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REGULARITIES OF CAVITY DEVELOPMENT IN ALUMINUM ALLOYS IN CONDITIONS OF HIGH-TEMPERATURE SUPERPLASTICITY

V.V. Bryukhovetsky, A.V. Poyda, V.P. Poyda, D.E. Pedun*
Institute of Electrophysics & Radiating Technologies NAS of Kharkiv, Ukraine
E-mail: ntcefo@yahoo.com;
**V.N. Karazin Kharkiv National University, Kharkiv, Ukraine*
E-mail: postmaster@univer.kharkov.ua

The typical peculiarities of cavity development in aluminum alloys 1421, AK4-1p and model alloy "avial", deformed in optimal conditions of high-temperature superplasticity are investigated. The morphological peculiarities of cavity structure are revealed. The mechanisms of generation and development of deformation cavitation during high-temperature superplasticity of these alloys are studied.

INTRODUCTION

The effect of superplasticity has a good combination of technological characteristics: resource of materials deformability is ten times more, and the deformation resistance is several times less than similar characteristics in the plastic state. The investigation of regularities of this effect is the impotent and actual task, which will give both the new technologies and will complete the scientific knowledge about the physical nature of this effect. To the present time it is firmly determined that in all the materials, which perform structural superplasticity in solid state, the grain boundary deformation cavitation develops during superplastic deformation. Cavitation can cause premature failure of superplastic state, excessive cavitation may impose severe restrictions on the commercial application of superplastic processing for forming parts [1-3].

Aluminum based alloys are the main constructional materials not only in aircraft manufacture and missilery, but also in nuclear power engineering. They are used, in particular, for production of centrifuges for enrichment of uranium 235. Therefore engineering and inculcation of new aluminum alloys needs to take to account such restrictions as enhanced strength, plasticity, long service life, simplicity of processing, performance in extreme temperature, dynamic and fatigue conditions. The presence of cavitation is also typical for multicomponent aluminum alloys deformed under high temperature superplasticity in the presence of the liquid phase inclusions in their local structure. It should be mentioned, that no enough investigation is performed to study this process. Perhaps this is related to ideas, that the presence of a liquid phase, which plays an important role in the accommodation of grain boundary sliding leads to a decrease in the level and growth rate of cavitation during high temperature superplastic deformation [4, 5]. At the same time, cavitation characteristics of materials that have shown high temperature superplasticity are given in a number of papers [6, 7]. Despite the reported literature data on cavitation in conditions of high superplastic deformation, the question about the causes and nature of its development is still poorly studied and is not fully understood.

In this study, we investigated the morphology and the regularities of cavitation development in aluminum alloys 1421, AK4-1h and model alloy of "Avial" type exhibiting high temperature superplasticity.

MATERIALS AND METHODS

In the present work the investigations are performed on the specimens of aluminum alloys 1421, AK4-1h and model alloy of "Avial" type exhibiting high temperature superplasticity [8-10]. The initial structure of alloy 1421 is characterized by the presence of fine uniaxial grains, the average size of them is 5 micrometers. The initial structure of alloy AK4-1h is more coarse grained than the initial structure of alloy 1421 and is characterized by uniaxial shape of grains with average grain size about 40 micrometers. The grain structure of every investigated alloy tends to increase during the superplastic deformation. It is reported in [8-10] in details about the structural state of alloys, their chemical composition and conditions of high temperature superplasticity.

Structural investigations are performed with the help of light microscopy and scanning electron microscopy using standard methods of quantitative metallography. The grain structure was detected by chemical etching and by creating a strain relief. The relative volume of grain boundary cavitation was assessed not according to densitometric studies, but according the data obtained using metallographic analysis because of significant oxidation of alloy specimens during superplastic deformation. Measurements of at least 100 linear segments in a sufficiently large number of fields of view, uniformly distributed on the area of the section in the working part of the specimen, allowed to determine the volume cavitation content with an absolute error not exceeding ±5%.

RESULTS AND DISCUSSION

The process of cavitation consists of three stages, which usually occur simultaneously: nucleation of cavities, cavity growth and their coalescence. The impotent moment of the problem is the process of cavity nucleation. It is well known that in conditions of structural superplasticity in solid state cavities can nucleate during the grain boundary sliding on irregularities of different type – triple junctions, behind the second phase particles, in places of intersections of grains with slip bands and so on [1, 2, 11]. Their appearance is a result of decohesion because of not sufficient accommodation under the grain boundary sliding.

