Materials Physics and Mechanics 38 (2018) 69-75 Received: March 16, 2018

ON ANISOTROPY OF MECHANICAL PROPERTIES OF ALUMINUM ALLOYS UNDER HIGH TEMPERATURE DEFORMATION

G.E. Kodzhaspirov[1], D.A. Kitaeva[1*], Sh.T. Pazylov[2], Ya.I. Rudaev[2]

[1]Peter the Great St.Petersburg Polytechnic University, Polytechnicheskaya st. 29, 195251, St.Petersburg, Russia

[2]Kyrgyz-Russian Slavic University, Kiev st. 44, 720000, Bishkek, Kyrgyz Republic

*e-mail: dkitaeva@mail.ru

Abstract. The anisotropy factor assessment under various parameters of thermomechanical loading is estimated by the example of experimental studying deformation and structural parameters of anisotropic Al alloy 1561. It is found that the smallest value of the anisotropy factor corresponds to the formation of equiaxed fine-grained structure formed in the temperature-rate conditions of superplasticity.

Keywords: anisotropy factor; dynamic superplasticity; aluminum alloys; phase transformations.

1. Introduction

The anisotropy of mechanical properties is inherent to the majority of structural materials. It is known [1] that anisotropy assessment based on the ratio of cross- and longitudinal specimens properties of sheets is insufficient. However, as experimental creation of spatial charts of deformation is labor-consuming, the attempt to find theoretical calculation methods with the limited number of experimental data is seems to be reasonable.

The effect of technological and structural factors on the anisotropy of mechanical properties of metals is discussed in [2]. Accounting and targeted using of anisotropy promotes the effective utilization of structural metals. It is quite justified to consider the desire in different ways to reduce anisotropy, including thermomechanical and other processing methods. The last ones include methods based on the possibility of implementing superplasticity of the dynamic type [3, 4].

In experimental and theoretical studies related to the problem associated with superplasticity, it should be noted the interdependence of mechanical behavior and the current structural state of the material. Superplasticity will be defined [3] as a special state of polycrystalline material which is plastically deformed at low stress with preservation of the fine-grained structure (structural plasticity) obtained at the preliminary stage or formed during heating and deformation (dynamic superplasticity).

It should be noted that for both types of superplasticity, the prevalence of the mechanism of grain boundary slipping over other forms of mass transfer is supposed to be considered common [5]. Therefore, to realize the superplasticity of dynamic type, the initial structural state of the material must be replaced with another one ready for superplasticity. Such changes are due to coherent superposition of the strain rate and structural (phase) transitions of the evolutionary type in open nonequilibrium systems [6, 7]. The nature of these transformations, of course, depends on the characteristics of the boundary structural states.

http://dx.doi.org/10.18720/MPM.3812018_10

2. The peculiarities of temperature-rate deformation of aluminum alloys

We will focus on the results of an experimental study of high-temperature deformation regularities in the wide strain rate ranges, including thermomechanical regimes of superplasticity of industrial aluminum alloys.

