MATERIALS PHYSICS AND MECHANICS RESEARCH ARTICLE

Submitted: February 02, 2025 **Revised: April 28, 2025** **Accepted: May 29, 2025**

Creep and long-term strength of high-entropy alloys

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ABSTRACT

High-entropy alloys 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 high-entropy alloys 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. In the work, to describe the creep and long-term strength of high-entropy alloys a damage conception is used. A system of interconnected kinetic equations for the creep rate and damage parameter is formulated. A compressible medium is considered, and the mass conservation law is taking into account. The damage parameter is specified in the form of the ratio of the current density of the material to the initial one. The analytical solutions of these equations are obtained. The theoretical creep and long-term strength curves are plotted and compared with the experimental results for CrMnFeCoNi and CrFeCoNi alloys. The experimental results are in good agreement with the theoretical ones.

KEYWORDS

creep • damage parameter • high-entropy alloys • long-term strength

Funding*. This work has been supported by the grant of St. Petersburg State University, ID No. 119081549.*

Citation: Saitova RR, Arutyunyan AR. Creep and long-term strength of high-entropy alloys. *Materials Physics and Mechanics*. 2025;53(3): 116–121.

http://dx.doi.org/10.18149/MPM.5332025_9

Introduction

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.

As materials with superior properties are continuously searched, HEAs, formed by the physical metallurgy of five or more metallic elements with equal or nearly equal quantities, emerge as a class of revolutionary materials. HEAs break down the traditional wisdom of alloy design in which a primary element serves as the foundation of properties, and small amounts of additional elements are inserted for fine tuning, therefore, open innumerable possibilities in developing advanced alloys [1,2].

One decade of dedicated research has revealed that many HEAs possess unparalleled properties in comparison with traditional alloys, for instance, great thermal and microstructural stability [3], high hardness [4], high strength at a wide range of temperatures [5] and excellent resistance to wear [6], corrosion [7], fatigue [8], fracture [9] and high-temperature softening [10]. Given these merits, applications of HEAs in various fields, particularly in structural engineering (e.g., used for gas-turbine engines), are being actively explored. Among many performance indices, a thorough understanding of creep, fatigue, and fracture behaviors of HEAs is crucial and indispensable to their sophisticated engineering applications.

Kinetics of damage and deformation accumulation under high temperature creep conditions

Literature survey

High-temperature creep of metals and alloys is characterized by the fact that in the body, along with the accumulation of irreversible creep deformations, the formation and development of defects (pores, micro- and macrocracks) occur, leading to fracture. In 1826, the phenomenon of creep was observed by Claude Louis Marie Henri Navier. First systematic studies on creep processes were published by Edward Neville da Costa Andrade [11].

To describe a brittle region of the long-term strength curve studies based on continuum mechanics were conducted. These studies taking into account the accumulation of damage, have led to the development of a separate direction of continuum mechanics - the Continuum Damage Mechanics. This direction was created by two outstanding Soviet scientists: L.M. Kachanov [12] and Yu.N. Rabotnov [13]. At the end of the 1950s, they considered and introduced a new parameter at creep under uniaxial tension: material continuity (Kachanov) and material damage (Rabotnov). Soon Rabotnov, based on this approach, developed the kinetic theory of creep and long-term strength.

Subsequently, significant results in this area were obtained in the Soviet Union/Russian Federation. Following Kachanov and Rabotnov, the mechanics of continuum fracture began to develop in Europe, mainly in relation to the processes of creep of metals. Since then, this area of research has been in the center of attention all over the world with regard to the development of both its foundations (not all theoretical problems have been solved) and applications [14–18].

When formulating the interrelated equations of creep and damage, the damage parameter should be given a physical meaning. To materialize the damage parameter various definitions were offered. The relative size of pores or irreversible change of volume (loosening on Novozhilov's terminology) are considered in [19]. The crack length is taken as damage parameter in [17]. Maruyama and Nosaka [20] measured damage of material based on micro-grinding using a transparent reference square grid. The ratio of the number of nodes entering the region of pores and microcracks to the total number of nodes in the grid was considered. In [21], it is analyzed dislocation density. Many authors [22–25] considered the density of the material to be the most representative characteristic of porosity and damage. Density measurement is carried out by known methods using accurate weighing in air and in liquid (hydrostatic weighing). No methods of introducing the damage parameter mentioned above allow its measurement during creep tests. To determine the damage value at a given time by these methods, it is necessary to stop the experiment, and when metallographic methods are used, in addition the specimens must be cut. In [26], a method for measuring structural changes in metal directly during high temperature creep, without cooling and unloading of specimens is considered. It is proposed to conduct the measurement of electrical resistance of the specimens during stretching and to compare these data with the results of the length measurement of specimens at the same time values.

Kinetic equations for damage parameter and creep strain

In this paper, the parameter of continuity is determined by the ratio $\psi = \rho/\rho_0$ (ρ_0 is initial, ρ is current density) and it is considered as integral measure of the structural microdefects accumulation during long-term high-temperature creep [27,28].

