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Superplasticity of alloy 01420T with the initial bimodal grain structure

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The temperature – strain rate conditions of high-temperature structural superplasticity are determined for the 01420T alloy with the initial bimodal structure. The structural state of specimens of alloy 01420T, superplastically deformed to failure under the conditions of high-temperature structural superplasticity, is studied. It is revealed that in the working part of specimens of the alloy 01420T during the superplastic deformation fibrous structures forms as a result of the viscous flow. They are localized in grain boundary cavities and cracks. The probable causes of partial melting of the 01420T alloy and the mechanism of its superplastic deformation are analyzed.
Keywords: superplasticity; grain boundary sliding; structural anisotropy; bimodal structure.

Д.Е. Мілая, В.П. Пойда, В.В. Брюховецький, А.В. Пойда

Для сплаву 01420Т з вихідною бімодальною структурою визначені температурно-швидкісні умови прояву високотемпературної структурної надпластичності. Вивчено структурний стан зразків сплаву 01420Т, надпластично продеформованих до руйнування в умовах високотемпературної структурної надпластичності. Виявлено, що в робочій частині зразків сплаву 01420Т при надпластичної деформації утворюються волокнисті структури в результаті в'язкого плину. Вони локалізовані в примежевих порах і тріщинах. Проаналізовано ймовірні причини часткового плавлення сплаву 01420Т і механізм його надпластичної деформації.
Ключові слова: надпластичність; зерномежеве проковзування; структурна анізотропія; бімодальна структура.

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Для сплава 01420Т с исходной бимодальной структурой определены температурно-скоростные условия проявления высокотемпературной структурной сверхпластичности. Изучено структурное состояние образцов сплава 01420Т, сверхпластично продеформированных до разрушения в условиях высокотемпературной структурной сверхпластичности. Выявлено, что в рабочей части образцов сплава 01420Т при сверхпластической деформации образуются волокнистые структуры в результате вязкого течения. Они локализованы в приграничных порах и трещинах. Проанализированы вероятные причины частичного плавления сплава 01420Т и механизм его сверхпластической деформации.
Ключевые слова: сверхпластичность; зернограничное проскальзывание; структурная анизотропия; бимодальная структура.

Introduction

It is known that semifinished products of industrial deformable aluminum alloys in the initial state have an inhomogeneous structure [1, 2]. In order for these alloys to exhibit the effect of structural superplasticity (SSP), it is necessary to perform their additional thermomechanical treatment aimed at forming a uniform ultrafine-grained structure. It takes time and additional energy costs. In this connection, it becomes necessary to determine the temperature – strain rate conditions for the development of the SSP for various deformable aluminum alloys that, in the initial state, have a non-uniform grain structure.

The results of experimental studies aimed at determining the temperature – strain rate conditions in which specimens of the 01420T alloy with the initial bimodal structure during their deformation in the creep regime at a constant flow stress show the SSP effect are considered in the article. It also contains data on the structural state of superplastically deformed specimens of this alloy and the concept of their superplastic deformation mechanisms (SPD).

Materials and methods of the experiment

Medium-durable alloy 01420T (5,0-6,0%Mg; 1,9-2,3%Li; 0,09-0,15%Zr; 0,1-0,3%Si; 0,3%Fe; 0,1%Ti; 0,3%Mn; 0,005%Na; base Al, % wt.) has strength limit σ_B = 440-470 MPa [3]. This alloy belongs to the lightest of aluminum-lithium alloys. Its structure is matrix-type. In the 01420T alloy of the Al-Mg-Li system in equilibrium with the matrix phase (α-solid solution on the aluminum base) there are such phases: β (Mg_3Al_3), γ ($Mg_{17}Al_{12}$), δ (AlLi), S_1 ($MgLiAl_2$) [3]. It is found that a stable phase S_1 is predominantly localized at the grain boundaries of the matrix phase, forming them almost continuous [3]. In the body of the matrix phase grains, in addition to the above phases, phase particles δ' (Al_3Li) are also located, which provide hardening of the alloy after artificial aging, as well as dispersed particles of β' ($ZrAl_3$). They are used for stabilization of the grain structure of aluminum alloys at high homological temperatures [1-3].

