Deformation Behavior of 7475 Aluminum Alloy at High Temperatures

R. Kaibyshev[1], O. Sitdikov[1], A. Goloborodko[1] and T. Sakai[2]

[1] Institute for Metals Superplasticity Problems, Khalturina 39, Ufa RU-450001, Russia

[2] Department of Mechanical and Control Engineering, The University of Electro-Communications, Chofu, Tokyo 182-8585, Japan

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Abstract

Deformation behavior of the 7475 aluminum alloy was studied in temperature range T=623-793K by compression test. It has been shown that the 7475 alloy exhibits a threshold behavior. Analysis in terms of threshold stress has shown that there are two characteristic modes of deformation behavior in the power-law regime in the examined temperature range. At normalized strain rate $\dot{\varepsilon}RT/D_lGb \leq 1.6\cdot10^{-3}$ mol^{-1} the value of the stress exponent, n, is equal 4, and at normalized strain rate $\dot{\varepsilon}RT/D_lGb \geq 1.6\cdot10^{-3}$ mol^{-1} the value of the stress exponent, n, is equal 6. Value of activation energy is close to that for lattice self-diffusion in pure aluminum at temperatures above 763K and close to the value of pipe diffusion at T≤723K. Deformation behavior of the 7475 alloy was interpreted in terms of transition from low temperature climb to high temperature one. Two types of temperature dependence of threshold stress was observed in the examined temperature region. Strong temperature dependence with the energy term, Q_o=130 kJ/mol was revealed at T=743-793K. At T=673-743K the dependence with Q_o= 42 kJ/mol was found. The role of second phase dissolution in threshold behavior of the alloy is considered.

1 Introduction

Deformation behavior of high strength 7XXX Al-alloys was extensively studied in the past in the low temperature range where precipitations of η-phase on aging take place and the high creep resistance of these alloys is caused by the interaction between fine particles and dislocations. By contrast, no investigation has yet been conducted to study the deformation behavior of Al-Zn-Mg alloys with coarse grain structure in high temperature range where dissolution of reinforced phase occurs and a transition in the mechanisms controlling the plastic deformation is expected. Numerous authors [1,2,3] paid a great attention to examination of superplasticity in these aluminum alloys with fine grain structure at high temperatures.

The purpose of this paper is two-fold. Firstly, to report the data of a detailed examination of deformation behavior of modified 7475 aluminum alloy with Zr additives over a wide temperature range. Secondly, careful inspection of these experimental data will be perform to reveal the role of secondary phases in deformation behavior of the alloy and to examine the operating deformation mechanisms.

2 Experimental procedure

The modified 7475 aluminum alloy was used in the present study. The chemical composition (in wt%) of the alloy is 6.4%Zn, 2.46%Mg, 1.77%Cu, 0.23%Cr, 0.16%Zr, 0.03%Si, 0.04%Fe, 0.03%Mn and the balance is Al. The alloy was initially produced by semicontinuous casting by Kaiser Aluminum and was homogenized at 768K for 20h. Initial microstructure of alloy consisted of lamella type grains with size 1 - 10 mm in longitudinal direction and about 50 - 100 μm in transverse direction and bands of essentially equiaxed grains with size from 50 to 100 μm. Both bands and lamellas were located in parallel to the ingot axes. Compression specimens of a diameter 10 mm and a height 12 mm were machined from the ingot. Compression tests were conducted in air at temperatures between 673 K and 793 K at various strain rates from 10^{-5} to 10^{-2} s^{-1} using a screw-driven Schenck machine. In addition, strain rate change tests were performed. The deformation relief was investigated using a JSM-840 SEM. The thin foils were examined with a JEOL-2000EX TEM utilizing a double-tilt stage. Samples for SEM and TEM observation were electropolished in a solution of 30% HNO_3 and 70% methanol at 25V and 243K. Samples for surface observation at high temperatures were plated by platinum. The threshold stress and creep parameters were determined by methods described in detail in [4-10]. Note that the deformation behavior of material was analyzed only in the stable stage (ss) of plastic flow, when $\sigma_{ss}(\varepsilon)$=const. In this case, the deformation under active loading can be treated in the same way as creep [4].