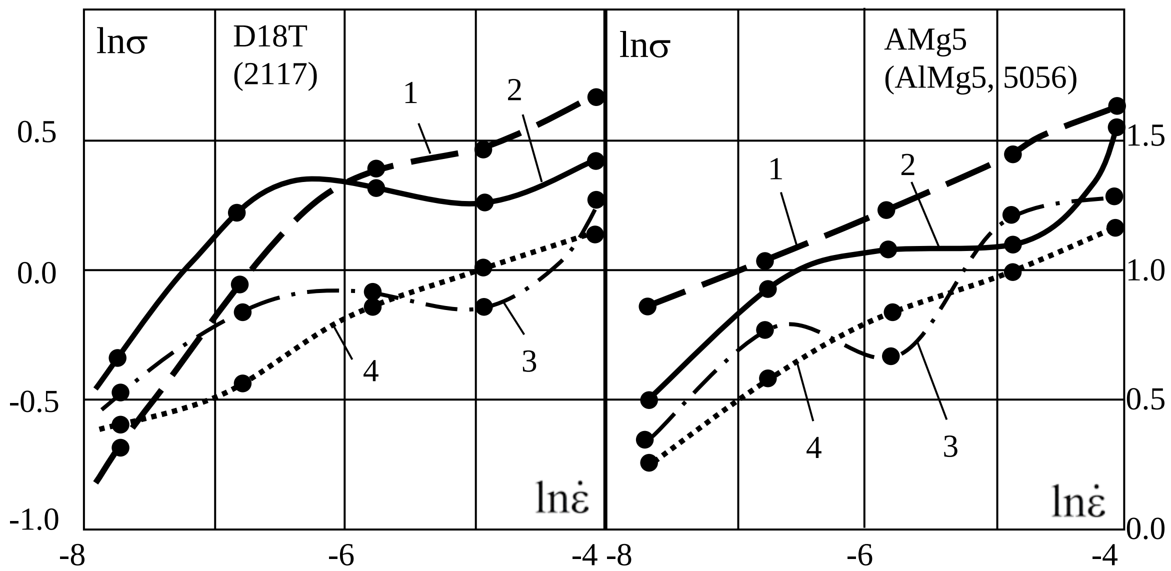
The state of deformed alloys is studied taking into account changes in temperatures and strain rates in the form of

$$\sigma = \sigma\left(\dot{\varepsilon}, \overline{\varepsilon}, \theta\right), \quad (1)$$

where σ – true stress; θ – temperature; $\overline{\varepsilon}$ – strain; $\dot{\varepsilon}$ – a strain rate.

The experimental procedure, recording and measuring equipment, the results of experiments and the method of statistical processing of experimental data are described in [3]. Testing of tensile experiments it were limited by the deformation of “Gagarin-type” specimens.

In Fig. 1 presented the dependence of the dimensionless flow stress $\sigma / \sigma_э$ versus the dimensionless strain rate $\dot{\varepsilon} / \dot{\varepsilon}_э$ for the deformed AMg5 and D18T alloys at a constant of strain degree $\overline{\varepsilon} = \ln\left(1+\varepsilon\right) = 0.427$ ($\sigma_э = 10\ \text{MPa}$; $\dot{\varepsilon}_э = 1\,\text{s}^{-1}$; ε – relative strain at the tensile).



a) b)

Fig. 1. Stress versus strain rate for $\overline{\varepsilon} = 0.427$ and various temperatures:
a – D18T (2117) alloy (1 – $\theta = 793\,\text{K}$; 2 – $\theta = 813\,\text{K}$; 3 – $\theta = 833\,\text{K}$; 4 – $\theta = 853\,\text{K}$);
b – AMg5 (AlMg5, 5056) alloy (1 – $\theta = 713\,\text{K}$; 2 – $\theta = 733\,\text{K}$; 3 – $\theta = 773\,\text{K}$;
4 – $\theta = 753\,\text{K}$).

For aluminum alloys it can sets off the class of isotherms, where the ambiguous dependence stress-strain rate takes place (Fig. 1). The falling branches of the obtained dependences correspond to the manifestation of superplastic properties [3]. The obtained experimental data allow to determine the interval of superplasticity temperatures for alloy AMg5 $\theta = 743...773\,\text{K}$, for D18T $\theta = 783...823\,\text{K}$ [3]. The characteristic features of superplasticity are observed in the mentioned above ranges: low stress level, high strain capacity (up to 250%) under tensile. It is known that in aluminum alloys during heating and deformation there is only one type of structural transformation – dynamic recrystallization, first revealed in compression experiments [8], and then tensile [9,10]. The structural changes occurring during dynamic recrystallization consist in the appearance of an equiaxial microstructure with very small grains in transient regimes, the sizes of which (1...10 microns) are approximately equal. to the sizes of sub-grains. The effects on grain boundaries described in [11] and the formation of fine-grained structure make it possible to predict the appearance of a structure that contributes to the manifestation of superplasticity. In this case, sliding between grains is observed [5]. This mechanism is not determined by the initial structural state (cast or deformed), but it is partly due to the proper stress-strain state scheme. For example, in 1561 cast aluminum alloy [12], superplastic properties are manifested only under compression conditions because fracture of the specimen at the tensile test occurs before dynamic recrystallization. Consequently, the transition of aluminum alloys to the superplastic state depend not only the chemical composition and the thermomechanical history of the process, but also on the conditions of formation of the initial structure [5].