Mechanical tests of the alloy 01420T specimens with dimensions of the working part of 10 mm and cross section of *3.0-5.0 mm* were performed in air by straining in a creep mode at a constant flow stress in accordance with the procedure detailed in at [4]. The experimental creep curves recorded using a Sanwa PC 500a digital multimeter were rearranged in the coordinates "true strain" - "time" and served to determine the true strain rate $\dot{\varepsilon}_{true}$.

To detect grain boundaries during metallographic studies, a chemical etchant of the following composition was used: *17 ml* of HNO_3, *5 ml* of HF, *78 ml* of H_2O.

The grain structure, cavity morphology, and fibrous structures in the specimens were examined using a light microscope MIM-6 with a Pro-MicroScan digital camera and a scanning electron microscope Tescan VEGA 3 LMH, as well as standard quantitative metallography methods [5].

The average grain size *‹d›* was determined from microphotos by the method of random secants [5].

To reveal grain boundaries on the surface of the working part of superplastically deformed specimens of the investigated alloy, along with chemical etching, the deformation relief method was used, which was described in [4].

Results and Discussion

As a result of structural studies, it was determined that the initial grain structure of the working part of specimens of the 01420T alloy prepared for mechanical testing is bimodal (Fig.1).

The overwhelming majority of grains that are concentrated in the colony, occupying a large area in the working part of the specimens, are ultra-small. Their average size is approximately *5 μm* (Fig.1, a). In some sections of the working part of the specimens, which have the form of strips (Fig.1, b), the major oblong grains are mainly concentrated (Fig.1, c). They are separated from each other by low-angle boundaries, which are parallel or approximately perpendicular to the strain direction of the specimens. The average size of large polygonized grains is approximately *25 μm*. In the strips, there is also a certain number of equiaxial fine grains, which have high-angle boundaries. Their average size is about *12 μm*. Specimens of the alloy 01420T were deformed in the creep regime at a constant flow stress σ = 2.0-7.0 MPa and a temperature T = 520°C, at which, as was determined in [6], partial melting of the 01420T alloy occurs. It leads to the formation of the local arias of the metastable liquid-solid phase on the grain boundaries.

As a result of the mechanical tests, it was determined that specimens of the 01420T alloy, which had undergone