In a number of works [12, 13] it is shown, that the grain boundary sliding is the main deformation mechanism as for the structural superplasticity so for high-temperature structural superplasticity. That's why, likely, the main mechanism of cavity nucleation for the high-temperature superplasticity is the same as for the structural superplasticity.

The deformation relief of model alloy of "Avial" type deformed in optimal conditions of superplasticity is shown on Fig.1. From this figure is clearly seen that the cavity nucleation occur exactly as a result of grain boundary sliding. This is evidenced by displacement of previously deposited reference marks on the polished specimen surface on the grain boundaries, within the cavity (fig.1). After detail study of deformation relief of alloys, which perform high-temperature superplasticity it can be argued that the cavity nucleation is the result of the grain boundary sliding during the superplastic deformation. The additional factors, which affect on the possibility of cavity nucleation is the local inclusions of liquid phase. If we take to account the earlier works about the influence of the liquid phase inclusions on the creep of materials (for example [14]), there was noted, that the inclusions of liquid phase on the grain boundaries formed due to high content of more fusible elements. It leads to a decrease in viscosity at a high temperature, which leads to earlier formation of intergranular cavities.

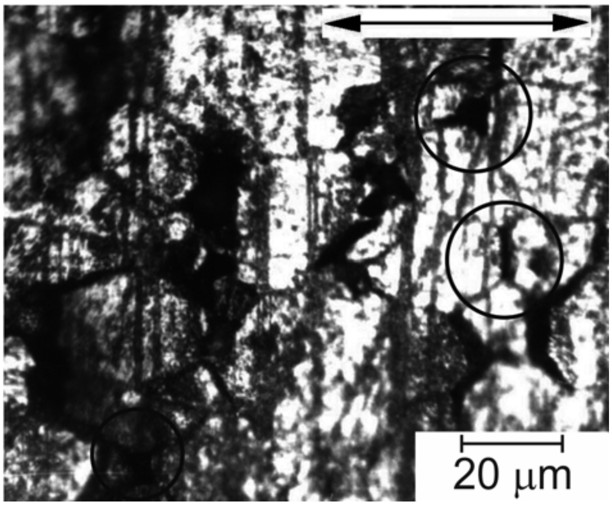

Fig. 1. The typical view of deformation relief of model alloy of "Avial" type deformed to $\varepsilon = 40\%$ under $\sigma = 4{,}0$ MPa and $T = 833$ K

On Fig. 2 some typical views of cavitation, which develops during the superplastic deformation of investigated alloys are shown. The morphology of this cavity structure in all the investigated alloys have similar regularities. Also it should be mentioned that the view of cavity structure is similar to that of materials which performed the structural superplasticity in solid state, for example [15]. The presence of individual grain boundary cavities, which take place in the deformation process of superplastic flow and provide mass transfer

