experimental results:

**Creep,** the alloy Ni-0.1 at. -%Pd, at 1300°C [2].

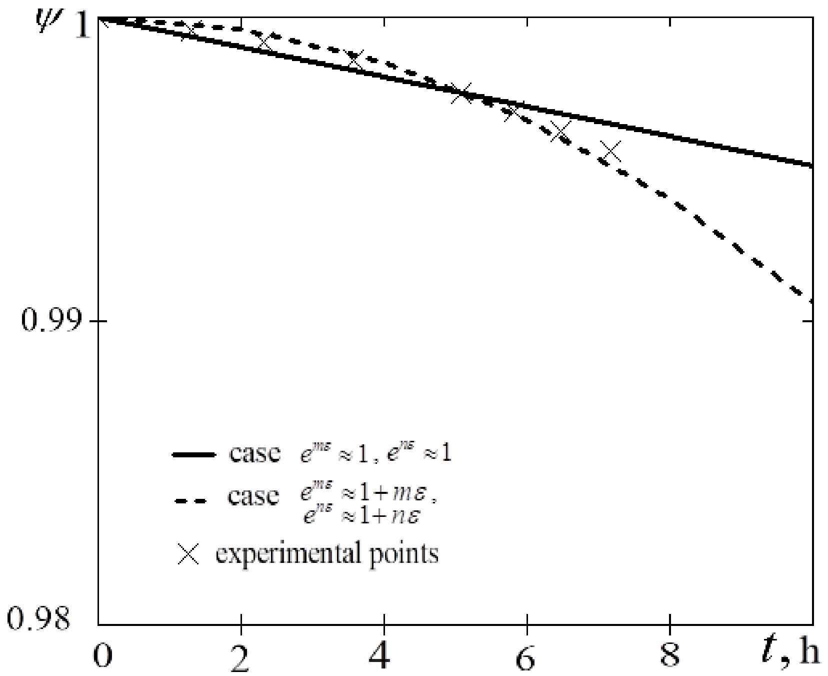
Solid line: $A = 25.5 \cdot 10^{-9} [MPa]^{-2} \cdot [h]^{-1}$, $\sigma_0 = 137.9\, MPa$,

$n = 2$, $m = 4$, $\alpha = 6$;

dotted line: $A = 1.2 \cdot 10^{-12} [MPa]^{-7} \cdot [h]^{-1}$,

$B = 0.2 \cdot 10^{-9} [MPa]^{-1} \cdot [h]^{-1}$, $\sigma_0 = 137.9\, MPa$, $n = 1 + \alpha$,

$m = \beta$, $\alpha = 6$, $\beta = 1$.




[2] Bowring P., Davies P.W., Wilshire B. The strain-dependence of density changes during creep // Metal science journal. 1968. vol. 2. № 9. P. 168-171..

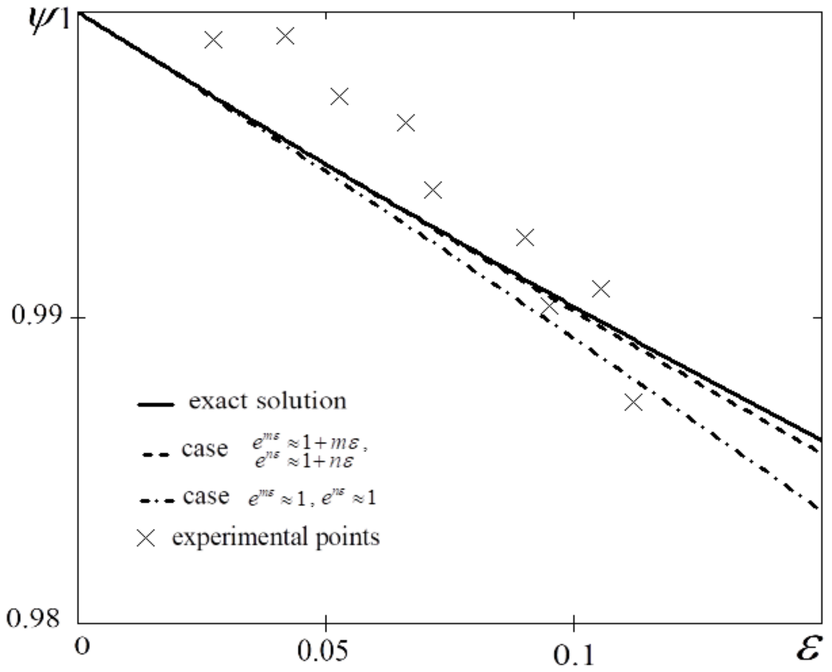
# Comparison of the obtained solutions with experimental results:

**Creep,** pure copper, at 250°C [1].

$$A = 7.1 \cdot 10^{-9} \left[MPa\right]^{-2} \cdot \left[h\right]^{-1},$$

$$B = 13.1 \cdot 10^{-12} \left[MPa\right]^{-4} \cdot \left[h\right]^{-1},$$

$$\sigma_0 = 72.6\ MPa,\ n = 2,\ m = 4,\ \beta = 1,\ \alpha = 6.$$




[1] Brathe L. Macroscopic measurements of creep damage in metals // Scand. J. Metal. 1978. vol. 7. № 5. P. 199-203.

# Comparison of the obtained solutions with experimental results:

**Creep,** oxygen-free copper, at 500°C [2].

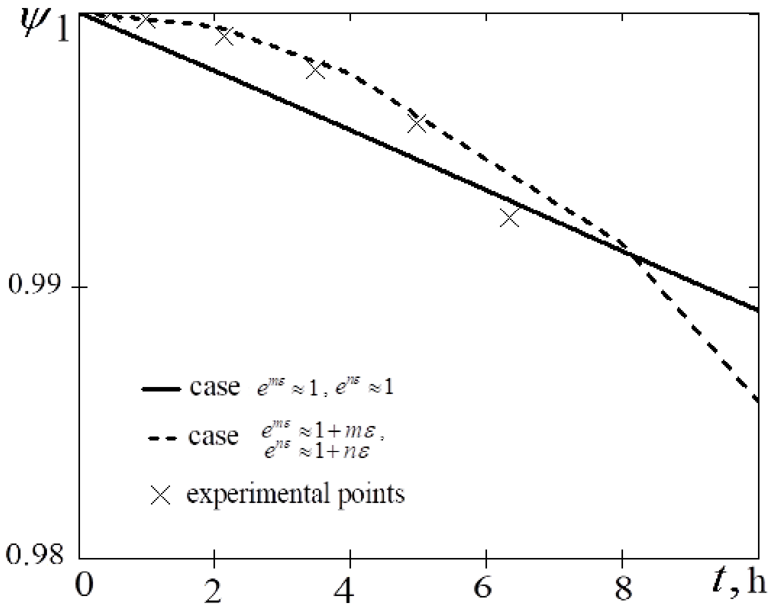
Solid line: $A = 0.9 \cdot 10^{-6} [MPa]^{-2} \cdot [h]^{-1}$, $\sigma_0 = 34.47 MPa$,

$n = 2$, $\alpha = 6$;

Dotted line: $A = 1.2 \cdot 10^{-7} [MPa]^{-7} \cdot [h]^{-1}$, $B = 0.2 \cdot 10^{-9} [MPa]^{-1} \cdot [h]^{-1}$,

$\sigma_0 = 34.47 MPa$, $n = 1 + \alpha$,

$m = \beta$, $\alpha = 6$, $\beta = 1$.





[2] Boettner R.C, Robertson W.D. A study of the growth of voids in copper during the creep process by measurement of the accompanying change in density // Trans. of the Metallurg. Society of AIME. 1961. vol. 221. № 3. P. 613-622.

