ISSN 1027-5495. Functional Materials, 26, No.1 (2019), p. 88-91.
doi:https://doi.org/10.15407/fm26.01.88

Features of the occurrence and development of cracks in polycrystalline aluminum samples with different grain sizes

E.E.Badiyan, A.G.Tonkopryad, O.V.Shekhovtsov, R.V.Shurinov

V.Karazin Kharkiv National University,
4 Svobody Sq., 61022 Kharkiv, Ukraine

Received November 25, 2018

The results of the study of the regularities of the occurrence and development of cracks during plastic deformation of polycrystalline aluminum samples which contain only through grain boundaries (parquet structure) are presented. It was experimentally shown that in the studied polycrystalline aluminum samples, the average size of which varied from 1 to 15 mm grain-boundary, transcrystalline and mixed failure can occur. The regularities of the occurrence and development of cracks and the physical mechanisms for various types of failure of polycrystalline aluminum samples are determined. It has been shown that grain-boundary failure is caused by the presence of pores in the grain bound aries of a general type, and transcrystalline failure is caused by the deformational boundaries or a well-developed rotational structure that occurs during sample deformation.
Keywords: plastic deformation, grain boundary, failure, polycrystalline samples, crack.

Приведены результаты исследования закономерности возникновения и развития трещин при пластическом деформировании поликристаллических образцов алюминия, содержащих только сквозные границы зерен (паркетная структура). Экспериментально показано, что в исследованных поликристаллических образцах алюминия, средний размер которых менялся от 1 до 15 мм, возможно зернограничное, транскристаллитное и смешанное разрушение. Выявлена закономерность возникновения и развития трещин при различных способах разрушения поликристаллических образцов алюминия и определены физические механизмы. Показано, что зернограничное разрушение обусловлено наличием в границах общего типа пор, а транскристаллитное — границами деформационного происхождения или возникающей в процессе деформирования образца хорошо развитой ротационной структуры.

Особливості виникнення та розвитку тріщин у полікристалічних зразках алюмінію з різним розміром зерен. *Є.Ю.Бадіян, А.Г.Тонкопряд, О.В.Шеховцов, Р.В.Шурінов.*
Наведено результати дослідження закономірностей виникнення та розвитку тріщин при пластичній деформації полікристалічних зразків алюмінію, які містять тільки наскрізні межі зерен (паркетна структура). Експериментально показано, що е досліджених полікристалічних зразках алюмінію, середній розмір яких змінювався від 1 до 15 мм, є можливими зернограничне, транскристалітне та змішане руйнування. Виявлено закономірності виникнення та розвитку тріщин при різних способах руйнування полікристалічних зразків алюмінію та визначено фізичні механізми. Показано, що зернограничне руйнування обумовлено наявністю у межах зерен загального типу пор, а транскристалітне — межами деформаційного походження або добре розвиненою ротаційною структурою, яка виникає у процесі деформування зразка.

1. Introduction

The problem of the failure of crystalline materials including metals has been central to the creation of various structural materials for decades. The study of the macroscopic patterns of the occurrence and development of cracks and the search for a connection between the nature of the fracture process and the microstructure of the sample is one of the possible approaches to solving this problem. This is mostly true for polycrystalline samples in which the grain boundaries differ in type, shape, length, and other characteristics.

In the present paper, experimental studies of the patterns of the occurrence and development of cracks in the process of plastic deformation of polycrystalline aluminum samples with different average grain sizes are carried out. Use as samples of two-dimensional aluminum polycrystals containing only through grain boundaries and original techniques [1–3] studies of structural, substructural and orientational changes accompanying plastic deformation of the sample made it possible not only to trace the origin and development of cracks in different areas of the sample but also to determine the physical mechanisms of their occurrence and further development.