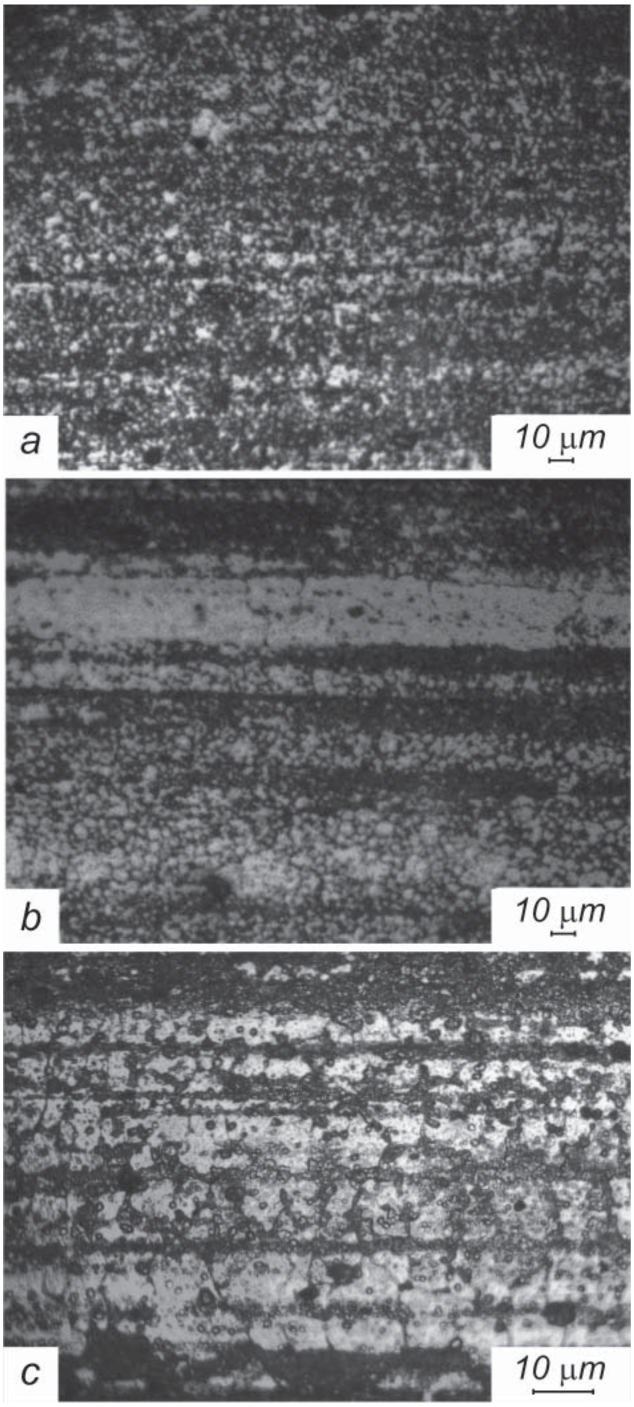

Fig.1. Characteristic types of the initial bimodal microstructure of the working part of specimens of alloy 01420T; a - a colony consisting of ultra-fine grains; b - colony in which large and small grains are concentrated; c - characteristic types of grains which are in the colony, shown in Fig. 1, b. Light microscopy.

thermomechanical treatment, exhibit the effect of high-temperature SSP. Analysis of creep curves, one of which is shown in Fig.2, showed that they have small areas of unsteady creep and some stages of accelerated creep. The main deformation, which is several hundred percent, specimens of alloy 01420T accumulate, deforming superplastically at the stage of flow, which corresponds to steady creep. It is determined that the values of the true deformation rates of specimens of the alloy 01420T deformed at T = 520°C and flow stresses σ = 2.0-7.0 MPa lie in the range 10^{-3}-10^{-5} s^{-1}.

It is determined that the maximum elongation to failure δ, which is 450%, is observed in specimens superplastically deformed at T = 500°C, σ = 4.5 MPa and the true strain rate $\dot{\varepsilon}_{true}$ = $2.2 \cdot 10^{-3} s^{-1}$. These temperature – strain rate conditions are optimal for the manifestation of the effect of high-temperature SSP of specimens of the investigated 01420T alloy with the initial bimodal structure.

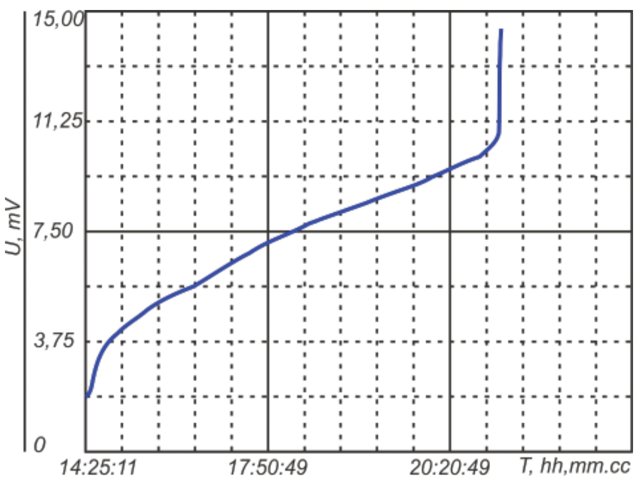

Fig.2. The experimental creep curve of a specimen of the 01420T alloy superplastically deformed to failure under the optimal conditions at T = 520°C and a flow stress σ = 4.5 MPa.