# Comparison of the obtained solutions with experimental results on creep deformation:

Tab. 1. Coefficients for relation **(10), a.**

| $\sigma_0$,MPa | $A$, $\times 10^{-18}$ [MPa]$^{-4}$ $\times$ [h]$^{-1}$ | $B$, $\times 10^{-9}$ [MPa]$^{-2}$ $\times$ [h]$^{-1}$ | $m$ | $n$ | $\alpha$ | $\beta$ |
|---|---|---|---|---|---|---|
| 98 | 5.1 | 5 | 2 | 6 | 6 | 2 |
| 80 | 5.1 | 0.1 | 2 | 6 | 6 | 2 |
| 120 | 5.1 | 3 | 2 | 6 | 6 | 2 |

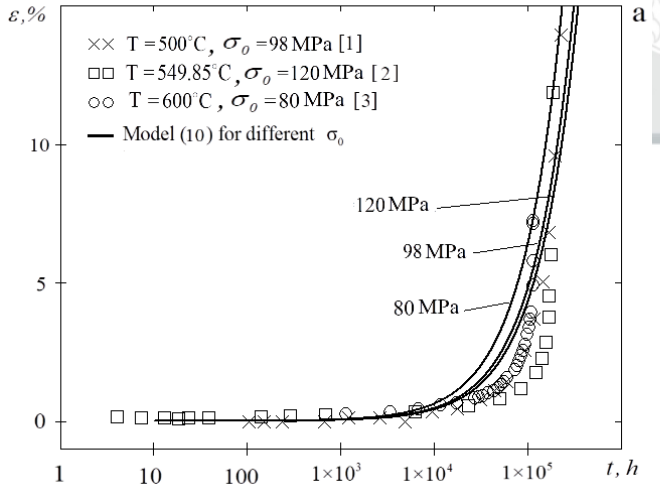
Tab. 2. Coefficients for relation **(16), b**.

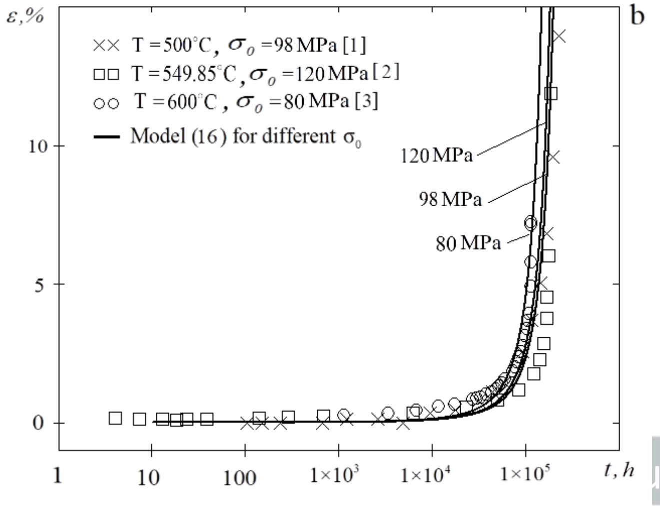
| $\sigma_0$,MPa | $B$, $\times 10^{-9}$ [MPa]$^{-2}$ $\times$ [h]$^{-1}$ | $m$ |
|---|---|---|
| 98 | 0.9 | 2 |
| 80 | 1.8 | 2 |
| 120 | 0.65 | 2 |


[1]. Wolf H.-D. Kriechen der legierungen NiCr22Co12Mo and 10CrMoT10 bei konstanter und zyklischer beanspruchung, D. Ing Thesis, Erlangen University, Erlangen. 1990.

