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FEATURES OF THE ORIGIN AND DEVELOPMENT OF CRACKS IN POLYCRYSTALLINE ALUMINUM SAMPLES

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The study investigates the patterns of crack initiation and propagation during the plastic deformation of two-dimensional aluminum polycrystals with different grain sizes. The high-purity (99.96%) research objects are aluminum polycrystals containing only through grain boundaries. The samples were subjected to uniaxial tension at a constant strain rate of $\dot{\varepsilon} = 5 \times 10^{-5} c^{-1}$ at room temperature. An original method based on light diffraction on a quasi-periodic surface structure was used, allowing real-time tracking of crystallographic orientation changes in any region of the sample during plastic deformation and simultaneously recording the initiation and propagation of cracks leading to the destruction of the sample.

Experimental results showed that cracks most often originate at the sample edge due to stress concentration and structural features of the material. Their subsequent development can occur both within the grains and along their boundaries, depending on local deformation conditions, the type, and structure of the grain boundaries. It was found that before a crack forms in a specific region of the sample, significant crystallographic orientation changes occur, which may play a crucial role in the initiation of fracture.

In some cases, the formation of a "torch" of orientation changes – a zone into which the crack propagates, leading to accelerated sample destruction was experimentally recorded. This effect may be related to the redistribution of internal tensions and the activation of plastic deformation in the zone ahead of the crack. The study also documented a rare case of “recrystallization” during deformation, where two adjacent grains "merged into" one due to a change in the crystallographic orientation of one of the grains as a whole during plastic deformation. The ability of entire grains to reorient in two-dimensional samples under plastic deformation was experimentally confirmed in previous studies.

Keywords: *polycrystalline aluminum samples, plastic deformation, destruction, mechanical properties.*

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INTRODUCTION

It is well known that fracture is a multi-stage and multi-scale process, and in this regard, fracture mechanisms should be considered within an approach that accounts for the interaction of various deformation processes at different levels. When polycrystalline samples are subjected to loading, structural and substructural heterogeneity leads to a complex stress state, which can relax in different ways, either sequentially or simultaneously. These processes include the development of crystallographic slip in specific regions of the polycrystal with high Schmid factor values; the formation and evolution of rotational structures that differ in shape, type, and mode of initiation and development; and the initiation and propagation of one or multiple cracks in different regions of the polycrystal (within the grain body or along grain boundaries).

The nature and sequence of crack initiation and propagation during plastic deformation remain insufficiently studied. The aim of this work is to investigate the patterns of crack initiation and propagation during the plastic deformation of two-dimensional aluminum polycrystals with different grain sizes using a highly sensitive, original method for obtaining color orientation maps (COM).

SAMPLES AND EXPERIMENTAL METHODS

The objects of study were two-dimensional aluminum polycrystals (containing only through grain boundaries) with a purity of 99.96%. As experimental results show [1], in such objects, due to the absence of constraints in the direction perpendicular to the sample surface, rotational processes are most prominently manifested.

Samples with working part dimensions of $100 \times 20 \times 0.15$ mm^3 were cut from aluminum foil. The required average grain size, ranging from 5 mm to 20 mm, was achieved by selecting an appropriate thermomechanical treatment regime. Grain boundaries were revealed using the chemical etching method with the well-known Keller's reagent [2]. All samples were deformed under tensile loading conditions at a constant strain rate of $\dot{\varepsilon} = 5 \times 10^{-5} c^{-1}$.

The absence of constraints during the plastic deformation of two-dimensional aluminum polycrystals in the direction perpendicular to the sample surface allowed for the identification of specific features of crack initiation and propagation, as well as the influence of orientation changes on this process.

An original method [3–10], based on the effect of light diffraction on the quasi-periodic surface structure of the sample, was used. This structure arises as a result of chemical etching and produces a color image of different regions of the sample surface depending on their crystallographic orientation. This approach makes it possible to continuously track any orientation changes and the patterns of crack initiation and propagation across the entire sample surface in real-time during deformation.