3 Experimental results

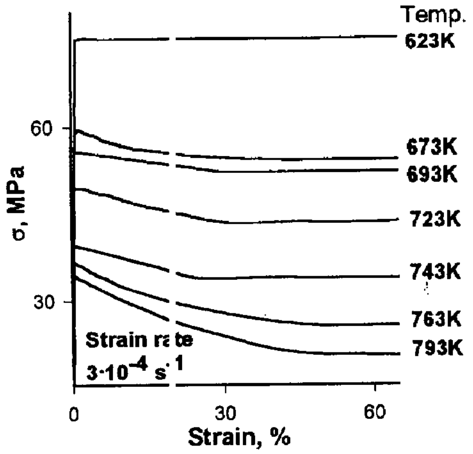
3.1 Deformation behavior of 7475 Al alloy

Flow stresses. The typical true stress-strain curves in the temperature range from 623 K to 793 K and strain rates from 10^{-5} s^{-1} to 10^{-2} s^{-1} are presented in Fig.1. Two different temperature regions distinguished by a shape of curves are revealed. At T=763-793K and $\varepsilon=10^{-5}$-10^{-4} s^{-1} the peak stress is observed in the initial stage of plastic deformation (ε_{peak}=2-4%). During subsequent deformation a gradual softening takes place. A decrease in flow stress by at least one and half times is observed after ε_{ss}=40 50%. At lower temperatures (T=673K-723K) the minor peak stress was revealed. The stable stage of plastic flow is reached after strains ε_{ss}=15-25% and values ε_{ss} are diminished with decreasing temperature in this region. Note, that further temperature decrease leads to peak stress disappearance and the stable stage of plastic flow is attained after ε= 3-5%.

The analyze of the effect of the strain rate $\dot{\varepsilon}_{ss}$ and temperature on the flow stress σ_{ss} in the stable stage was performed by the σ-$\dot{\varepsilon}$ plot drown on double logarithmic scale (Fig. 2). It is seen that in both revealed temperature intervals the σ-$\dot{\varepsilon}$ dependence obeys the power law [5-7]:

$$\dot{\varepsilon} = A_1 \cdot \left(\frac{\sigma}{G}\right)^{n_a} \cdot \exp\left(-\frac{Q_a}{RT}\right) \quad (1)$$

where $\dot{\varepsilon}$ is the strain rate, σ is the flow stress, Q_a is the activation energy for plastic deformation, R is the gas constant per mole and T is the absolute temperature. A and n_a are coefficients. The flow stress exponent n_a=dlog($\dot{\varepsilon}$)/dlog(σ) strongly depends on temperature and increases from n_a~ 4-5 to n_a~ 7-9 with transition from the high temperature interval (T=763-793K) to the lower one (T=673-723K).



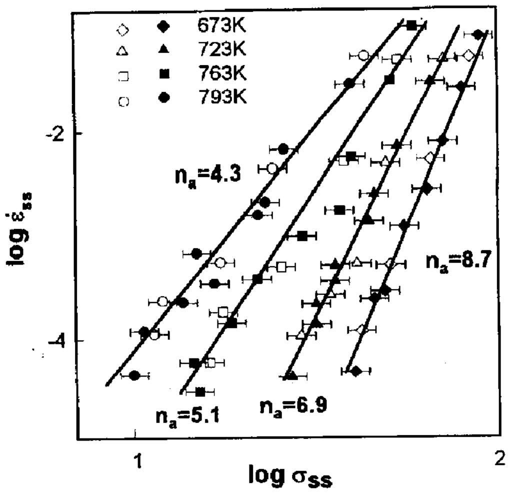


Fig. 1 (left) True stress-strain curves of the AA 7475 at various temperatures.