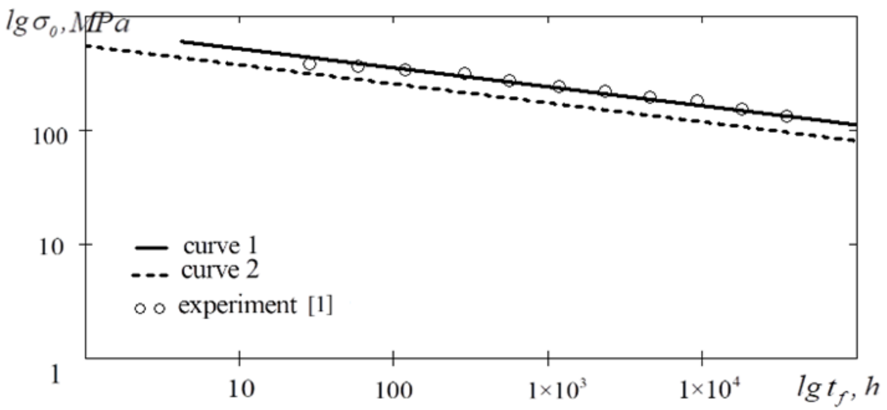
[2]. Aghajani A. Evolution of Microstructure during Long-term Creep of a Tempered Martensite Ferritic Steel. // Dissertation to obtain the degree of Doctor of Engineer of the Faculty of Mechanical Engineering of the Ruhr University Bochum. Bochum, 2009. 108 p.

[3]. C.G. Panait et al. Evolution of dislocation density, size of subgrains and MX-type precipitates in a P91 steel during creep and during thermal ageing at 600 ◦C for more than 100,000 h // Materials Science and Engineering A 527 (2010) 4062–4069.

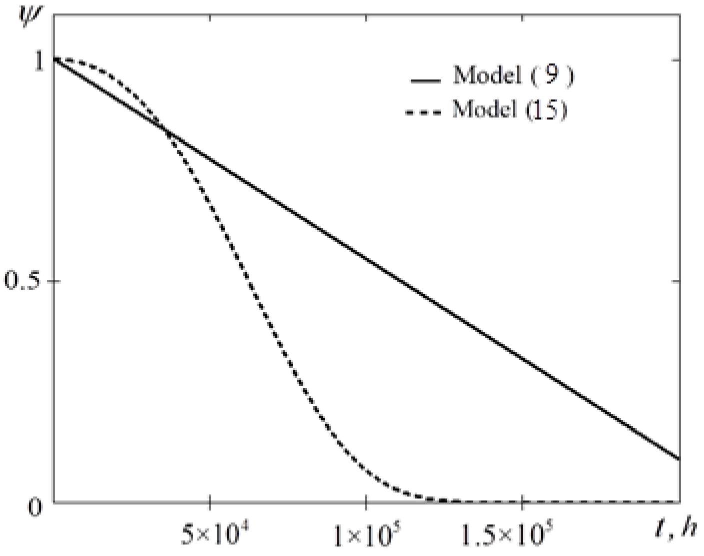



# Long-term strength criterion (17) and continuity curves according to relations (9) and (15) for similar values of the coefficients:




$A=5.1\times10^{-18}\,[MPa]^{-4}\times[h]^{-1}$, $B=0.9\times10^{-9}\,[MPa]^{-2}\times[h]^{-1}$, $\sigma_0=98\,MPa$,

$n=6$, $m=2$, $\alpha=6$, $\beta=2$.




**Curve 1 -** Long-term strength curve according to criterion **(17)**
**Curve 2** –Kachanov-Rabotnov's criterion
**Эксперимент:**
Steel 2.25Cr-1Mo at 500°C according to [1].

**Model (9)** – $e^{m\varepsilon}\approx1,\ e^{n\varepsilon}\approx1$

**Model (15)** – $e^{m\varepsilon}\approx1+m\,\varepsilon,\ e^{n\varepsilon}\approx1+n\,\varepsilon$


[1]. Wolf H.-D. Kriechen der legierungen NiCr22Co12Mo and 10CrMoT10 bei konstanter und zyklischer beanspruchung, D. Ing Thesis, Erlangen University, Erlangen. 1990.

## High-entropy alloys (HEAs) :

**High-entropy alloys (HEAs)** are a new class of metallic alloys without a principal component. These materials are attractive because of their unique structures and properties, including mechanical ones. Some of HEAs based on refractory metals are considered as advanced high-temperature materials.

