Research of creep deformation in amorphous and nanocrystalline alloys at variable temperature field

V A Fedorov[1], A D Berezner[1] and T N Pluzhnikova[1]
The Tambov state university n.a. G.R. Derzhavin,
392000, Internatsionalnaya str.,33, Tambov city, Russia

E-mail: qwert1009@mail.ru

Abstract. Investigations of Co-based amorphous alloys and Fe-based nanocrystalline alloy failure strain at creep tests within a temperature range being from 300 to 1023 K have been performed. A creep curve analytical form for all investigated alloys has been established.

1. Introduction

Investigation of processes running in amorphous and nanocrystalline metal samples is of interest considering that the given type of materials has unique magnetic and mechanical properties in relation to base metals. It is common knowledge that in the process of amorphous and nanocrystalline metals heating their structure can be rebuilt and, consequently, the above-said properties can change.

In spite of various scientific works [1-3] aimed at search of mechanical creep strain state reference parameters, explicit establishment of these parameters' relation with a material structure is complicated due to non-uniqueness of   models in the framework of which these parameters were suggested. The three models being applied for qualitative description of processes running in amorphous and nanocrystalline metal alloys are most often considered. Among these are: a free volume model [4], a structure relaxation model [5] and a fluid model [6].

Within the framework of these models there are values related to creep strain parameters: ductility and a relative strain value at creep. However, due to elongation function explicit form absence data applying within the framework of the given models is complicated. In this context the aim of the work hereof is the following one: the experimental and analytical investigation of amorphous and nanocrystalline metal alloys creep strain behavior at the combined effect of a temperature field and fixed load.

2. Materials and research methods

Co-based amorphous and Fe-based nanocrystalline metal alloys, prepared by rolling at cooling rate 10^6 K/s and were used in the experiments, their elemental composition being shown in Table 1.

Table 1. Alloys elemental composition.

Alloy (AMAG)	Co%	Fe%	Ni%	Si%	Mn%	B%	Cr%	Cu%	Nb%
170	70.42	4.7	10.46	9	2.1	2	1.3	-	-
179	78.1	3.31	8.19	5.48	1.61	2	1.31	-	-
180	78.65	4.03	4.73	7.22	1.88	2	1.49	-	-
183	82.69	2.21	-	7.77	4.19	2	1.14	-	-
186	85.41	2.27	-	5.15	4.07	2	1.1	-	-
200	-	80.22	-	8.25	-	-	-	1.44	10.09

Band samples of 50 mm (length), 3.5mm (width), 0.02 mm (thickness) dimensions served as subjects of research. Heating rate was maintained constant as 1-3 K/s at creep tests. Sample temperature was measured with a Testo-845 laser pyrometer. Samples elongation was measured with a laser triangulating sensor.

3. Experimental results and their discussion

It has been shown that creep curves for amorphous and nanocrystalline alloys have characteristic view at different heating rates (see Fig.1).
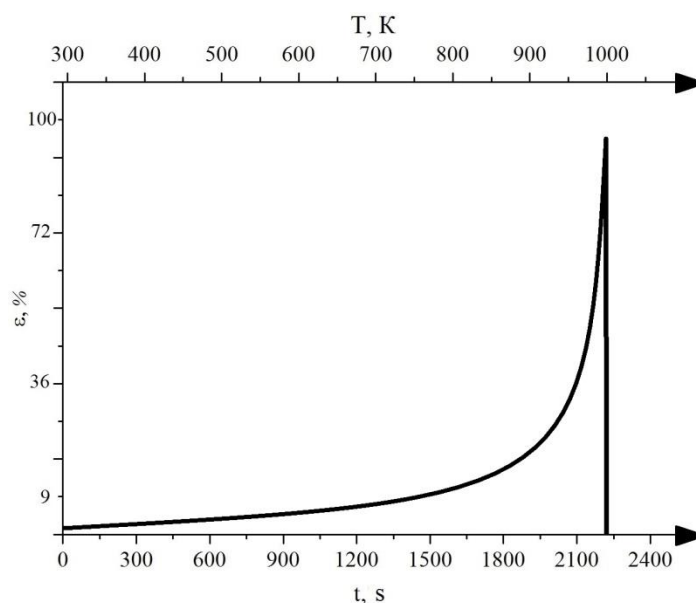

Figure 1. Typical creep curve for amorphous and nanocrystalline alloys.

It is found that for all experimental curves the selection of the following hyperbolic dependence form is possible:

$$x(t) = x_0 + \frac{Ct}{B^2 - Bt} \tag{1}$$

Where x_0 means sensor initial reading; C, B mean analytical parameters with fixed values.