Fig. 2 (right) The stable state strain rate as function of the stable state stress of the AA 7475. Closed and open symbols indicate the data obtained from the strain rate change test and uninterrupted test, respectively.

Activation energy for plastic deformation. The Eq.1 was used to determine the apparent activation energy for plastic deformation by plotting the stable stage flow stresses vs the reciprocal temperatures in semi-logarithmic scale and taking the slope of tangent to be Q/Rn (Fig. 3). Two temperature intervals could be distinguished in this figure. In range T=723- 793K the slope is equal to 5.5 K^{-1} and values, Q_a, lie in interval 196-233 kJ/mol. These values of Q_a are much higher than the activation energy for lattice self-diffusion in Al (Q_l=142 kJ/mol [8]). At lower temperatures (T=673 to 723K) the slope was found about 2.1 K^{-1}, that led to Q_a=120-152 kJ/mol.

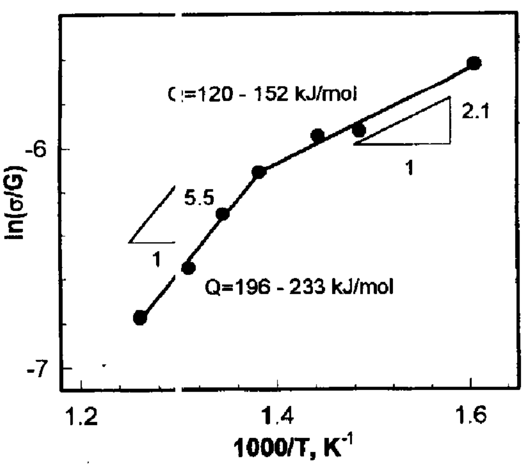


Fig. 3. Shear modulus - compensated stable state flow stress vs inverse of temperature and values of activation energy for deformation.

3.2 Deformation relief

In the temperature region T=673-723K the dislocation sliding is essentially uniform (Fig. 4a). The distribution of slip lines is largely homogeneous within the grain interior. At the same time, slip features vary from one grain to another. In some grains wavy slip lines attributed to the cross-slip are observed and straight slip features are revealed inside other grains. One operating dislocation glide system is in dominant in most grains.

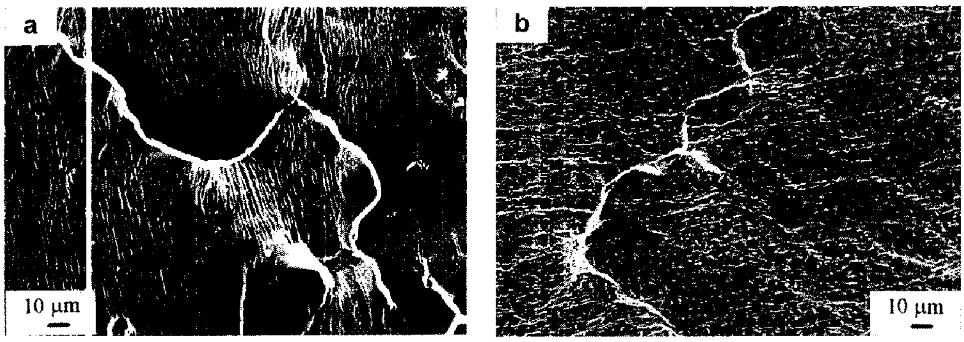


Fig. 4. Deformation relief of the AA 7475 (ε=15%, $\dot{\varepsilon}=10^{-4}$ s^{-1}): (a) T=723K, (b) T=793K.

At higher temperatures (T= 763K- 793K) the dislocation slip is non-homogeneous. The multiple cross-slip is the main deformation mechanism. Slip lines are grouped in slip bands (Fig. 4b).

3.3 TEM observations

The inspection of TEM micrographs reveals the following features and findings.