In this regard, the study and description of the behavior of such materials under conditions of **creep, fatigue** and **long-term strength** is of great interest.

## High-entropy alloys (HEAs) :

As high-entropy alloys (HEAs) are being actively explored for next-generation structural materials, gaining a comprehensive understanding of their **creep, fatigue, and fracture** behaviors is indispensable.

These three aspects of mechanical properties are particularly **important because**

- creep resistance dictates an alloy’s high-temperature applications;
- fatigue failure is the most frequently encountered failure mode in the service life of a material;
- fracture is the very last step that a material loses its load-carrying capability.

# Comparison of the obtained solutions with experimental results:

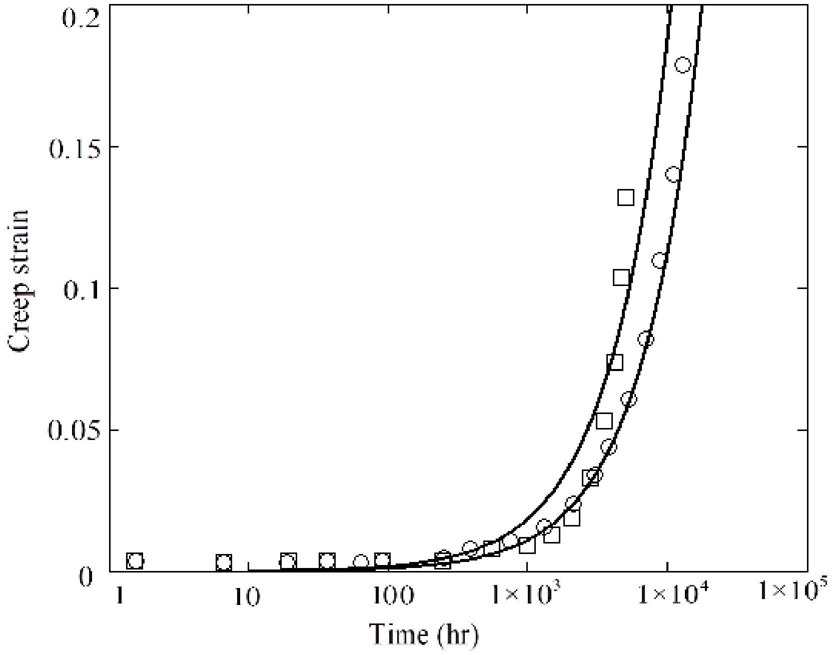



**Fig. 3.** Theoretical creep curves according to relation (10) and the experimental results for CrMnFeCoNi alloy at 650°C, 50 MPa (squares) and CrFeCoNi alloy at 650°C, 75 MPa (circles).

| $\sigma_0$, MPa | $A$,[MPa]$^{-6}$[h]$^{-1}$ | $B$,[MPa]$^{-2}$[h]$^{-1}$ | $m$ | $n$ | $\alpha$ | $\beta$ |
|---|---|---|---|---|---|---|
| 75 | $3.1\times10^{-17}$ | $2\times10^{-9}$ | 2 | 6 | 6 | 2 |
| 50 | $2.8\times10^{-16}$ | $7.5\times10^{-9}$ | 2 | 6 | 6 | 2 |

[1] M.-G. Jo, J.-Y. Suh, M.-Y. Kim, H.-J. Kim, W.-S. Jung, D.-I. Kim, H. N. Han, High temperature tensile and creep properties of CrMnFeCoNi and CrFeCoNi high-entropy alloys, Materials Science and Engineering: A, vol. 838, 2022, 142748.