Creep strain time t can be determined through experiment initial conditions (i.e. heating rate and temperature) in the form of the following linear relation:

$$t = \frac{T - T_0}{V} \tag{2}$$

where T_0 means the initial temperature of the experiment ($\sim$ 293 K), T is sample heating temperature. The (1) and (2) relations allow establishing between heating and elongation of the bands:

$$x(T) = x_0 + \frac{C(T - T_0)}{B^2 V - BT + BT_0} \tag{3}$$

Correlation between analytically suggested function (1) and the statistical data obtained in the course of the experiment was checked by means of covariation and a correlation coefficient. A $\{r\}$ data correlation coefficient value was calculated and the value is as follows: 0.9< $\{r\}$ <1 ($\{r_{max}\}$ = 0.9972). The $x(t)$ values calculated separately from the (1) formula with a maximal accuracy coincide with the experimental (tabular) data by 99.97 per cent (accurate to triangulating sensor indicated error being $\pm$ 0.001 mm, average-absolute error being $\pm$0.0000049 mm and relative error being δ_{min}= 0.000244). Consequently, correlation method applying to the (1) equation and the experimental data is adequate and the suggested formula (1) actually describes a creep process to the extent that makes this process worthwhile (the scope of continuum mechanics).

The physical meaning of the B value was determined at the (1) dependence analyzing; the B value takes on time values at which band rupture occurs, this depending on experiment initial conditions (i.e. sample quality, etc.) and also on a heating mode. A dimensional analysis of the C value showed that the given parameter is a coefficient with a m·s quantity dimension, and its values depend only on experiment initial conditions. This means the (1) analytical form persistence accurate to the variation of sensor reading initial value x_0.

For the achievement of the object in view in the work hereof an additional experimental check was performed allowing assessing the adequacy of C and B values applying. Sensitivity of the given parameters to the initial heat treatment effect and heating rate variability was assessed. The measured curves were interpolated with the (1) analytical dependence together with applicable coefficient values selection so that the interpolation accuracy calculated by means of a correlation coefficient would have the prescribed value of 99.97 percent. The averaged magnitudes of the C and B values were then obtained for each set of experiments. The averaged analytical curves plotted by the C and B values correspond to the averaged experimental curves plotted by the experiment tabular data. Prediction calculation of resistivity constant average quantity was performed in order to additionally check the (1) and (3) analytical equations in accordance with Ohm's law:

$$R = \int \frac{\rho dl}{S} = \frac{U}{I} = \frac{\overline{\rho} \Delta l}{\overline{S}} \tag{4}$$

The calculation showed that samples resistivity at creep (temperature) decreases and varies within the interval of values being from 10^{-4} to 10^{-5} Ohm/m. The (1) derived functions passed the check for conformity to dimensionality and predict the magnitude of the resistance value. This result is confirmed by methods of four- point probe measurement and bridge tests within the interval of preservation of sample's cross-section area measured in mm^2, this interval being equivalent to the temperature interval before crystallization.

Consequently, the (1) and (3) equations and their derivatives together with the C and B parameters included in them not only describe the creep process but also allow predicting the behavior of not initially considered values.

From the [7] literary source it is known that amorphous samples creep strain is a non-homogeneous process; and this fact can indicate the absence of Newtonian flow in the creep process. This fact

permits performing a check to prove practicality of the (1) equation by means of alternative proof of Newtonian flow absence in the amorphous alloys structure at variable temperature field effect.

The calculation was performed in accordance with the assumption of pure shift presence in the creep process. This hypothesis is put forward in the [6] work. It is known that viscosity of Newtonian and non-Newtonian liquids differs in functional view [8]. This condition permits viscosity function applicability assessing in order to investigate internal processes proceeding in the alloys being under consideration in the present work.

According to the classic approach, Newtonian liquid viscosity with the presence of internal friction can be derived from the following equation:

$$\eta = \frac{\tau}{\dot{\gamma}} \tag{5}$$

η is laminar flow viscosity, τ is shearing mechanical stress, $\dot{\gamma}$ is sample's relative strain rate.

If the (5) equation is not satisfied then the alloys under consideration cannot be considered Newtonian substances. As the creep process investigated by the present work methods is a thermally-activated one, then the strain rate is a temperature function and, consequently, is related to viscosity; and this is an infeasible condition for Newtonian flow presence [8].

The (5) viscosity is merely a temperature function and cannot be calculated according to the creep test data due to curve slope continuous changing of the $\tau(\dot{\gamma})$ function graph; this function should be a straight line with a fixed slope of curve.

However, creep process special features assume the presence of pseudoplastic or thixotropic flow in the samples under consideration. Such assumptions being true, creep strain can proceed according to the power rheology law of pseudoplastic flow:

$$\tau(\dot{\gamma}) = \mu \cdot (\dot{\gamma})^n \tag{6}$$

where μ is a value of alloy consistency related with viscosity by direct dependence.