Let's consider the following system of equations [29,30]:

$$\psi^{\beta} \frac{d\varepsilon}{dt} = B\sigma^{m}, \tag{1}$$

$$\psi^{\alpha} \frac{d\psi}{dt} = -A\sigma^{n}, \tag{2}$$

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

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:

$$\frac{d\varepsilon}{dt} = B\sigma_0^m \psi^{m-\beta} e^{m\varepsilon}, \tag{3}$$

$$\frac{d\psi}{dt} = -A\sigma_0^n \psi^{n-\alpha} e^{n\varepsilon}. \tag{4}$$

The system (3)–(4) can be solved approximately, for the case of purely brittle fracture and small deformations, when the following approximations $e^{m\varepsilon} \approx 1$, $e^{n\varepsilon} \approx 1$ or $e^{m\varepsilon} \approx 1 + m\varepsilon$, $e^{n\varepsilon} \approx 1 + n\varepsilon$ can be taken into account. Let us consider each of these two cases. In the case of $e^{m\varepsilon} \approx 1$, $e^{n\varepsilon} \approx 1$, the system (3)–(4) takes the following form:

$$\frac{d\varepsilon}{dt} = B\sigma_0^m \psi^{m-\beta}, \tag{5}$$

$$\frac{d\psi}{dt} = -A\sigma_0^n \psi^{n-\alpha}. \tag{6}$$

Under the initial conditions $t = 0,\ \psi = 1$, from Eq. (6) we get:

$$\psi = [1 - (\alpha - n + 1)A\sigma_0^n t]^{\frac{1}{\alpha - n + 1}}. \tag{7}$$

Under the initial conditions $t = 0,\ \varepsilon = 0$, from Eq. (5) we can obtain that:

$$\varepsilon = \frac{B\sigma_0^{m-n}}{A(m-\beta+\alpha-n+1)} \left\{ 1 - [1 - (\alpha - n + 1)A\sigma_0^n t]^{\frac{m-\beta}{\alpha-n+1}+1} \right\} . \tag{8}$$

Let us consider the case of purely brittle fracture and small deformations at $e^{m\varepsilon} \approx 1 + m\varepsilon$, $e^{n\varepsilon} \approx 1 + n\varepsilon$, then the system of equations (3)–(4) can be written as:

$$\frac{d\varepsilon}{dt} = B\sigma_0^m \psi^{m-\beta}(1 + m\varepsilon); \tag{9}$$

$$\frac{d\psi}{dt} = -A\sigma_0^n \psi^{n-\alpha}(1 + n\varepsilon). \tag{10}$$

Under the conditions $m = \beta$, $n = 1 + \alpha$, the system (9)–(10) is reduced to a non-linear differential equation of the second order [31]. Under the initial conditions $t = 0$, $\psi = 1$, the expression for the continuity parameter has the following form:

$$\psi = e^{\left[\frac{A\sigma_0^{n-m}(m-n)}{Bm^2}\left(e^{mB\sigma_0^m t} - 1\right) - \frac{A\sigma_0^n (m-n)}{m} t\right]}. \tag{11}$$

Taking into account the conditions $m = \beta$, $n = 1 + \alpha$, under the initial conditions $t = 0$, $\varepsilon = 0$, from the system (9)–(10) we will have the flowing relation for creep strain

$$\varepsilon = \frac{e^{Bm\sigma_0^m t} - 1}{m}. \tag{12}$$

Long-term strength criterion

Taking the fracture conditions in the form $\boldsymbol{t} = \boldsymbol{t}_f$, $\boldsymbol{\psi} = \boldsymbol{\psi}_*$, from Eq. (7) we can obtain the following long-term strength criterion:

$$t_f = \frac{1-\psi_*{}^{\alpha-n+1}}{A(\alpha-n+1)\sigma_0^n}. \tag{13}$$

Comparison of the solutions obtained with experimental results

The theoretical creep curves and the experimental results on creep for CrMnFeCoNi and CrFeCoNi alloys are shown on Figs. 1 and 2, respectively [32]. The values of the coefficients used in the calculations for Eq. (8) under the condition $e^{m\varepsilon} \approx 1$, $e^{n\varepsilon} \approx 1$ and Eq. (12) under the condition $e^{m\varepsilon} \approx 1 + m\varepsilon$, $e^{n\varepsilon} \approx 1 + n\varepsilon$ are presented in Tables 1 and 2, respectively.