Figure 3 shows a general view of a specimen of the 01420T alloy deformed to failure under the optimum conditions of high-temperature SSP in comparison with the initial one.

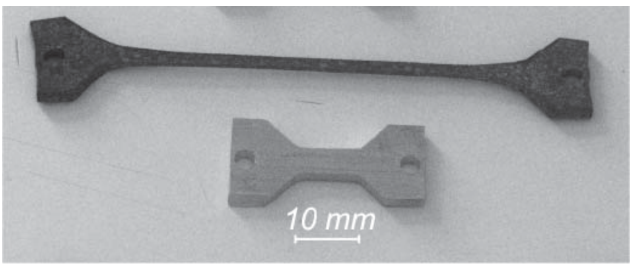

Fig.3. The general view of the specimen of the 01420T alloy deformed to 450% under the optimal conditions of the high-temperature SSP in comparison with the initial one.

It was found that, at a macroscopic level, the superplastic flow of specimens of the 01420T alloy was stable, and their failure occurred without neck formation. Figure 4 shows a characteristic view of the deformation relief formed on the surface of the working part of the specimen of the 01420T alloy deformed to failure under the optimal conditions of the high-temperature SSP. It can be assumed that it arose as a result of the development of grain boundary sliding (GBS), which was intensively carried out along the high-angle boundaries of ultrafine and fine grains with the participation of grain-boundary cavities in accordance with the SPD mechanism proposed in [7], and also on the low-angle boundaries of large grains.

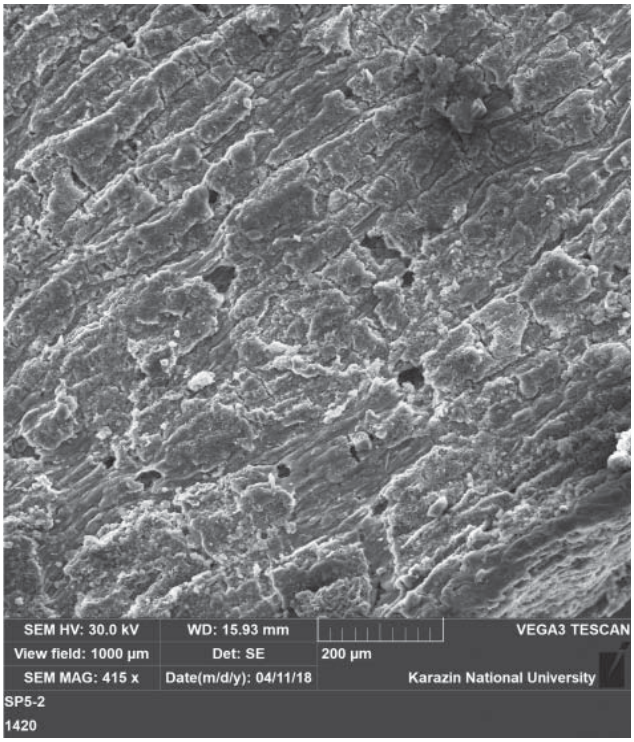

Fig.4. A characteristic view of deformation relief formed on the surface of the working part of the specimen of the 01420T alloy superplastically deformed to failure under the optimal conditions of the high-temperature SSP.

It should be noted that the observed mutual sliding of large polygonized grains occurs through low-angle intergranular boundaries parallel to the strain direction, which is not characteristic for existing classical ideas of the development of GBS under conditions of a micrograin SSP [2]. The GBS of polygonized grains over low-angle boundaries was observed by us earlier in the investigation of the SSP of alloy 1933 [8].