2. Experimental

The objects of study were two-dimensional polycrystalline samples of aluminum containing only through grain boundaries. The research samples with the working part size of about $100\times20\times0.15$ mm^3 were cut out from an aluminum foil (99.96 %) 0.15 mm thick with average grain size of about 0.01 mm. The necessary average grain size from 1 to 12 mm was provided by selection of preliminary strain and recrystallization annealing regime which included pre-annealing at a temperature of 400°C for 3 h, subsequent plastic deformation of the sample by 1.0–5.0 % and recrystallization annealing at a temperature of 600–630°C for 5 h. Grain boundaries were detected by chemical etching using Keller etchant [4]. The crystallographic orientation of all grains relative to the tensile axis and the complete certification of all grain boundaries were performed using the Laue X-ray technique before and after the deformation of the large-grained samples. The specimens were strained under active tension conditions at a constant straining rate $\dot{\varepsilon} \approx 10^{-5}$ s^{-1}. During deformation of the samples from their entire surface color orientation maps were continuously recorded and color shades were visualized. The color shades characterized the structural and orientational heterogeneity of the samples [5–6]. This made it possible to trace the substructural and orientational changes in each of the grains that occur during the deformation of polycrystalline samples.

3. Results and discussion

Grain-boundary, transcrystalline and mixed failures were observed in the studied samples (there were more than 200), depending on the grain size during plastic deformation. It has been experimentally shown that it is impossible to unambiguously determine how the grain size affects the type of failure of a sample. However, the probability of grain-boundary failure in polycrystalline aluminum samples increases with decreasing average grain size. Figure shows the dependence of the probability of grain-boundary failure on the average grain size $\bar{d}$ of the studied samples. Failure almost always occurs along the grain boundaries in samples with an average grain size of not more than 5 mm. The occurrence of cracks almost always occurs within the grain boundaries of a general type (Fig.). This was shown using the developed computer-aided technique of automatic full certification of all grain boundaries in a sample after scanning the Laue patterns received from all grains. Almost all grain boundaries are of a general type in samples with an average grain size of not more than 5 mm. Thus grain-boundary failure is associated with the presence of general type grain boundaries in the samples. Pores are found in almost every one of these boundaries. These ones are the source of cracks during the deformation of the samples. It was experimentally shown that the character of the distribution of pores in the grain boundaries of a general type and their number (density) are different. This makes it possible to explain the specifics of grain-boundary damage in fine-crystalline aluminum samples, which consists in the variety of types for the occurrence and development of grain-boundary cracks. The process of failure of the sample can be carried out by the occurrence of a single crack and its successive development in other grain boundaries. The appearance of cracks can occur in the grain boundaries in the entire sample (multiple grain-boundary failure). In this case, it is impossible to predict the number

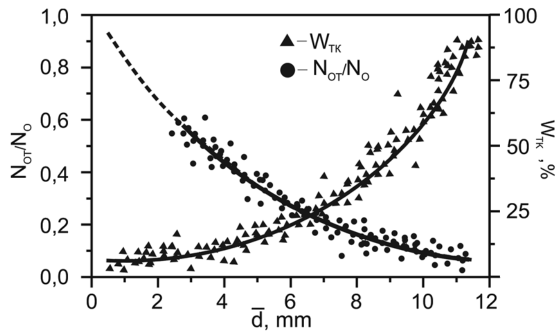

Fig.. The dependencei of the relative number of the grain boundaries of a general type N_{OT}/N_O and the transcrystalline failure probability W_{TK} on the average grain size in polycrystalline aluminum samples (N_O is the total number of grain boundaries in the sample, N_{OT} is the number of the grain boundaries of a general type).

of grain-boundary cracks and determine the crack in the boundary which ultimately will lead to the failure of the sample. One of the appeared grain-boundary cracks can stop its development, and the other to continue. During plastic deformation, this crack can stop its development, and the first crack will begin to develop again. Such a development may also occur for other appeared grain-boundary cracks. As noted above, everything is determined by the number of grain-boundary pores in the sample and the character of their distribution.