RESEARCH RESULTS

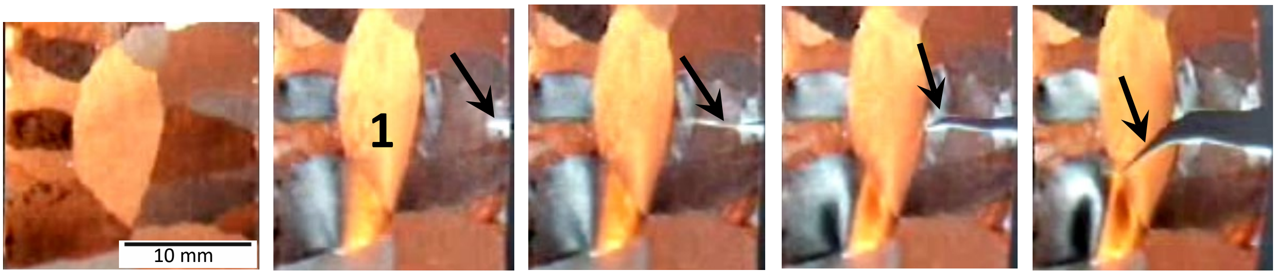
The main research results are presented in Figures (1 – 5) as color orientation maps (COM), continuously obtained during the deformation process from the entire sample surface. The figures show only fragments of the sample surface areas where cracks initiate and propagate, ultimately leading to destruction. Each COM is labeled with the total sample strain ε (in percentage) and the elapsed time Δt from the start of deformation. It should be emphasized once again that any color changes in the sample surface regions during deformation indicate changes in the crystallographic orientation of that region [2].

Of particular interest are the results obtained for Sample № 1, shown in Figure 1. When the sample reaches a relative strain of approximately 10%, it appears that the strain in one of the grains has exceeded 20%. A detailed examination of the COM reveals that this grain elongation occurs due to the incorporation of an adjacent grain and the disappearance of the grain boundary. Based on these observations, "recrystallization" occurs during sample deformation – two grains merge into one (Figure 1b). This effect is clearly visible in an enlarged fragment of this sample region (Figure 1f). Thus, it can be confidently stated that during the plastic deformation of a two-dimensional aluminum polycrystal, "recrystallization" takes place, leading to grain coarsening. The mechanism of this recrystallization is the orientation change of one of the neighboring grains, which occurs due to the absence of constraints on rotations in the direction perpendicular to the sample surface.

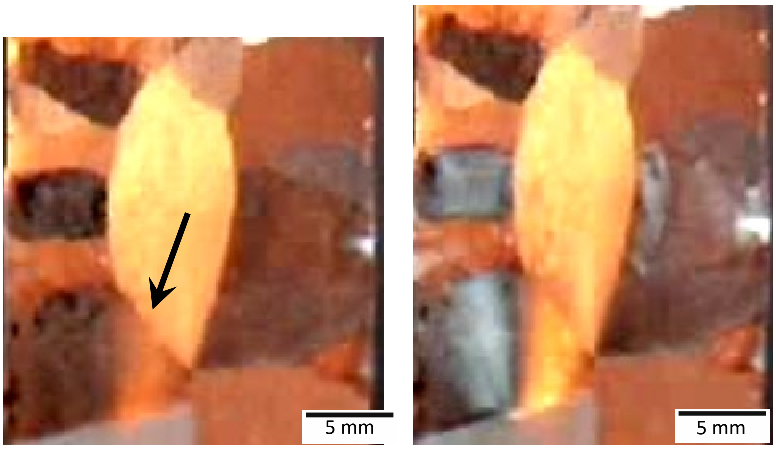
With further deformation, a well-developed rotational structure emerges between the boundary of this grain and the sample edge, within which a crack forms. The crack then propagates within the recrystallized grain, changing its propagation direction and affecting the rate of sample destruction. From the moment of crack initiation to complete sample destruction, approximately 4 minutes elapse.

For the polycrystalline aluminum sample whose COM is shown in Figure 2, crack initiation also occurs at the sample edge. As the crack develops within the grain, this process is preceded by orientation changes. Subsequently, the crack propagates along the boundary of a neighboring grain, altering its direction. The time required for this sample to fail from the moment of crack initiation does not exceed 2 minutes.

In Figure 3, the crack, similar to the previously described samples, initiates in one of the grains at the