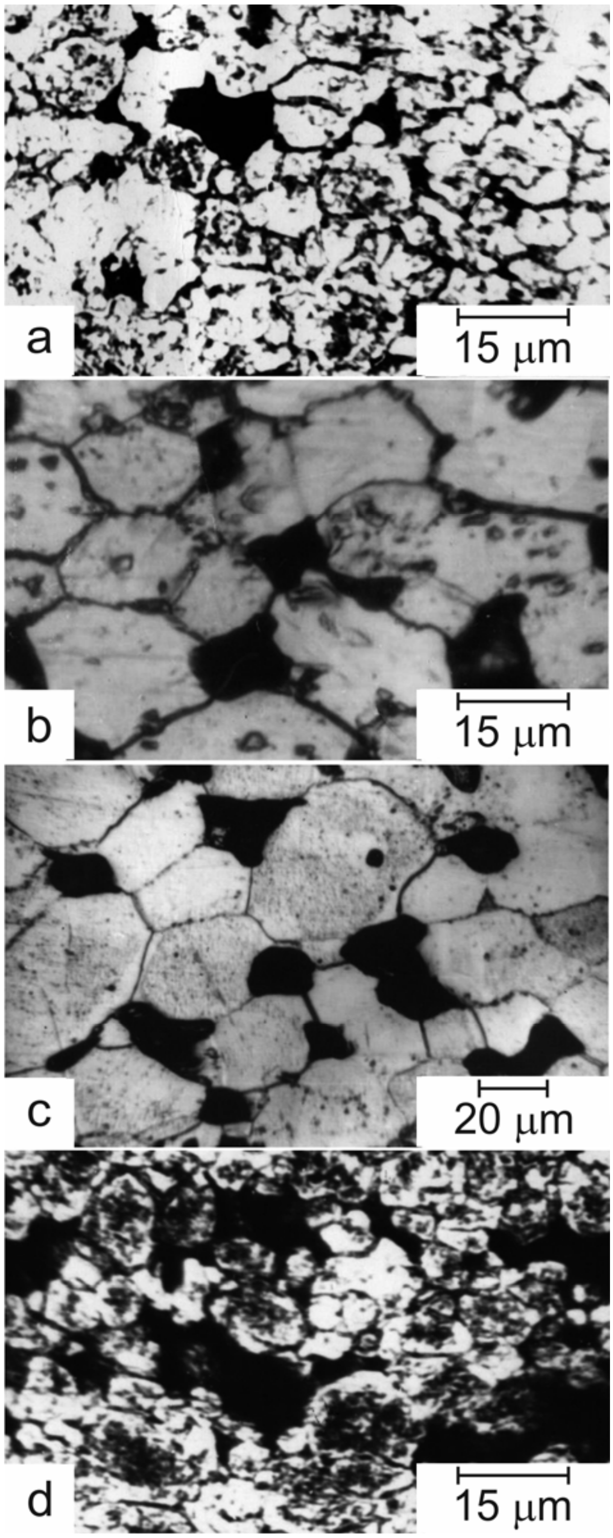

Fig. 2. The cavity structure, which develops in investigated alloys during their deformation in optimal conditions of high-temperature superplasticity: a – 1421; b – AK4-1p; c – "avial"

under grain boundary sliding is typical [16]. However, in the later stages of deformation in the structure of studied alloys which performed high temperature superplasticity the cavitation of another morphology is observed, namely, macroscopic cavities, elongated along the strain direction.

Numerous works are devoted to the study of the cavitation degree from strain rate under the superplastic deformation [17-19]. Cavitation volume accumulated by specimens deformed to failure in conditions of high-temperature superplasticity is usually significant. The investigations, performed in this work, show that the relative cavitation volume increases with the increase of strain rate and, for example, for the alloy 1421 it can reach 24%.

Usually the cavity growth mechanisms in superplastic metals can be classified into three categories [20]: diffusion-controlled growth [21], superplastic diffusion-controlled growth [22] and plasticity controlled growth [23]. The fact that there are present cavities, elongated parallel to the tensile axis indicates that the cavity growth is plasticity-controlled. Plasticity-controlled cavity growth occurs by plastic deformation of the material surrounding a cavity. Most researchers conclude that the increase of cavitation volume during the superplastic deformation is plasticity-controlled [23]. The dependence of cavity volume from strain is written as follow [24]:

$$V=V_0 \exp(\eta\varepsilon), \quad (1)$$

where V_0 – cavitation at zero strain, $\eta = d\ln\nu/d\ln\varepsilon$ – index of cavity growth rate, where ν – volume of individual cavity.

The dependences of the relative cavity volume from degree of true strain, shown on Fig. 3, have the form described by equation (1). This indicates that the cavitation growth in conditions of high-temperature superplastic deformation is controlled by plastic deformation of itself. However, it can also be called as superplastic deformation-controlled growth because the main deformation mechanism of high-temperature superplasticity is the grain boundary sliding and not intergranular deformation.

As it can be seen from Fig. 3, for the index of cavity growth the following inequality can be written: $\eta_3 > \eta_2 > \eta_1$. This is probably due to the different initial grain size in the studied alloys. Evidently, the greater the initial grain size, the higher is the rate of cavity growth in the initial stages of deformation. Therefore, alloys with larger grains are more prone to accumulation of cavitation during the initial stages of deformation. As is known, one of the features of superplasticity is that intergranular cavities may cure during deformation. Curing performs both by the grain boundary sliding and by the diffusion processes, developing during superplastic deformation. The more effective curing of deformation cavities by diffusion processes is observed exactly in fine-grained materials. This can explain the slower rate of cavity accumulation in the initial stages of deformation. At the same time one of the reasons that the more coarse-grained alloys exhibit lower elongations to failure is a significant amount of cavities, which they accumulated in the early stages of superplastic deformation.