(a) Strong temperature influence on phase composition of the 7475 alloy was revealed. At T ≤ 723K two types of secondary phase particles are observed (Fig.5.a) both in grain interior and in vicinity of grain boundaries. Distribution of coarse precipitate particles with size 0.4-0.5 μm is not uniform. Clusters of these precipitations are observed in some grains. Dispersoids with size less than 0.1 μm are distributed essentially uniform. Most likely that these particles are intermetallic dispersoids of Al_3Cr and Al_3Zr phases. Temperature increase above 723 K leads to gradual dissolution of coarse precipitate particles and does not significant effect volume fraction of nanoscale particles. At T=763-793K coarse particles of the reinforcement phase does not observed.

(b) An extensive interaction between lattice dislocations and secondary phase particles is observed at all examined temperatures (Fig.5). It is seen, that the dislocations are attached to precipitate particles

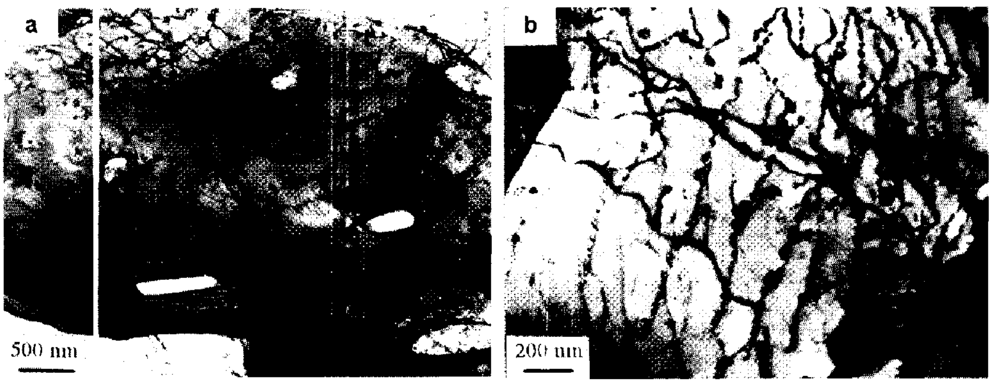


Fig. 5. TEM micrographs of the AA 7475 after deformation: (a) T=723K, $\dot{\varepsilon}=10^{-4}$ s^{-1}, ε=70%, (b) T=763K, $\dot{\varepsilon}=10^{-4}$ s^{-1}, ε=50%.

as well as to dispersoids of transition metals and tangled. Particles play a role of obstacles for dislocation glide. In some areas of grains the lattice dislocations are captured by dispersoids. At T≥763K weak interaction between lattice dislocations and dispersoids takes place. Dissolution of precipitations enhances dislocation mobility and yields more uniform dislocation distribution inside grains.

(c) Extensive occurrence of dislocation climb is evident from observation of helicoidal dislocations [11] at T≥763K (Fig. 5.b).

4 Analysis and Discussion

4.1 Analysis in terms of threshold stress

The deformation behavior of the 7475 aluminum alloy with initial coarse grain structure is very complicated and can not be interpreted in terms of the creep transition from class II (metal class) to class I (alloy class) as deformation behavior of other solid-solution aluminum alloys [4,7,9]. In contrast, the 7475 alloy demonstrates relatively high values of apparent activation energy for plastic deformation at high temperatures and there is a great gap between the stress exponents n=4.3 at T=793K and the value n=8.7 at lower temperature T=673K. It is seen from TEM observations that interaction between dislocations and dispersoids plays an important role in plastic deformation of the 7475 alloy. Threshold stress, σ_{th}, caused by the presence of secondary phase particles may exist and, consequently, deformation behavior of the 7475 Al alloy resembles that of dispersion-strengthened alloys [7,9].