3. Experimental results and discussion

We will consider the results of the deformed alloy 1561 sheet samples study with thickness of 10^{-2} m produced by multi-stage longitudinal rolling according to the conventional technology [13]. The circular section samples for tensile test were cut in longitudinal direction. The chemical composition of the alloy was the following: 5.88%Mg; 1.03%Mn; 0,16%Zr; 0,12%Si; 0,08% Fe; 92,73%. Al. The tensile tests were carried out at $\theta = 533...773\,\mathrm{K}$ and speed: $V_3 = 0.36 \cdot 10^{-3}\,\mathrm{m/s}$; $V_4 = 0.15 \cdot 10^{-3}\,\mathrm{m/s}$; $V_5 = 0.056 \cdot 10^{-3}\,\mathrm{m/s}$; $V_6 = 0.023 \cdot 10^{-3}\,\mathrm{m/s}$; $V_7 = 0.008 \cdot 10^{-3}\,\mathrm{m/s}$.

The tests of 1561 alloy [3] at high strain rates (to 240%) revealed no signs of strain-rate softening (Fig. 1). It is supposed that this is due to the formation at the initial stage of a with an elongated grain oriented in the rolling direction. The peculiarities of the initial structure caused the manifestation of plastic deformation anisotropy in mutually perpendicular transverse directions of the tensile specimen, causing a loss of stability of the cross-section shape. To evaluate the plastic deformation anisotropy it was proposed an anisotropy coefficient [14-17] or its analogue – the coefficient of normal plastic anisotropy [18], which is the ratio of deformations measured by small (ε'') and large (ε') axes of an ellipse cross-section:

$$\psi = \varepsilon'' / \varepsilon', \ \psi \geq 1. \tag{2}$$

Figure 2 presents the experimental dependence $\psi \sim \varepsilon'$ at the temperature 693 K at the various speeds of movement of the grips V_n of the testing machine (n is the speed at the transmission). It can be seen from the graphs that the ψ decreases with increasing strain ε'. In this case, it is possible to note the tendency to approach curves $\psi \sim \varepsilon'$ with increasing strain, and the minimum values ψ correspond to low strain rates.

In Fig. 3 the data of the effect of the strain rate on the value of the parameter in the form of isotherms at strain degrees 0.083 (Fig. 3a) and 0.4166 (Fig. 3b) are presented. From the presented graphic dependences we will pay attention to the temperature range 743...783 K, in which the effect of superplasticity of the alloy 1561 is realized [3]. Isotherms 4 and 5 correspond to the specified range. Note that curve 4 on Fig. 3a and curve 5 on Fig. 3b is close to horizontal at all strain rates [14-17]. Of particular interest are the experimental dependences of the anisotropy coefficient on temperature at different values of strain rate and strain (Fig. 4). The analysis of the experimental data (Fig. 2-Fig. 4) shows that the coefficient of anisotropy depends significantly on the thermo-mechanical process conditions. Thus, in the vicinity of temperature at all values of the deformation speed there is a local increase in the coefficient (Fig. 4). As this takes place the decrease in the maximum values corresponds to an increase in the strain speed. Note that as the strain degree increases, the influence of strain speed on the anisotropy coefficient (Fig. 4) is decreases. The established in [3] effect is observed at temperatures preceding the values corresponding to the metastable state.