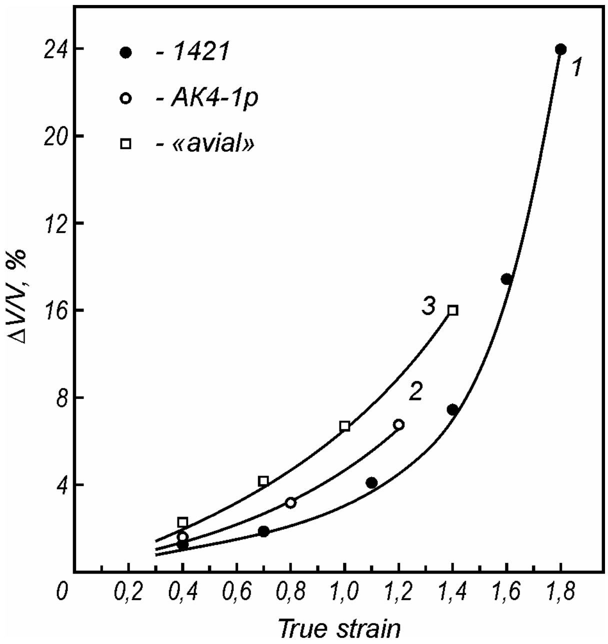

Fig. 3. The dependence of relative cavity volume, accumulated by the specimens of alloys during the superplastic deformation from the true strain. 1) – 1421, 2) AK4-1p, 3) "avial"

Macrofailure of specimens of studied alloys occur under accumulation of significant volume of cavities. On Fig. 4 the fracture surfaces of studied alloys are shown. A number of details, which are typical for fracture surfaces of specimens, deformed to failure in the solid state under micrograin structural superplasticity are observed on it [25]. Also there are some details which are typical for fracture surfaces for specimens, fractured in liquid-solid state [26]. From Fig. 4 is evident, that the fracture surfaces of specimens contain plots occupied by merged cavities and plots of intergranular and transgranular fracture. Also on fracture surfaces facets formed as a result of intragranular and intergranular fracture of areas which were in the solid state during fracture are visible. Also the ridges representing narrowed areas of internal mikronecks which fractured as a result of plastic flow are visible. It is also seen that some of the edges of the grains contain the fringe of the fibrous structures, which apparently are the result of the viscous flow of the melt at the moment of separation of the grains. In particular, this may indicate about the partial melting of the peripheral regions of the grains. On the fracture surfaces some individual cone-shaped formation are also seen, which are of a type similar to the broken halves of macroscopic specimens, which as a result of flow had a significant necking, indicating that the mechanism was viscous flow. The morphology of all the fracture surface suggests that the specimens during the superplastic deformation were, apparently, in solid-liquid state. In general, the failure of the specimens of alloys 1421, AK4-1h and of "Avial" type deformed under high temperature superplasticity is different: quasibrittle on macrolevel, and mixed at the micro level.