As a result, the deformation is driven by the effective stress $\sigma_{eff}=\sigma-\sigma_{th}$, and not by the applied stress σ. In this case, the deformation behavior can be described by a rate equation in the form [3,6,9]:

$$\dot{\varepsilon} = A_2 \cdot \left(\frac{\sigma - \sigma_{th}}{G}\right)^n \cdot \exp\left(-\frac{Q}{RT}\right). \quad (2)$$

In examining the possibility of threshold stress in the 7475 Al alloy the data were plotted as $\dot{\varepsilon}^{1/n}$ vs σ on a double linear scale. A value of σ_{th} at each temperature was estimated by extrapolation of this plot to zero: $\sigma_{th} = \sigma\ (\dot{\varepsilon}^{1/n} \rightarrow 0)$ [6,9]. The coefficient n was chosen to obtain the $\dot{\varepsilon}^{1/n}$-σ dependence approximated linearly with the maximum regression coefficient. The results of the best linear fit between $\dot{\varepsilon}^{1/n}$ and σ at some temperatures from lower and high temperature intervals are represented in Fig. 6 a and b, respectively. It is evident that in the temperature interval from 673 to 723K the threshold stresses are relatively high. The values σ_{th} reach 30-50% from applied stresses σ_{ss}.

The temperature dependence of threshold stresses is not monotone (Fig.6c). Values σ_{th} drop sharply from 19 to 1.8 MPa with increasing temperature from 673 to 793K. At T=793K threshold stresses normalized to σ_{ss} hardly exceed 10-15% even at $\dot{\varepsilon}=10^{-5}$ s^{-1}. Such a decrease of threshold stresses cannot be accounted for by the temperature dependence of the shear modulus. As it was demonstrated for dispersion-strengthened alloys, a threshold stress can be described by the relation [3,9]:

$$\frac{\sigma_{th}}{G} = B_0 \exp\left(\frac{Q_0}{RT}\right), \quad (3)$$

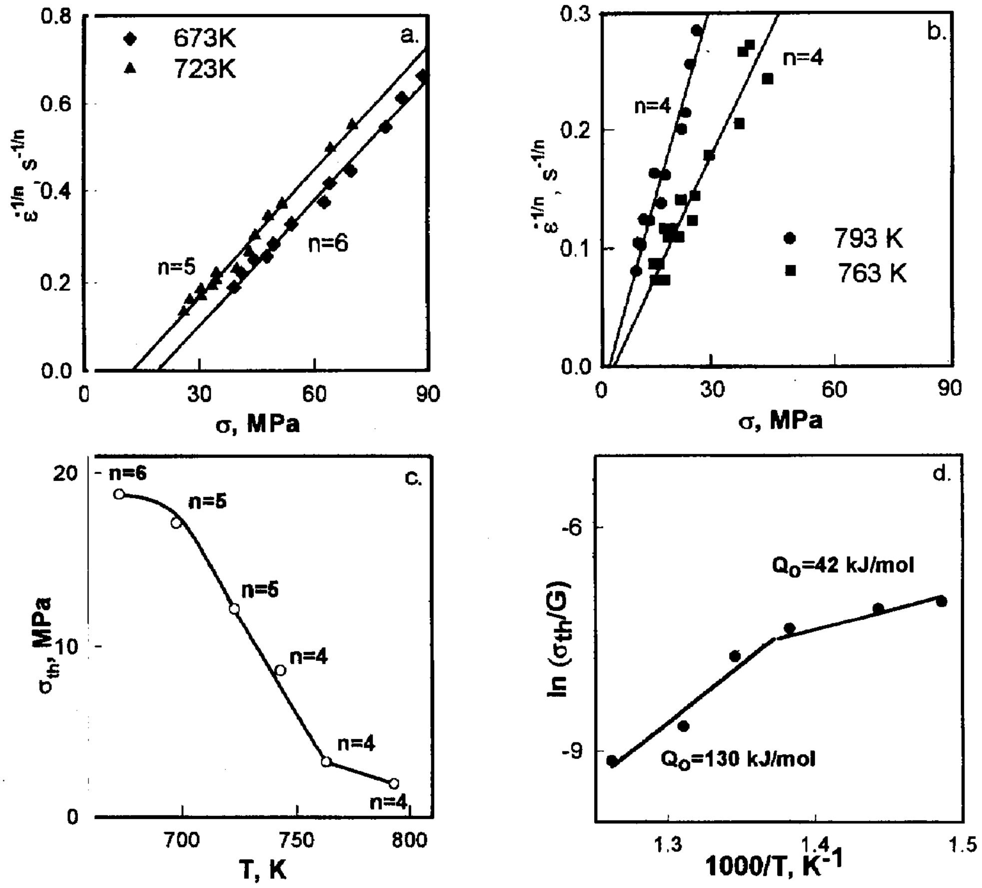


Fig. 6. (a)-(b) plot of $\dot{\varepsilon}^{1/n}$ vs σ_{ss} for determination of σ_{th} at various testing temperatures; (c) temperature dependencies of σ_{th} and n values; (d) plot of σ_{th}/G vs 1000/T showing the temperature dependence of σ_{th}.

where B_o is a constant and Q_o is an energy term. Fig. 6.d in which σ_{th}/G is plotted vs 1/T confirms the validity of Eq. 3. to the results of the present investigation. It is seen, that the strong temperature dependence with the energy term, Q_o= 130 kJ/mol is revealed at T=743-793K. At lower temperatures (T=673-743K) the weak dependence of σ_{th}/G on 1/T with Q_o=42 kJ/mol was obtained.

Also it is important to note that the coefficient n obtained from this plotting is equal to 4 in the high temperature interval and from 5 to 6 at lower temperatures (Fig. 6.a to c).

4.2 Deformation behavior

Using the datum points (Fig. 2.), Fig.7 shows a double logarithmic plot of the normalized strain rate, $\dot{\varepsilon}RT/(D_l Gb)$, against the normalized effective stress, $(\sigma-\sigma_{th})/G$. It is seen that deformation behavior of the 7475 alloy obeys the power law and almost all experimental points lie below the Sherby-Burke criterion, representing the breakdown of power law creep [4,10]. At the same time there are two

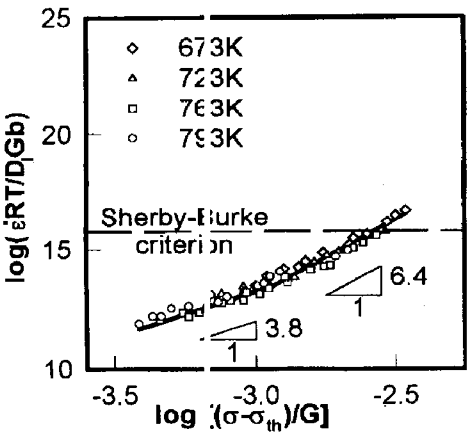


Fig. 7. Dependence of normalized strain rate on normalized effective stress.

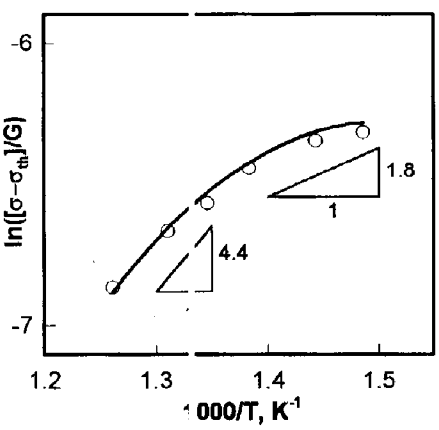
different slopes of the dependence. At normalized effective stress bellow $1.2{\cdot}10^{-3}$, there is a line with slope of n=3.8 and at higher stresses n=6.4. These values of stress exponent are closed to n=4 and n=6 which were found by calculation of threshold stresses and, consequently, it is possible to consider the region of lower temperatures where deformation behavior is controlled by pipe-diffusion with increasing stress exponent to (n+2).

Activation analysis supports this approach to description of deformation behavior of the 7475 alloy. The true activation energy was calculated according to the plot represented in Fig. 8 as 146 kJ/mol in temperature interval 763-793 K (Fig. 9).

The activation energy tends to decrease down to 76 kJ/mol with temperature reduction from 673K to 723K. Determined values of Q_c are in a very good agreement with values of activation energies of lattice self-diffusion (Q_l=142 kJ/mol) and pipe diffusion (Q_c=82 kJ/mol) in pure aluminum, respectively [8].