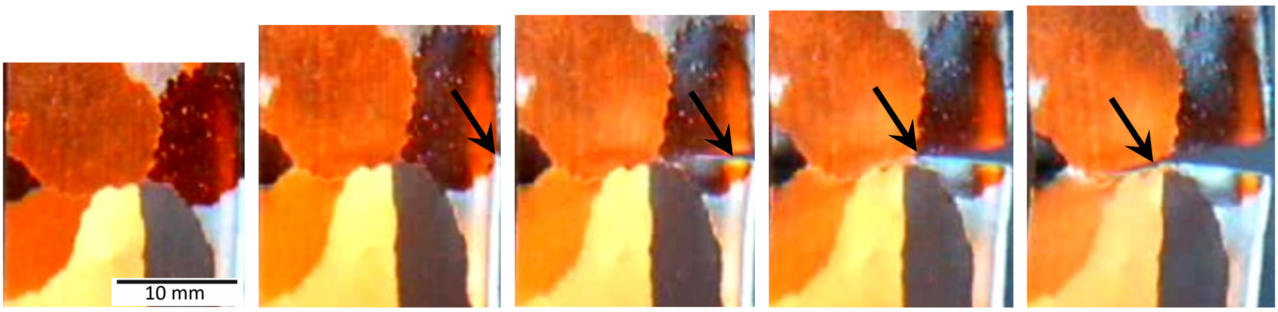


a) Δt =0 min 00 sec $\varepsilon = 5\%$ b) $\Delta t = 35$ min 00 sec $\varepsilon = 10.0\%$ c) $\Delta t = 37$ min 06 sec d) $\Delta t = 38$ min 22 sec e) $\Delta t = 40$ min 43 sec



f) $\Delta t = 17.0$ min 00 sec, $\varepsilon = 5\%$ g) $\Delta t = 35$ min 00 sec, $\varepsilon = 10.0\%$

Fig. 1. Fragments of COM obtained from the entire surface of polycrystalline sample № 1 during its deformation at different levels of plastic strain ε and elapsed time Δ*t*.

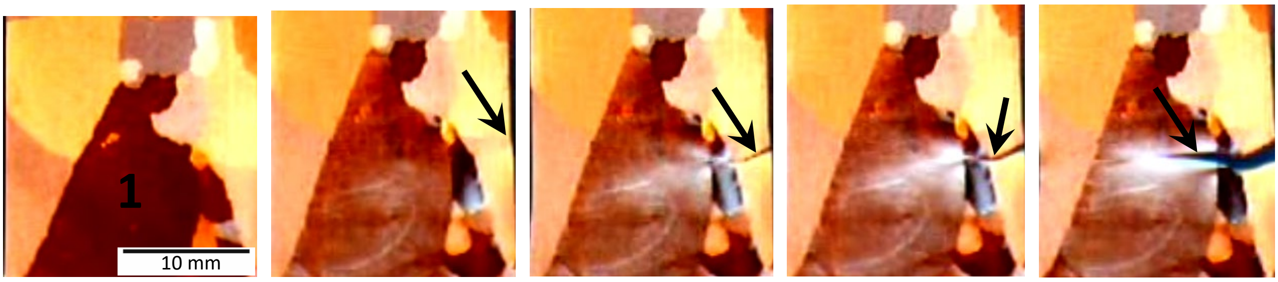


a) $\Delta t = 0$ min 00 sec $\varepsilon = 0\%$ b) $\Delta t = 33$ min 00 sec $\varepsilon = 9.4\%$ c) $\Delta t = 33$ min 18 sec d) $\Delta t = 33$ min 54 sec e) $\Delta t = 34$ min 30 sec

Fig. 2. Fragments of COM obtained from the entire surface of polycrystalline sample № 2 during its deformation at different levels of plastic strain ε and elapsed time Δ*t*.

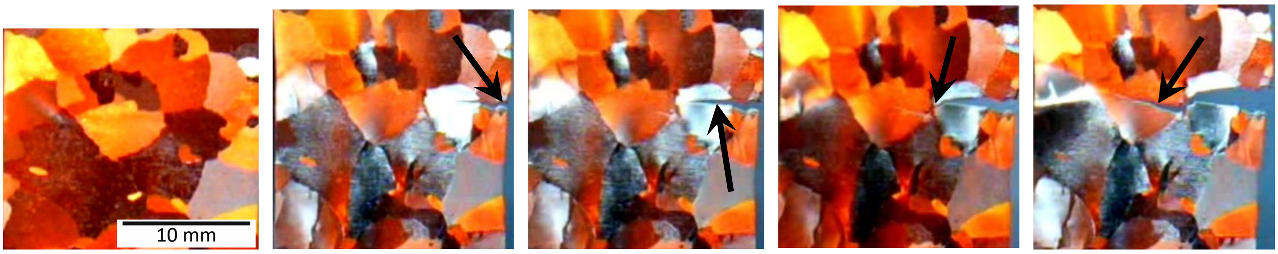
sample edge. During its propagation, it crosses two grains and their boundary without changing direction. At a considerable distance from the crack, orientation changes manifest themselves in the form of a “torch”, the sharp end of which is directed in the direction opposite to the crack. When the specimen is deformed, this “torch” expands and the crack moves into the area of the “torch”, which leads to rapid fracture of the specimen. In this case, the time from crack initiation to complete fracture is about 2 minutes. In the next (fine-grained) sample (Fig. 4), the crack initiates at the edge of the sample. As it propagates, it moves into a grain where orientation changes occur. Despite the fine-grained structure of the sample, crack propagation occurs only within the grains. At a certain stage of crack development, orientation changes appear in a narrow region on the opposite edge of the sample, causing the crack to shift into this region, ultimately leading to sample failure. The time from crack initiation to failure is approximately 2 minutes.