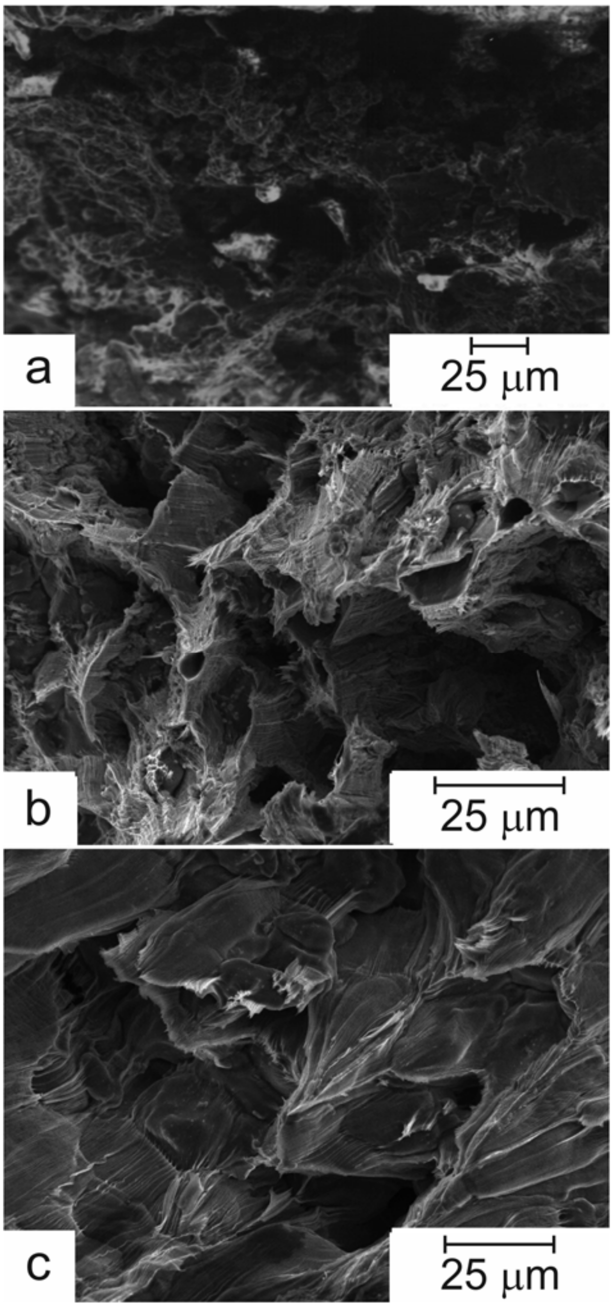

Fig. 4. Fracture fragments of alloy specimens: 1421 (a), AK4-1h (b) and "Avial" type (c), deformed to failure under the optimal conditions of high-temperature superplasticity

CONCLUSIONS

1. Superplastic deformation at high homologous temperatures is accompanied by intense cavitation. Nucleation of cavitation is the result of the grain boundary sliding during superplastic deformation. An additional factor, which affects on the possibility of nucleation of cavities, is the presence of the local inclusions of the liquid phase at the grain boundaries, leading to a decrease in the viscosity coefficient.

2. The cavity volume, accumulated by specimens of alloys, deformed in conditions of high-temperature superplasticity to failure, is usually significant, and may exceed the 20%. The cavitation growth is controlled by plastic deformation itself. However, it can be called superplastic deformation-controlled growth. In this case during the initial stages of deformation the coarse-grained alloys are more prone to the accumulation of cavitation. This can be a likely factor causing their premature failure. The failure of materials, deformed in conditions of high-temperature superplasticity has some regularity, typical for structure superplasticity, but there are some peculiarities, which are typical only for high-temperature superplasticity.

3. On microlevel the failure is different. On the fracture surfaces the presence of microareas of quasibrittle failure with liquid phase and of microareas of viscous failure is typical.

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ЗАКОНОМЕРНОСТИ РАЗВИТИЯ ПОРИСТОСТИ В УСЛОВИЯХ ВЫСОКОТЕМПЕРАТУРНОЙ СВЕРХПЛАСТИЧНОСТИ АЛЮМИНИЕВЫХ СПЛАВОВ

В.В. Брюховецкий, А.В. Пойда, В.П. Пойда, Д.Е. Педун

Исследованы характерные особенности развития пористости в образцах промышленных алюминиевых сплавов 1421, АК4-1ч и модельном сплаве типа «Авиаль», продеформированных в оптимальных условиях высокотемпературной сверхпластичности. Выявлены морфологические особенности пористой структуры. Изучены механизмы образования и развития деформационной пористости в ходе высокотемпературной сверхпластической деформации этих сплавов.

ЗАКОНОМІРНОСТІ РОЗВИТКУ ПОРИСТОСТІ В УМОВАХ ВИСОКОТЕМПЕРАТУРНОЇ НАДПЛАСТИЧНОСТІ АЛЮМИНІЄВИХ СПЛАВІВ

В.В. Брюховецький, А.В. Пойда, В.П. Пойда, Д.Є. Педун

Досліджено характерні особливості розвитку пористості в зразках промислових алюмінієвих сплавів 1421, АК4-1ч і модельному сплаві типу «авіаль», які було продеформовано в оптимальних умовах високотемпературної надпластичності. Виявлено морфологічні особливості пористої структури. Вивчено механізми утворення і розвитку деформаційної пористості в ході високотемпературної надпластичної деформації цих сплавів.