4.3 Interpretation of deformation behavior

Analysis of deformation behavior has shown that the 7475 alloy exhibits two characteristic modes of behavior in the power-law creep regime. First, in the temperature interval 763-793K the values of activation energy and the stress exponent are in consistent with plastic deformation controlling by high temperature climb. Processes of dislocation rearrangement occur at these temperatures, easily. Multiple dislocation cross-slip is a main deformation mechanism. The small values of threshold stresses were found in this region. In addition, the energy term Q_o =130 kJ/mol was determined as a value closed to the activation energy for lattice self-diffusion in Al. It can be explained in terms of the



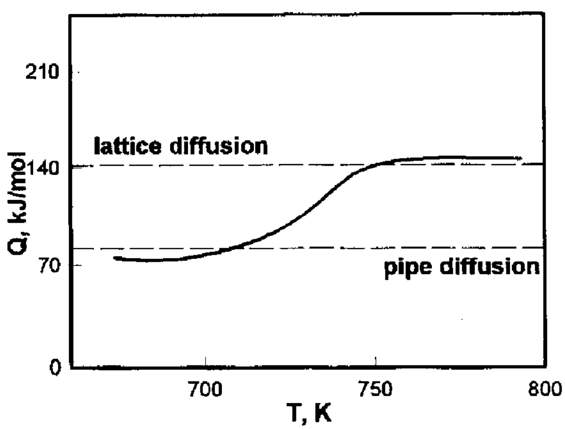


Fig. 8 (left). Shear modulus - compensated effective stress vs inverse of temperature.
Fig. 9 (right). Temperature dependence of activation energy for deformation.

small contact between a dislocation and a particle, when the dislocation overcomes the particle by a manner of general climb [3]. Second, at T=673-763K the transition from high temperature climb to low temperature one takes place with temperature decrease. It reduces dislocation mobility caused by climb. Concurrently single dislocation slip becomes in dominant and cross-slip is hampered. It decreases the ability of lattice dislocations to surmount obstacles by-pass. It is possible to presume that the change of controlling deformation mechanism is the main reason yielding strong increase of threshold stress with temperature decrease at T=673-723K. It means that the characteristics of dislocation climb influence interaction mechanism between lattice dislocations and dispersoids and determine threshold behavior of the material.

Another reason for observing strong temperature dependence of threshold stress in range T=673-763K is associated with dissolution of the secondary η-phase, since solvus of this phase is located near 723K [12]. Strong decrease of dispersoid volume fraction due to disappearance of η-phase at temperatures above the solvus temperature may give a significant contribution to the threshold stress drop.

5 Conclusions

1. The deformation behavior of the modified 7475 aluminum alloy was investigated at temperatures from 673 to 793K and could be described in terms of power law at all examined temperatures.
2. The 7475 alloy demonstrates threshold behavior. Strong temperature dependence with the energy term, Q_o=130 kJ/mol was revealed at T=743-793K. At lower temperatures (T=673-743K) the weak temperature dependence with Q_o= 42 kJ/mol was found.
3. By incorporating a threshold stress into the deformation behavior analysis, it was shown that the value of the stress exponent, n, is 6.4 at normalized effective stresses higher than $1.2\cdot10^{-3}$, and n=3.8 at lower normalized effective stresses.
4. The true activation energy for plastic deformation, Q_c, decreases from value ~146 kJ/mol at T=793K to ~76 kJ/mol at T=673K. These values match values of activation energy for lattice self-diffusion (142 kJ/mol) and pipe diffusion (82 kJ/mol) in aluminum with excellent accuracy.
5. The transition from climb controlling by lattice diffusion to climb controlling by pipe diffusion is accompanied by a change in the temperature dependence of threshold stress.

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For correspondence: Prof. R. Kaibyshev, fax: +7(3472)253856, e-mail: sitdikov@imsp.da.ru