Of particular interest are the results of studying crack initiation and propagation in polycrystalline aluminum sample № 5.



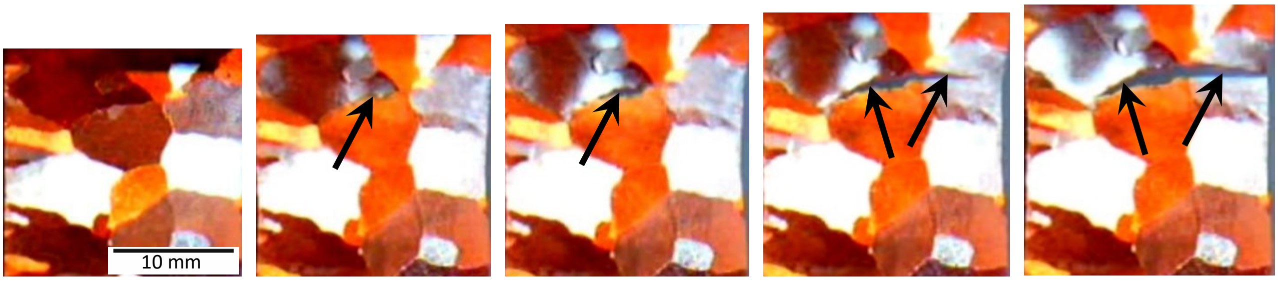
a) Δt = 0 min 00 sec ε = 0% b) Δt = 30 min 00 sec ε = 8.6% c) Δt = 31 min 01 sec d) Δt = 31 min 14 sec e) Δt = 33min 07 sec

Fig. 3. Fragments of COM obtained from the entire surface of polycrystalline sample № 3 during its deformation at different levels of plastic strain ε and elapsed time Δ*t*.

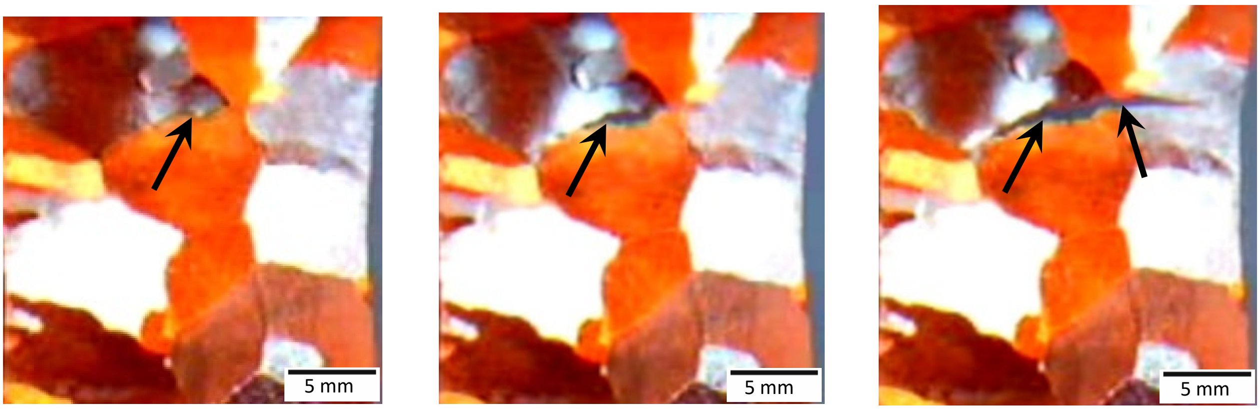


a) Δt = 0 min, ε = 0% b) Δt = 31.5 min ε = 8.9% c) Δt = 32 min 03 sec d) Δt = 32 min 47 sec e) Δt = 33 min 41 sec

Fig. 4. Fragments of COM obtained from the entire surface of polycrystalline sample № 4 during its deformation at different levels of plastic strain ε and elapsed time Δ*t*.



a) Δt = 0 min 00 sec ε = 0% b) Δt = 22 min 00 sec ε = 6.0% c) Δt = 23 min 27 sec d) Δt = 24 min 32 sec e) Δt = 24 min 57 sec



f) Δt = 22 min 00 sec, ε = 6.0% g) Δt = 23 min 00 sec h) Δt = 24 min 32 sec

Fig. 5. Fragments of COM obtained from the entire surface of polycrystalline sample № 5 during its deformation at different levels of plastic strain ε and elapsed time Δ*t*.