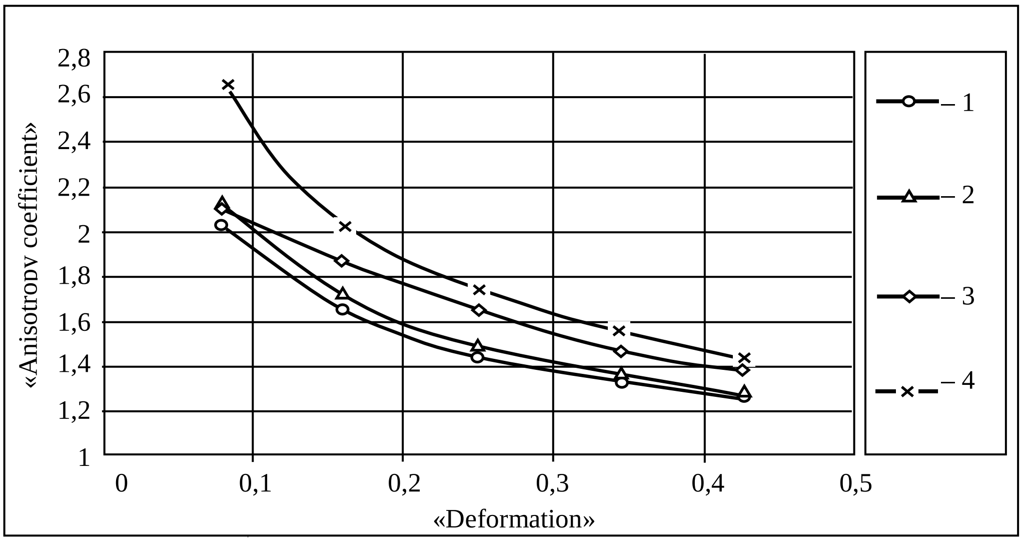


Fig. 2. Anisotropy coefficient ψ versus deformation ε' for temperature 693 K and strain rates: 1 – $V_3 = 0.36 \cdot 10^{-3}$ m / s ; 2 – $V_4 = 0.15 \cdot 10^{-3}$ m / s ; 3 – $V_5 = 0.056 \cdot 10^{-3}$ m / s ; 4 – $V_6 = 0.023 \cdot 10^{-3}$ m / s .