The pattern of the occurrence and development of cracks may be different if there are special or similar types of grain boundaries in a polycrystalline sample. If a crack appears in the grain boundary of a general type, it spreads in the grain body due to the impossibility of its further development in the neighboring boundary of a special type. If it crosses the general type grain boundary, its further development can occur along this boundary. Otherwise, it develops in the body of the neighboring grain. This is the so-called mixed character of the failure of polycrystalline samples which contain the grain boundaries of a special and general type. Failure is almost always transcrystalline in the large-gr ained aluminum samples ($\bar{d} \geq 10$ mm). It was experimentally shown that the occurrence of cracks in the body of a grain is possible in two cases. In the first case, it is necessary that the tensile axis of the sample coincides with the direction of the {311} type, and the normal to the surface of this grain coincides with the direction {411}. If there is a grain with such a crystallographic orientation in polycrystalline samples prior to their deformation, then a crack appears in such a grain almost always. If the crystallographic orientation of the grain differs from the above then its rotations may occur as a result of sliding. Such rotations favor the activation of the conjugate slip system and thus make the orientation of the grain or its individual regions unstable to failure [7–9]. In the grains that have experienced such a reorientation, the sequence of deformation processes and failure is as follows. Initially, the deformation occurs due to the action of the primary slip system. Then, the accompanying reorientation of the crystal lattice, the activation of the conjugate slip system, double slip and failure as the final result occur. In the second case, the occurrence of a crack in the body of the grain is associated with the formation of a well-developed rotational structure or a new interface in it during plastic deformation. Such a boundary is as a rule small-angle.

It should be noted that the development of cracks in the body of a grain always takes place in certain crystallographic directions and is viscous in nature. The direction of crack development always changes if it intersects with the grain boundary and extends further in the grain with a different crystallographic orientation.

4. Conclusions

Investigation of the pattern of the appearance and development of cracks in polycrystalline aluminum samples containing only through grain boundaries showed that there are three possible types of failure depending on the grain size: grain-boundary, transcrystalline and mixed. In the first case, the formation and development of cracks occurs only along the grain boundaries. In the second case, the formation of cracks and their development can occur only in the body of the grain. In the third case, the formation of cracks can occur at the grain boundary but its development always occurs only in the grain body.

It has been experimentally shown that the grain boundaries of a general type, in the region of which pores are found, predetermine the grain-boundary failure of polycrystalline samples. The relative number of the grain boundaries of a general type in the studied samples increases with decreasing average grain size. This leads to an increase in the probability of grain-boundary failure with a decrease in the average grain size. In case of transcrystalline failure, the occurrence of cracks is associated with the presence of a well-developed rotational structure in the body of the grain, which occurs during deformation of the sample, or the boundary of deformation origin, which as a rule is small-angle.

References

1. E.E.Badiyan, A.G.Tonkopryad, O.V.Shehovtsov et al., *Inorg. Mater.*, **15**, 1663 (2011).
2. E.E.Badiyan, A.G.Tonkopryad, O.V.Shekhovtsov, R.V.Shurinov, *Functional Materials*, **13**, 411 (2006).
3. Ua Patent 89743 (2010).
4. M.Beckert, Ch.Klemm, Spravochnik po Metallograficheskomu Travleniju, Metallurgia, Moscow (1980).
5. E.E.Badiyan, A.G.Tonkopryad, O.V.Shekhovtsov et al., *Functional Materials*, **21**, 307 (2014).
6. Ua Patent 104249 (2014).
7. E.E.Badiyan, A.G.Tonkopryad, O.V.Shekhovtsov, R.V.Shurinov, *Functional Materials*, **14**, 249 (2007).
8. V.V.Rybin, Large Plastic Deformation and Failure of Metals, Metallurgia, Moscow (1986) [in Russian].
9. I.I.Novikov, V.A.Ermishkin, Micromechanisms of Failure of Metals, Nauka, Moscow (1991) [in Russian].