Figure 5 shows the characteristic microstructure of the working part of specimens of the alloy 01420T, superplastically deformed under the optimal conditions to failure, obtained using light microscopy methods. It is determined that as a result of heating the specimens of the alloy 01420T to the test temperature, and also during their

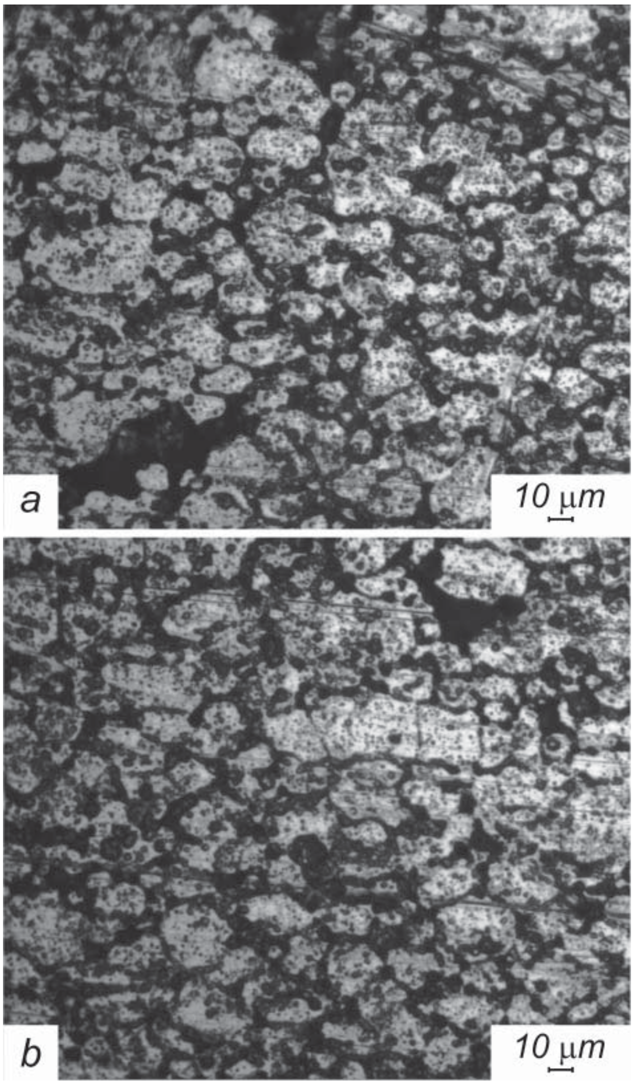

Fig.5. Characteristic types of microstructure of the working part of specimens of alloy 01420T, superplastically deformed to failure under the optimal conditions of high-temperature SSP. Light microscopy. The direction of stretching is horizontal.

SPD, the bimodal structure, due to the development of static and dynamic recrystallization, basically turns into a homogeneous grain structure.

This is evidenced by the absence in the microstructure of the working part of specimens of colonies of grains that have substantially different sizes and shapes (see Fig.5). It was found that the predominant number of grains in the working part of specimens superplastically deformed to failure under the optimal conditions of the SSP is ultra-small. Their average size is about *10 µm*. However, in some of its parts, a few large polygonized grains, separated by low-angle boundaries, have been preserved (see Fig.5, b). Their average size is approximately *20 µm*. In the structure of the alloy there are also fine grains, whose average size is *15 µm*.

It is determined that in the working part of the specimens during their SPD, grain boundary cavities were formed and developed due to the GBS. The average size of cavities is comparable with the average size of the mutually slipping grains adjoining them (see Fig.4 and Fig.5). In the structure of the failured specimens, along with grain-boundary cavities, magisterial cracks formed because of their unification are observed.

As a result of the research of the characteristic types of deformation relief of the specimens of the 01420T alloy working part, fibers were found (see Fig.6), localized in near-surface grain boundaries and microcracks. It is found