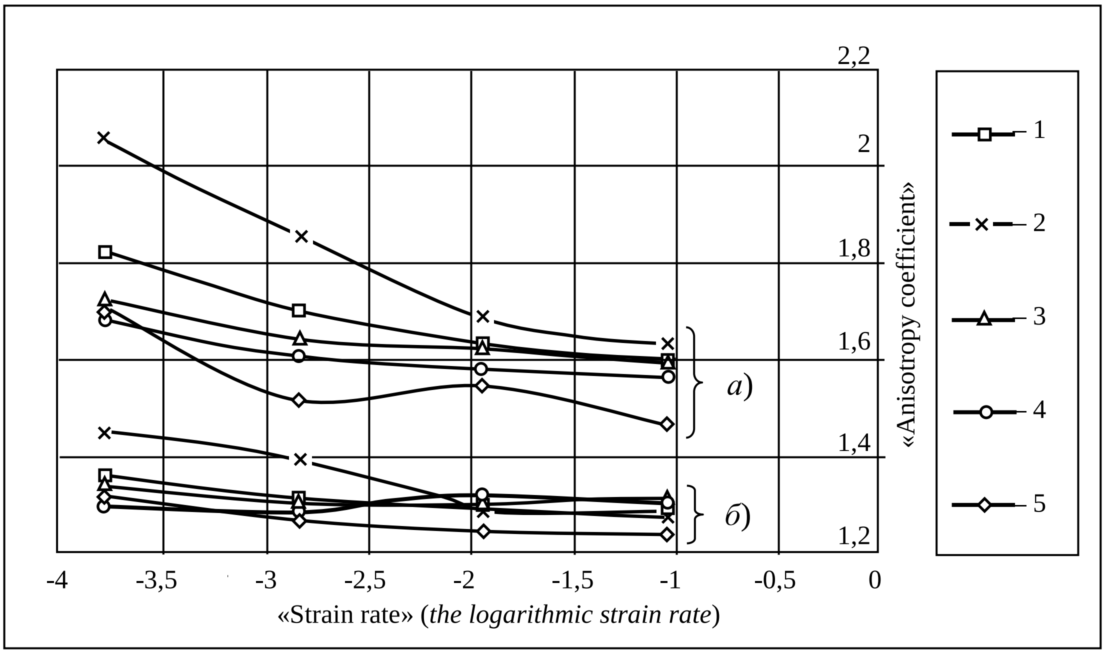


Fig. 3. Anisotropy factor ψ versus strain rate ($\psi \sim \ln V$) for deformation: a) $\varepsilon' = 0.083$ и b) $\varepsilon' = 0.4166$.
Curves 1…5 correspond temperatures: 1 – 653 K; 2 – 693 K; 3 – 733 K; 4 – 753 K; 5 – 773 K.

At high temperatures ($\theta > 723$ K) it is possible to allocate an interval 753...773 K in which superplasticity is realized. In this range the anisotropy is minimal, their importance in various strain rates are close, and at high strain degrees (Fig. 4) almost identical. This suggests that minimal values of the anisotropy coefficient ψ the superplasticity regimes are take place.

A similar result was obtained in [5], with the reduction of the coefficient due to superplastic deformation.

In [19, 20] it was found the correspondence between the results of mechanical experiments and the results of structural state study of the alloy 1561. It should be reminded that the experiments were carried out on samples made of 10^{-2} m thick sheet produced by multistage longitudinal rolling at the above values of temperature, speed and strain degree, including the values corresponding to the initial non-deformed state.

As was mentioned in [5], the formation of fine-grained structure is a prerequisite for the implementation of the slipping mechanism along grain boundaries, typical for superplasticity effect. The formation of fine-grained equiaxial structure during superplastic deformation of alloy 1561 contributed to practically isotropic deformation in mutually perpendicular directions in cross-sections of samples (anisotropy coefficient $\psi \approx 1.25$).