# Comparison of the obtained solutions with experimental results:

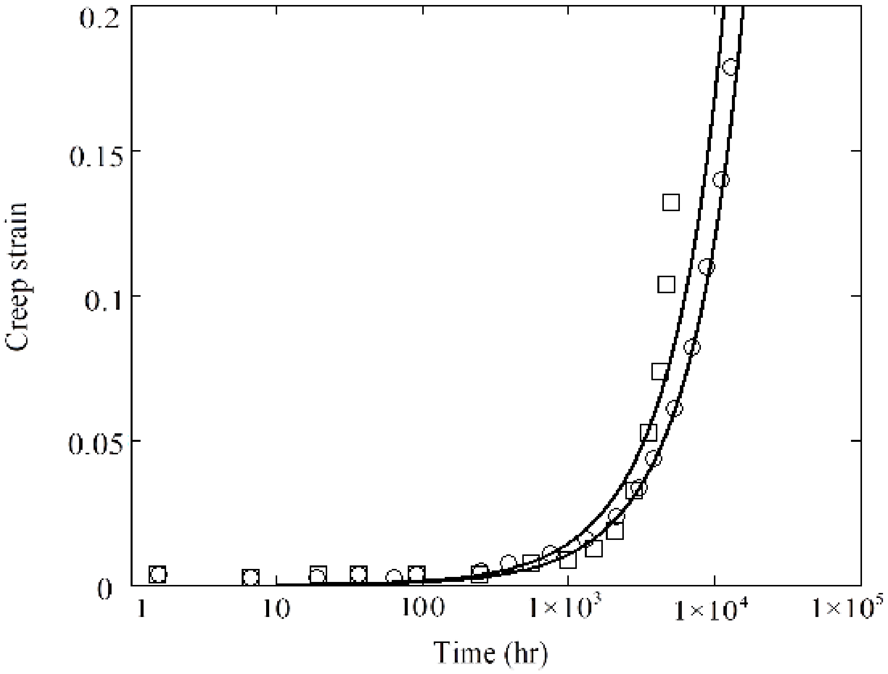



**Fig. 4.** Theoretical creep curves according to relation (16) and the experimental results for CrMnFeCoNi alloy at 650°C, 50 MPa (squares) and CrFeCoNi alloy at 650 °C, 75 MPa (circles).

| $\sigma_0$, MPa | $B$, $[MPa]^{-2}[h]^{-1}$ | $m$ |
|---|---|---|
| 75 | $1.9\times10^{-9}$ | 2 |
| 50 | $5.8\times10^{-9}$ | 2 |

[1] M.-G. Jo, J.-Y. Suh, M.-Y. Kim, H.-J. Kim, W.-S. Jung, D.-I. Kim, H. N. Han, High temperature tensile and creep properties of CrMnFeCoNi and CrFeCoNi high-entropy alloys, Materials Science and Engineering: A, vol. 838, 2022, 142748.

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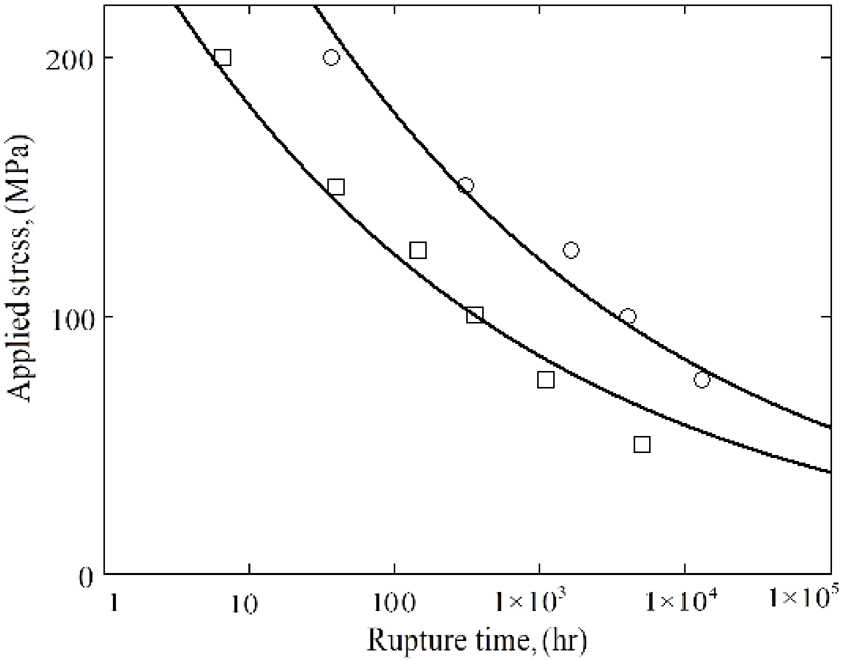