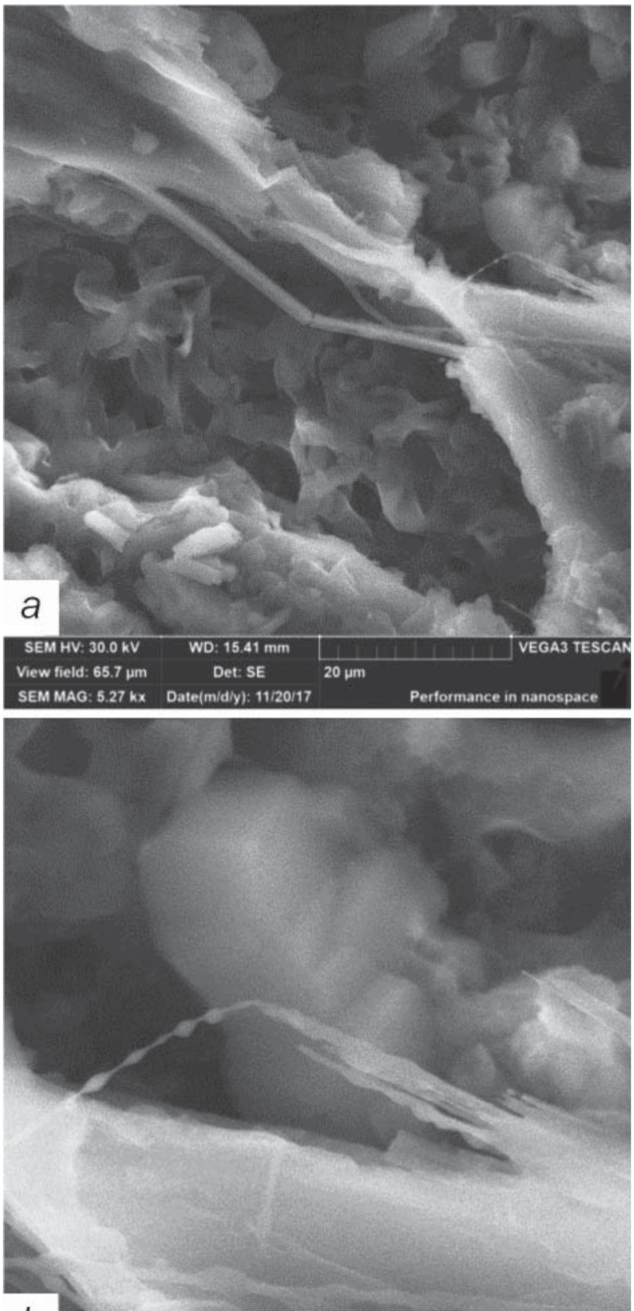

Fig.6. A characteristic type of fibrous structures formed in specimens of the alloy 01420T superplastically deformed to failure under optimal the conditions of the SSP.

that the ends of these fibers are connected to the surface of grain-boundary cavities and cracks formed in the course of GBS when the grains are separated from each other along grain boundaries approximately perpendicular to the extension direction. On some fibers (see Fig.6, b) there are drops. The number of fibers formed in the near-surface grain-boundary cavities is different. Apparently, it depends on the volume of the metastable liquid phase localized at the grain boundaries perpendicular to the strain direction of the specimen.

The presence of fibrous structures and a characteristic form of their morphology indirectly indicate that the SPD of the specimens of the 01420T alloy with the original bimodal structure, as well as of the other multicomponent aluminum alloys alloys [6, 8-16] and observed by other authors [17, 18], takes place with the presence on high-angle and low-angle grain boundaries of viscous metastable liquid-solid phases on some sections.

Let us analyze the probable causes of the formation of a metastable liquid phase in specimens of the 01420T alloy at high homological temperatures, using the ideas that were presented in [6, 8-16, 20, 21].

Apparently, the most probable reason for the formation of a metastable liquid phase in the specimens of the 01420T alloy, which takes place during the heating of specimens to the test temperature T = 520°C and during their SPD at this high homological temperature, is the local melting of the border sections of grains (their "mantle" and those sections of grain boundaries in which the aluminum-based solid solution has an increased concentration of lithium and magnesium atoms in comparison with the nominal composition of the alloy. As is known, the atoms of these elements, which are in the form of segregations at the grain boundaries or dissolved in aluminum-based solid solution to the limiting concentration, significantly reduce the melting temperature of the alloy in the local sections of its specimens [22].