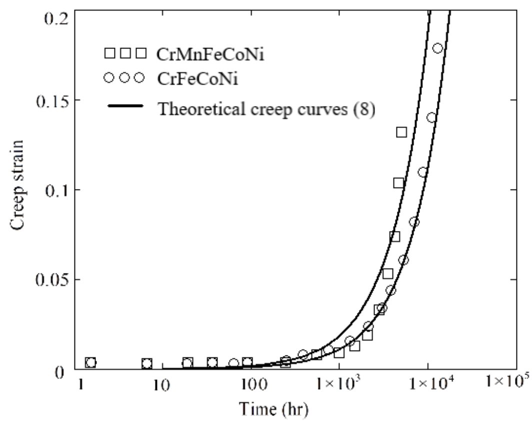

Fig. 1. Theoretical creep curves obtained by Eq. (8) and the experimental results for CrMnFeCoNi alloy at 650 °C and 50 MPa (squares) and CrFeCoNi alloy at 650 °C and 75 MPa (circles) [32]

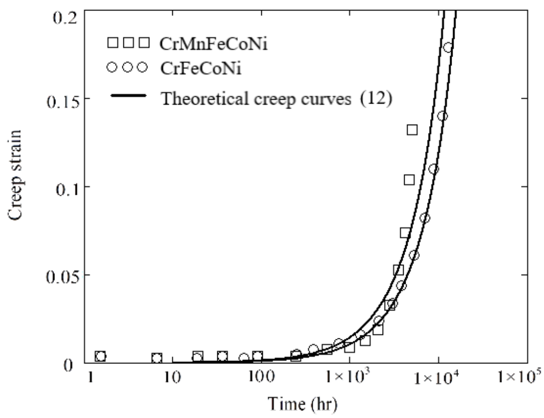

Fig. 2. Theoretical creep curves obtained by Eq. (12) and the experimental results for CrMnFeCoNi alloy at 650 °C and 50 MPa (squares) and CrFeCoNi alloy at 650 °C and 75 MPa (circles) [32]

Table 1. The values of the coefficients used in calculations according to Eq. (8)

$\boldsymbol{\sigma_0}$, [MPa]	$\boldsymbol{A}$, [MPa]$^{-6}[h]^{-1}$	$\boldsymbol{B}$, [MPa]$^{-2}[h]^{-1}$	$\boldsymbol{m}$	$\boldsymbol{n}$	$\boldsymbol{\alpha}$	$\boldsymbol{\beta}$
75	$3.1{\cdot}10^{-17}$	$2{\cdot}10^{-9}$	2	6	6	2
50	$2.8{\cdot}10^{-16}$	$7.5{\cdot}10^{-9}$	2	6	6	2

Table 2. The values of the coefficients used in calculations according to Eq. (12)

$\boldsymbol{\sigma_0}$, [MPa]	$\boldsymbol{B}$, [MPa]$^{-2}[h]^{-1}$	$\boldsymbol{m}$
75	$1.9{\cdot}10^{-9}$	2
50	$5.8{\cdot}10^{-9}$	2

Table 3. The values of the coefficients used in calculations according to Eq. (8)

	$\boldsymbol{\psi_*}$	$\boldsymbol{A}$, [MPa]$^{-6}[h]^{-1}$	$\boldsymbol{n}$	$\boldsymbol{\alpha}$
CrFeCoNi	0.9	$3.1{\cdot}10^{-17}$	6	6
CrMnFeCoNi	0.9	$2.8{\cdot}10^{-16}$	6	6

Figure 3 shows the long-term strength curves obtained by Eq. (13) for CrMnFeCoNi and CrFeCoNi alloys at 650 °C [32]. The following values of the coefficients are presented in Table 3. It was found that a good agreement between the theoretical and experimental creep and long-term strength curves (Figs. 1–3) is observed.

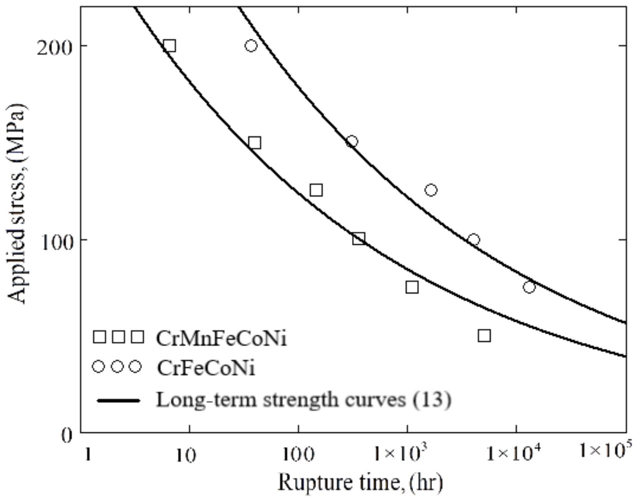

Fig. 3. Long-term strength curves obtained by Eq. (13) for CrMnFeCoNi (squares) and CrFeCoNi (circles) alloys at 650 °C [32]

Conclusions

In the paper to describe the creep and long-term strength of high-entropy alloys (HEAs) a damage conception is used. A system of interconnected kinetic equations for the creep rate and damage parameter for a compressible medium is formulated. The mass conservation law is taken into account, and the damage parameter is specified in the form of the ratio of the current density of the material to the initial one. Analytical solutions of these equations are obtained, and the long-term strength criterion is formulated. A comparison with the experimental results for CrMnFeCoNi and CrFeCoNi alloys is given. It was 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.

CRediT authorship contribution statement

Regina R. Saitova: writing-review and editing, conceptualization, supervision, data curation; **Alexander R. Arutyunyan**: writing-original draft, conceptualization, supervision, data curation.

Conflict of interest

The authors declare that they have no conflict of interest.

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