**Fig. 5.** Long-term strength curves according to relation (13) for CrMnFeCoNi alloy at 650°C (squares) and CrFeCoNi alloy at 650°C(circles).

| | $\psi_*$ | $A$,[MPa]$^{-6}$[h]$^{-1}$ | $n$ | $\alpha$ |
|---|---|---|---|---|
| CrFeCoNi | 0.9 | $3.1\times10^{-17}$ | 6 | 6 |
| CrMnFeCoNi | 0.9 | $2.8\times10^{-16}$ | 6 | 6 |

[1] M.-G. Jo, J.-Y. Suh, M.-Y. Kim, H.-J. Kim, W.-S. Jung, D.-I. Kim, H. N. Han, High temperature tensile and creep properties of CrMnFeCoNi and CrFeCoNi high-entropy alloys, Materials Science and Engineering: A, vol. 838, 2022, 142748.

## General conclusions:

- 1. A system of interrelated kinetic equations for creep deformation and damage parameter is proposed. In this system, it is assumed that the material is incompressible. The relative change in density is taken as the damage parameter. In the scientific literature, most authors consider density to be the most representative characteristic of porosity.
- 2. Solutions of the modified system of equations for creep deformation and damage parameter are obtained. The solutions have the following advantages:

-For creep deformation, we can describe the third creep section.

-For long-term durability, we can describe brittle fracture.

- And the Kachanov-Rabotnov criterion is a special case.

- 3. A comparison with the experimental results for CrMnFeCoNi and CrFeCoNi alloys is given. It is shown, that the experimental results are in good agreement with the theoretical ones. Thus, the proposed system of interrelated kinetic equations allows us to describe the creep and long-term strength behavior of HEAs.

# Approbation of the work:

- IX International Conference the Problems of Interaction of Deformable Media dedicated to the 75th anniversary of NAS RA, Goris, Armenia, October 1-6, **2018**;
- XLVII International Summer School – Conference "Advanced Problems in Mechanics 2019", APM 2019, Saint Petersburg, Russia, June 24-29, **2019**;
- XII All-Russian Congress on Fundamental Problems of Theoretical and Applied Mechanics, Ufa, Russia, August 19-24, **2019**;
- XIX All-Russian school-seminar "Modern problems of aerohydrodynamics", dedicated to the 60th anniversary of the Research Institute of Mechanics of Moscow State University named after M.V. Lomonosov, Sochi, Russia, September 5-15, **2019**;
- VI International Conference on Topical Problems of Continuum Mechanics, Dilijan, Armenia, October 1-6, **2019**;
- International Youth Scientific Conference "XXIV Tupolev Readings (School of Young Scientists)": dedicated to the 130th anniversary of the birth of aircraft designer I.I. Sikorsky, Kazan, Russia, November 7-8, **2019**;
- XLVI International Youth Scientific Conference "Gagarin Readings", Moscow, Russia, April 14-17, **2020**;
- XLVIII International Conference Advanced Problems in Mechanics, APM 2020, St. Petersburg, Russia, June 21-26, **2020**;
- All-Russian Scientific Conference with international participation "Actual problems of continuum mechanics - 2020", Kazan, Russia, September 28 - October 2, **2020**;
- International Summer School-Conference “Advanced Problems in Mechanics”, St. Petersburg, Russia, November 9-13, **2020**;
- XLVII International Youth Scientific Conference "Gagarin Readings", Moscow, Russia, April 20-23, **2021**;
- XLIX International Summer School-Conference "Advanced Problems in Mechanics": APM 2021, St. Petersburg, Russia, June 21-25, **2021**;
- VII International Conference On Topical Problems of Continuum Mechanics, Tsaghkadzor, Armenia, September 4-8, **2021**;
- 50th Anniversary International Summer School-Conference "Advanced problems in mechanics", St. Petersburg, Russia, June 20-24, **2022**;
- All-Russian Conference on Natural Sciences and Humanities with international participation "SCIENCE SPbU - 2022", St. Petersburg, Russia, November 21, **2022**;
- VIII International Conference Actual Problems of Continuum Mechanics, Tsakhkadzor, Armenia, October 01-05, **2023**.
- 51$^{st}$ School Conference «Advanced problems in mechanics » in memory of D.A. Indeitsev, Veliky Novgorod, Russia, June 19-21, **2024**.