It can also be assumed that a number of particles of the S_1 phase containing magnesium and lithium, dissolve in an aluminum-based α-solid solution during the heating of the specimens to the test temperature due to the development of diffusion processes in the solid state. The particles of the S1 phase remaining at the grain boundaries, which did not have time to dissolve at the time of the start of the SPD of the specimen, the nonequilibrium structural components into which this phase come in, as well as other intermetallide phases containing magnesium and lithium, apparently melt and also are foci of partial melting of the alloy. As a result of its realization, the areas occupied by the metastable liquid phase nucleate on the grain boundaries. The study of the surface of the working part of specimens of alloy 01420T, deformed to failure, showed that it is covered with loose oxide films (see Fig.5). This suggests that in the course of SPD, dynamic oxidation of the surface of solid grains as well as the surface of inclusions of the metastable liquid phase, which was present in small amounts at grain boundaries, intensively took place. Because of this, apparently, the formation of fragile oxide films consisting of Al_2O_3, MgO, and magnesium spinel $MgAl_2O_4$, characteristic for multicomponent aluminum alloys doped with magnesium, occurred [23-25]. It can be assumed that during the SPD, the metastable liquid phase accumulates a certain amount of dispersed particles formed upon the breakdown of loose oxide films. This process apparently leads to the formation of viscous suspensions at grain boundaries of inclusions according to the mechanism described in [27], which consists of a melt of aluminum-based α-solid solution and dispersed particles, which are fragments of oxide films. The resulting liquid-solid phase apparently has an important influence on the development of deformation and accommodation processes occurring during the SPD of specimens of the 01420T alloy.

It can be assumed that in the solid sections of the working part of the specimens of the investigated alloy 01420T during the SPD, such basic deformation mechanisms seem to act simultaneously and self-consistently: GBS, intragranular deformation, diffusion creep. Apparently, at the early stages of superplastic flow of specimens of the 011420T alloy, intragranular deformation, due to slipping and creeping of lattice dislocations, will develop both in large polygonized grains and in those small and ultra-fine grains in which the stresses, in accordance with the Schmid law, reached a critical shear stress. As is known [2], the interaction of lattice dislocations with grain boundaries during SPD is used to create a nonequilibrium state of the high-angle grain boundaries, over which the GBS takes place. It can be assumed that intense GBS on solid sections of the high-angle boundaries of small and ultra-fine grains occurs simultaneously with the viscous flow in those sections of the high-angle boundaries of fine and ultra-fine grains, as well as at low-angle boundaries of large grains parallel to the strain direction, which contain a viscous liquid-solid phase in accordance with the positions of the models described in [20, 21, 27, 28]. The effective accommodation to GBS in this case is due to the development of diffusion processes in the solid and liquid phases, as well as a result of the dislocation sliding in the core of grains and near their boundaries. Because of coordinated implementation of deformation and accommodation processes in the microstructure of the working part of the specimens of the 01420T alloy, an intensive grain rearrangement takes place. It can be assumed that viscous flow of a metastable liquid phase localized at high-angle grain boundaries perpendicular to the strain direction due to the opening of grain-boundary cavities during GBS leads to the formation and development of fibrous structures in the SPD process of specimens of the 01420T alloy in accordance with the mechanism described in [9, 11].

The joint manifestation of all deformation and accommodation mechanisms creates favorable conditions for the stable flow of specimens of the 01420T alloy with the initial bimodal structure and ensures their SPD by hundreds of percent.

Conclusions

1. The temperature – strain rate conditions are determined for which specimens of the 01420T alloy with the initial bimodal structure exhibit the effect of high-temperature structural superplasticity.

2. The structural state of specimens of alloy 01420T, superplastically deformed to failure under conditions of high-temperature structural superplasticity, is studied.

3. It is revealed that in the working part of specimens of the alloy 01420T during the superplastic deformation, as a result of the viscous flow, fibrous structures forms. They are localized in grain boundary cavities and cracks.

4. The probable causes of partial melting of the 01420T alloy and the mechanism of its superplastic deformation are analyzed.

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