Non-Newtonian viscosity of the pseudoplastic flow can be found out in the form of the following equation:

$$\eta = \mu \cdot (\dot{\gamma})^{n-1} \tag{7}$$

as a temperature function decreasing in the process of creep strain. In case of thixotropic flow presence shear load should simultaneously depend on strain durability and rate (as a function of two variables); however, material viscosity at thixotropic strain cannot be explicitly found due to complex dependence between basic rheological values. For purposes of the above-made assumptions analytical checking direct substitutions of the derived function of the (1) formula, were performed in the (5) and (6) equations, the derived function being in relative, dimensionless form, by means of the following additional constraint equation:

$$\varepsilon = \frac{x - x_0}{x_0} \tag{8}$$

and τ value increment was found out separately (the increment was obtained from the shearing flow equation). On account of shear stress determination

$$\tau = \frac{F}{A} \tag{9}$$

the sample shearing flow area was found, where A is a function of elongation and mean value of the $\bar{a}$ thickness (taking into account bands through-thickness rupture in the process of creep):

$$A = \bar{a}x_0. \tag{10}$$

As a result, in accordance with the equation of pure shift (taking into account the presence of the G shear modulus at strain) the dependence of the following form was obtained:

$$\tau = \frac{F}{A} = G \cdot arctg(\frac{\Delta x}{x_0}) ; \qquad (11)$$

The dependence can be transformed into the following form through substitution of $\Delta x = (x - x_0)$ for ε:

$$\tau = G \cdot arctg(\varepsilon) ; \qquad (12)$$

Taking into account (1) creep function preservation at differentiation the recurrence relationship between elongation and the rate of bands relative elongation was found:

$$\varepsilon = \sqrt{\frac{C\dot{\gamma}}{x_0} - \frac{C}{Bx_0}} \qquad (13)$$

By way of substitution of the (13) in the (12) a final condition of non-Newtonian flow of amorphous metal bands was obtained:

$$\tau(\dot{\gamma}) = G \cdot arctg(\sqrt{\frac{C\dot{\gamma}}{x_0} - \frac{C}{Bx_0}}) . \qquad (14)$$

The above equation can be transformed into the following form:

$$\tau(\dot{\gamma}) \approx G \cdot (\sqrt{\frac{C\dot{\gamma}}{x_0}} - \frac{C}{Bx_0}) \qquad (15)$$

under condition of small shearing angles presence.

From the (14) equation it is evident that the dependence of mechanical shearing creep stress on relative elongation rate is of nonlinear character and cannot be transformed into the (5) form; the dependence also do not have the $\tau(\dot{\gamma}, t)$ form due to the possibility of the time component elimination from the (13) equation.

However, the (14) equation shows the evident presence of material pseudoplastic behavior; consequently, viscosity can be found from the (7) equation at small strains:

$$\eta(T) \approx G \cdot (B - \frac{T - T_0}{V}) \qquad (16)$$

From the strength of materials course it is known that the G value is numerically equal to shear load at reference strain value, at the load of the following form:

$$. \tau = \frac{F}{A} = \frac{mg}{\bar{a}x_0} = \frac{mg}{\bar{a}\Delta x} \Leftrightarrow x = 2x_0 \qquad (17)$$

This permits numerical assessment of test samples viscosity value at room temperatures as follows:

$$\eta(T) \approx \frac{mg}{\bar{a}\Delta x} \cdot (B - \frac{T - T_0}{V}) \approx 10^{11} Pa \cdot s \qquad (18)$$

The obtained viscosity value coincides with the value measured according to other methods.

Thus the (14) equation analytically proves the absence of Newtonian and thixotropic flows within the temperature interval up to crystallization temperature values in the conditions of thermally-activated creep of amorphous alloys.

Similar arguments can also be given for a noncrystalline alloy at initial stages of strain when intercrystalline amorphous structure retains its phase. The rheological approach as a whole can take place only at the preservation of cross-section area value of the quantity and small strains.

System passing through the crystallization temperature threshold, the alloys creep more and more corresponds to metals creep curve and, consequently, the suggested (1) dependence permits deducing a single analytic expression from metal glass phase transition into metal state.

4. Conclusions

The obtained dependence of creep rate in a variable temperature field can be used for an analytical investigation of the given type of strain within the framework of various models; assuming description of phase transition through crystallization temperature.

Acknowledgements

References

[1]   Strombom J , Henderson P, Savage S 1992 *Script.Met.et Mat.* **27** 1179-1184
[2]   Kozikowski P et al. 2012 *Script.Mat.* **67** 763-766
[3]   Tsao S, Spaepen F 1985 *Acta Metall.* **33** 891-895
[4]   Granato A 1992 *Phys. Rew. Lett.* **68** 974-977
[5]   Vlasák G, Švec P, Duhaj P 2001 *Mat. Sci. and Eng.* A. **304** 472-475
[6]   Luborsky F 1983 *Amorphous metallic alloys* (*London: Butterworths*) p 543
[7]   Wilkinson W 1960 *Non-newtonian fluids* (*London: Pergamon Press*) p 17-63