The unique feature of this sample is that the crack initiates and propagates in the central region of the sample along a grain boundary. As it progresses along the boundary, the crack eventually stops. Its further development occurs in the opposite direction. Moving along the boundary, the crack exits it, crosses the grain body, the boundary, and the body of a second grain. This ultimately leads to sample failure. Thus, in this sample, the failure mechanism exhibits a mixed nature, with crack initiation occurring in the central part of the sample.

CONCLUSIONS

1. Experimental studies were conducted to investigate the patterns of crack initiation and propagation during deformation of two-dimensional polycrystalline aluminum specimens using the original technique of obtaining color orientation maps for the entire specimen surface. This approach allowed us to identify a number of features of the fracture process of the specimens and to establish a relationship between the initiation and development of cracks with orientational changes in the specimens.

2. It was shown that in most samples, cracks initiate at the sample edge; however, their subsequent propagation behavior is unpredictable. Crack development can occur both within the grain body and along grain boundaries, and this propagation pattern may change during the deformation process.

3. Crack formation is almost always preceded by orientation changes in the corresponding region of the sample. Such changes can also develop over a sufficiently large area around the crack as it propagates. Experimentally, during sample deformation, the formation of a "torch" of orientation changes was observed at significant distances from the crack. As the crack develops, it always moves into the "torch" region, which expands during the deformation process, ultimately leading to the failure of the sample.

4. In certain cases, a crack may initiate in the middle of the sample, most often along a grain boundary. This is typically preceded by orientation changes near the boundary. During sample deformation, the crack may reverse its propagation direction, leading to failure. This reversal is also driven by orientation changes occurring in the newly affected region.

5. An unusual type of "recrystallization" was discovered in polycrystalline aluminum samples, which involves a change in the crystallographic orientation of one of the neighboring grains, leading to the disappearance of the boundary between them.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interests.

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ОСОБЛИВОСТІ ВИНИКНЕННЯ ТА РОЗВИТКУ ТРІЩИН В ПОЛІКРИСТАЛІЧНИХ ЗРАЗКАХ АЛЮМІНІЮ

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В роботі досліджено закономірності зародження та розвитку тріщин під час пластичної деформації двовимірних полікристалів алюмінію з різними розмірами зерен. Об'єктами дослідження були високочисті (99.96%) полікристали алюмінію, що містять лише наскрізні границі зерен. Зразки піддавали одновісному розтягуванню з постійною швидкістю деформації $\dot{\varepsilon} = 5 \times 10^{-5} c^{-1}$ за кімнатної температури. Використано оригінальну методику, засновану на дифракції світла на квазіперіодичній структурі поверхні, що дозволяє в реальному часі відстежувати зміни кристалографічної орієнтації в будь-якій ділянці зразка під час пластичної деформації та одночасно реєструвати зародження і поширення тріщин при руйнуванні зразка.

Експериментальні результати показали, що тріщини найчастіше зароджуються на краю зразка, що пов'язано з концентрацією напружень і структурними особливостями матеріалу. Подальший їх розвиток може відбуватися як всередині зерен, так і вздовж їх границь, залежно від локальних умов деформування, типу та структури границь зерен. Встановлено, що перед утворенням тріщини у відповідній області зразка відбуваються значні зміни кристалографічної орієнтації, які можуть відігравати вирішальну роль в ініціюванні руйнування.

У деяких випадках експериментально зафіксовано формування «факела» орієнтаційних змін - зони, в яку поширюється тріщина, що призводить до прискореного руйнування зразка. Цей ефект може бути пов'язаний з перерозподілом внутрішніх напружень і активізацією пластичної деформації в зоні перед тріщиною. В роботі експериментально зафіксовано рідкісний випадок "рекристалізації" під час деформації, коли два сусідніх зерна «зливаються» в одне внаслідок зміни кристалографічної орієнтації одного із сусідніх зерен як цілого в процесі пластичного деформування зразка. Можливість переорієнтації зерен як цілого в двовимірних зразках при пластичному деформуванні було встановлено експериментально в попередніх дослідженнях.

Ключові слова: *полікристалічного зразки алюмінію, пластична деформація, руйнування, механічні властивості.*