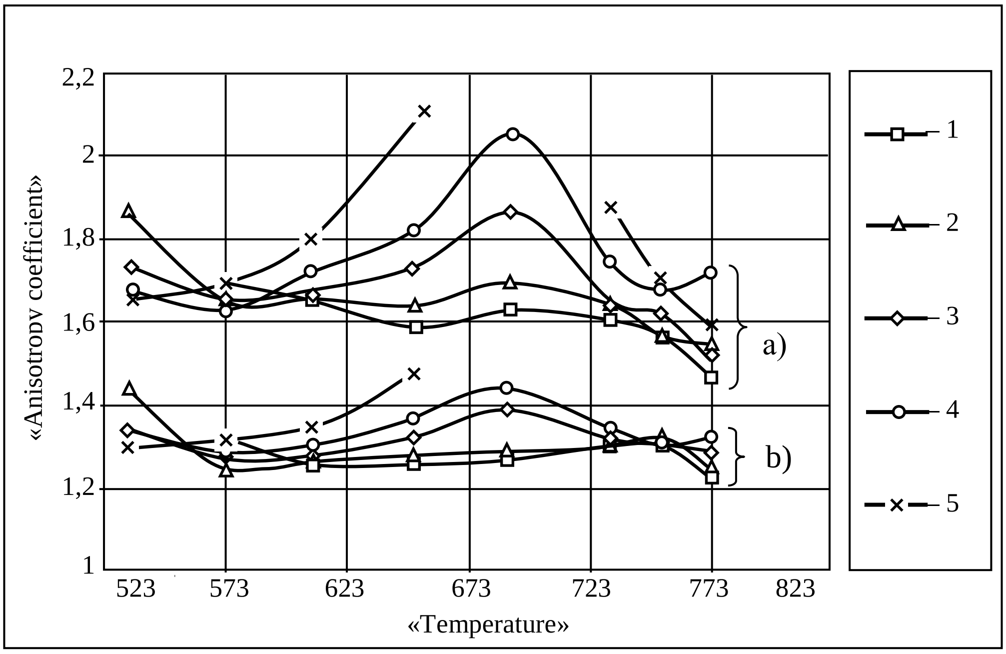


Fig. 4. Anisotropy coefficient ψ versus temperature ($\psi \sim \theta$) for deformation: a) $\varepsilon' = 0.083$ и b) $\varepsilon' = 0.4166$; and strain rates: 1 – $V_3 = 0.36 \cdot 10^{-3} \mathrm{m/s}$; 2 – $V_4 = 0.143 \cdot 10^{-3} \mathrm{m/s}$; 3 – $V_5 = 0.057 \cdot 10^{-3} \mathrm{m/s}$; 4 – $V_6 = 0.023 \cdot 10^{-3} \mathrm{m/s}$; 5 – $V_7 = 0.009 \cdot 10^{-3} \mathrm{m/s}$.

In [4, 13] an attempt was made to optimize the temperature-strain rate at rolling parameters of hot-rolled sheets of initially cast aluminum alloy 1561 based on the experiment data on superplasticity in axial compression [12]. The necessity of possible approximation of strain rate to the ones corresponding to the real rolling process was taken into account.

It was supposed that the optimal combination of power and kinematic parameters should arise the formation of the most favorable structure in the metal produced, approaching the structure of fine-grained, and as a result-to the most rational combination of strength and deformation characteristics, and, consequently, to a minimum anisotropy of mechanical properties. As a result of rolling in conditions of superplasticity the data confirming formation of structure close to fine-grained (7-12 microns) has been received. This is also evidenced by the data of mechanical tests of "Gagarin's" samples cut from the sheet in the longitudinal and transverse directions given in Table 1 [16].

Table 1. The average values of mechanical characteristics of alloy 1561 produced by rolling in the superplasticity regimes.

Direction	YS, MPa	TS, MPa	A, %
Longitudinal	164	350	21,6
Transverse	168	330	15,3

Note: YS – yield strength; TS – tensile strength; A – the maximum elongation

The data obtained result in the rolling of cast alloy 1561 are indirectly confirmed by the data of analytical solution of two-dimensional isothermal boundary (including the regimes of superplasticity) of the sheet rolling task at a small angle of tip with the assessment of the effect of high homological temperatures on the roll force [21-23]. The power and kinematic parameters of the process were established using the dynamic model [3, 7], which adequately reflects the experimental data obtained on the industrial aluminum alloys (Fig. 1). The founded solution allows to select and mathematically limit the area of superplasticity in the zone of deformation. Thus, it is possible to control the grain size in the process of heating and deformation and predict the production of parts and semi-finished products with a high-quality structure close to fine-grained. Naturally, the formation in temperature-strain rate conditions of superplasticity condition meet the minimum values of rolling force.

6. Conclusions

It is found that the anisotropy coefficient depends on the alloy structure. Deformation under conditions of superplasticity is one of the thermo-mechanical ways to reduce structural and deformation anisotropy of material. The anisotropy coefficient can be considered as one of the macroparameters of the material that characterizes the ongoing structural transformations and allows to estimate the degree and completeness of structural changes relative to the initial state in the changing field of temperatures and strain rates.

Thus, the study of the effect of thermo-mechanical conditions of deformation on the behavior of the anisotropy coefficient and the change in the structure of the alloy allows, for example, to select the proper rolling regimes apply to the sheets subjected to pneumatic and gas forming.