# Publications in journals (Scopus, VAK):

1. Arutyunyan A.R., Arutyunyan R.A., Saitova R.R. The Criterion of High-Temperature Creep of Metals Based on Relative Changes of Density // WSEAS Transactions on Applied and Theoretical Mechanics. V. 14. **2019**. P. 140-144. (**Scopus)**

2. Arutyunyan A. R., Arutyunyan R. A., Saitova R. Damage of metallic materials during high-temperature creep//Physical-Chemical Kinetics in Gas Dynamics. **2019**. V.20. I. 3. № 815. P.1-4. (in Russian). **(VAK)**

3. Arutyunyan A.R., Arutyunyan R.A., Saitova R.R. High-temperature creep and damage of metallic materials // Journal of Physics: Conference Series. V. 1474. I. 1. **2020**. №: 012005. Doi:10.1088/1742-6596/1474/1/012005. (**Scopus)**

4. Arutyunyan A.R., Arutyunyan R.A., Saitova R.R. The Definition of Damage Parameter Changes from the Experimental High-Temperature Creep Curves // Lecture Notes in Mechanical Engineering. **2020.** P. 53-59. Doi: 10.1007/978-3-030-49882-5_5. (**Scopus**)

5. Arutyunyan A.R., Saitova R.R. Exact and approximate solutions of the system of interrelated equations of the theory of creep and long-term strength // Journal of Physics: Conference Series. **2022**. V. 2231. I. 1. №: 012001. Doi: 10.1088/1742-6596/2231/1/012001. (**Scopus)**

6. Arutyunyan A.R., Saitova R.R. Exact and Approximate Solutions of the Modified System of Interrelated Kinetic Equations for Damage Parameter and Creep Deformation // Advanced Problems in Mechanics III. APM 2021. Lecture Notes in Mechanical Engineering. Springer International Publishing. **2023**. P. 196-201. (**Scopus)**

7. Arutyunyan A.R., Saitova R.R. Experimental and theoretical studies of high-temperature creep of aluminum alloy AMG2 under conditions of step loading // Reports of the Russian Academy of Sciences. Physics, technical sciences. **2023**. V. 511. №. 1. P. 37-40. (in Russian). **(VAK)**

8. Arutyunyan A.R., Saitova R.R. Experimental and Theoretical Investigations of High-Temperature Creep of the ENAW 5251 (AMg2) Aluminum Alloy under Step Loading // Doklady Physics. **2024**. V. 68. №. 7. P. 203–206. (in the press). (**Scopus)**

9. Arutyunyan A.R., Saitova R.R. Description of step loads at high temperature creep of metallic materials // Journal of Physics: Conference Series. **2024**. (in the press). (**Scopus)**

10. Saitova R.R., Borodich F.M., Arutyunyan A.R. Development of the damage concept in mechanics of materials // Journal of Applied Mathematics and Mechanics. **2024**. (in Russian, in the press). **(VAK)**

11. Saitova R., Arutyunyan A., Altenbach H. High Temperature Creep and Embrittlement in Metals and Alloys Under Conditions of the Long-Term Usage // Acta Mechanica. **2024.** (in the press). (**Scopus)**

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