Acknowledgements. *The research was carried out within the state assignment 11.12832.2018/8.9.*

References

[1] P.G. Miklyaev, Ya.B. Fridman, *Anisotropy of mechanical properties of metals* (Metallurgiya, Moscow, 1986).
[2] R.A. Adamesku, P.V. Geld, E.A. Mityushov, *Anisotropy of physical properties of metals* (Metallurgiya, Moscow, 1986).
[3] A.I. Rudskoy, Ya.I. Rudaev, *Mechanics of dynamic superplasticity of aluminum alloys* (Nauka, St.Petersburg, 2009).
[4] V.I Kuneev, Sh.T. Pazylov, Ya.I. Rudaev, D.I. Chashnikov // *Journal of Machinery Manufacture and Reliability* **6** (2002) 55.
[5] O.A. Kaibyshev, *Superplasticity of commercial alloys* (Metallurgiya, Moscow, 1984).
[6] A.I. Olemskoy, A.A. Katcnelson, *Synergetics of condensed media* (KomKniga (URRS), Moscow, 2003).

[7] D.A. Kitaeva, Ya.I. Rudaev // *St.Petersburg State Polytechnical University Journal* **4–1(183)** (2013) 274.
[8] Yu.M. Vainblat, N.A. Sharshagin // *Non-ferrous metals* **2** (1984) 67.
[9] Sh.T. Pazylov, V.A. Panyaev, In: *Strength of materials and constructions* (Frunze Polytechnical Institut, Frunze, 1987), p.87.
[10] Yu.S. Zolotorevskii, V.A. Panyaev, Ya.I. Rudaev et al. // *Ship-building industry. Series materials science* **16** (1990) 21.
[11] O.A. Kaibyshev, R.Z. Valiev, *Grain Boundaries and Properties of Metals* (Metallurgiya, Moscow, 1987).
[12] N.V. Zhdanov, V.A. Panyaev, Ya.I. Rudaev, D.I. Chashnikov // *Ship-building industry. Series materials science* **15** (1990) 45.
[13] N.H. Barakhtina, Yu.S. Zolotorevskii, Ya.I. Rudaev et al. // *The Problems of Materials Science* **19/20** (1992) 72.
[14] Sh.T. Pazylov, N.A. Omorov, Ya.I. Rudaev // *Tambov University Reports. Series Natural and Technical Sciences* **15(3)** (2010) 974.
[15] Sh.T. Pazylov, N.A. Omorov, A.K. Arzimatov // *Vestnik Kyrgyz-Russian Slavic University* **10** (2010) 144.
[16] D.A. Kitaeva, Sh.T. Pazylov, Ya.I. Rudaev // *Journal of Applied Mechanics and Technical Physics* **57(2)** (2016) 352.
[17] D.A. Kitaeva, Ya.I. Rudaev, Sh.T. Pazylov, G.E. Kodzhaspirov, In: *Proceedings of the 14th International Conference on Creep and Fracture of Engineering Materials and Structures (Creep2017)* (Publishing House of Polytechnical University, St.Petersburg, 2017), p.74.
[18] R.A. Adamesku, E.A. Mityushov, L.L. Mityushova, M.V. Frolova // *Metally* **1** (1990) 173.
[19] Sh.T. Pazylov // *Vestnik Kyrgyz-Russian Slavic University* **5** (2015) 116.
[20] D. Kitaeva, G. Kodzhaspirov, Y. Rudaev, In: *Proceedings of the 25th Anniversary International Conference on Metallurgy and Materials (METAL 2016)* (Tanger, Brno, 2016), p.1426.
[21] G.E. Kodzhaspirov, D.A. Kitaeva, Ya.I. Rudaev, E.A. Subbotina // *Materials Physics and Mechanics* **25(1)** (2016) 49.
[22] E. Sorochan, V. Artiukh, B. Melnikov, T. Raimberdiyev // *MATEC Web of Conferences* **73** (2016) 04009.
[23] A. Hirkovskis, D. Serdjuks, V. Goremikins, L. Pakrastins, N.I. Vatin // *Magazine of Civil Engineering* **57(5)** (2015) 86.