Critical stresses determination in case of pore formation for coarse- and ultrafine-grained Al-6101 under static tension

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Abstract. The stress-strain diagrams and the distribution of triaxial stresses, taking into account the difference in geometry for various structural states in Al-6101 under static loading, are analyzed in this paper.

1. Introduction
The problem of strength and durability calculations for various metal constructions is one of the most important in the modern world. Knowledge of various mechanical criteria of a material, such as strength, ductility, etc. is required to solve it \cite{1, 3, 4}. An important step in the process of a material fracture during loading is the pore formation in the area of critical stresses \cite{1}. In \cite{1}, the pore formation process was considered on steel and copper. The pore formation as well as their further merging and crack formation indicate the first step of a material fracture. Therefore, having data on the critical stresses of a material, it is possible to predict its rupture. A promising method for improving strength and other service properties of metals and alloys, including aluminum alloys, is the formation of ultrafine-grained (UFG) structures by severe plastic deformation (SPD). However, there are currently no studies on the pore formation for UFG aluminum alloys. Calculations of critical stresses that define the pore nucleation under static loading in coarse-grained (CG) and ultrafine-grained (UFG) Al-6101 alloy are presented in this paper.

2. Method
The technique is based on the article \cite{1}. We consider static loading of CG and UFG Al-6101. Samples of 6101 alloy were used in the form of rods with a diameter of 12 mm, obtained by combined casting and rolling. The initial samples were annealed at 550°C for 2 hours with subsequent water quenching at room temperature. After quenching, the samples with CG structure were subjected to artificial aging (AA) at 170°C for 12 hours.

The part of billets was processed by SPD via equal-channel angular pressing-Conform (ECAP-C) to obtain UFG structure. The grain size of UFG sample was about 500 nm. The technique, material and experiment are described in detail in \cite{3, 4}. The tension was performed at room
Figure 1. The samples with diameters of working sections of: a) 5 mm — geometry No. 1; b) 2 mm — geometry No. 2

temperature and constant tensile speed (strain rate of $1.4 \times 10^{-4}$ s$^{-1}$) on the Shimadzu AG-50kNX tensile machine. The deformation of the working part of the samples was registered using the Shimadzu TRViewX video extensometer. As in [1] various sample geometries for stretching were used: No. 1 — without a groove (diameter of the working section is 5 mm) and No. 2 — with a groove (diameter of the minimal section is 2 mm) (figure 1). The use of the samples of various geometry in the work was due to the interest in plotting the strain distribution map, as well as their relation to the areas where the pores were formed after the experiment.

Calculation of the critical stress value $\sigma_r$ at the metal matrix/particle interface was first carried out by the group of Argon, Im, and Needleman in [1]. They managed to derive the criterion of pore formation for rods made of coarse steel and copper with a groove:

$$\sigma_m + \sigma_{eq} \geq \sigma_r,$$

(1)

where

$$\sigma_m = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3)$$

(2)

is the hydrostatic stress,

$$\sigma_{eq} = \frac{1}{\sqrt{2}} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}$$

(3)

is the equivalent stress, $\sigma_1, \sigma_2,$ and $\sigma_3$ are the principal stress values.

The calculation for our material was carried out basing on this criterion.

Naturally, the formation of stresses and pores in a material depends on the geometry of the samples.

3. Results

At the first step, the samples of both types with CG and UFG structure were tested for tension to failure (table 1). The samples with UFG structure present larger strength and yield strength than samples in CG state (table 2). The obtained stress-strain curves were further used for simulation in the ANSYS program for constructing a map of stresses at various stages of extension. Critical stresses and the corresponding areas of the sample, where the pores should appear, were established using simulation. At the next step, the samples with CG and UFG structures were subjected to tension to some deformation, which were determined by simulation as critical for the pore formation. Then the tension was stopped.

Calculation of the triaxial (the sum of equivalent and hydrostatic) stresses distribution was made using the ANSYS 19.0 package for each geometry of UFG and CG samples. Table 2 presents the maps of the stresses distribution of the samples under tension. These stress
Table 1. The data on yield and tensile strength of CG and UFG Al-6101 samples of various geometry under static loading.

| Structure type | Sample No. | Yield strength, MPa | Tensile strength, MPa | Elongation, % |
|----------------|------------|---------------------|-----------------------|---------------|
| CG/AA          | 1          | 85                  | 226                   | 51            |
|                | 2          | 92                  | 237                   | 18            |
| UFG            | 1          | 304                 | 351                   | 33            |
|                | 2          | 310                 | 406                   | 8             |

Table 2. The triaxial stresses distribution for CG and UFG samples.

maps were compared with the cross section image of the sample and the pore formation region corresponds to the maximum stresses (figure 2).

After mechanical testing, samples were cut along the axis on the electro-erosion machine. Then the surface of the cut was grinded and polished to a surface roughness of 50 nm. The surface of the samples in the section (along the axis) was examined using the Zeiss Supra 40VP scanning electron microscope. The images of the axial sections of the samples as well as the sizes and location of pores inside the material were obtained (figure 2).

For visual clarity, let us mark the points with the pores in the image of the axial section of the sample with geometry No. 2.

Analysis of the triaxial stresses distribution with regard to differences in geometries shows that a groove leads to the stress values localization in the area of the section that has a minimal diameter, and the nature of the triaxial stresses distribution depends on the groove geometry.
Figure 2. a) The image of the section of CG and AA sample with geometry No. 2 (small areas around pores are highlighted in red for illustrative purposes); b) the triaxial stresses distribution for the same sample.

Table 3. The average void size for material with CG and UFG structure.

| Structure type | Grain size, µm | Void size, µm |
|---------------|---------------|---------------|
| CG/AA         | > 100         | From 3 to 7   |
| UFG           | 0.5 – 1.5     | From 1 to 2   |

The minimal value of the triaxial stresses, 331 MPa, refers to CG sample with geometry No. 1 (table 2), while the maximal value of the triaxial stresses, 944 MPa (ANSYS), is achieved in UFG sample (table 2).

The use of the Argon model and the results of a theoretical study of the triaxial stresses distribution in the samples during the tests made it possible to determine the critical stresses in case of pores $\sigma_r \approx 550$ MPa (equation (1)) for CG state of the sample No. 2. Analysis also suggests that the critical stress value during the pore formation in UFG material has higher values.

It was possible to clearly identify the area of the pore formation in the deformed samples of geometry No. 2. Comparing the image with the highlighted pores, obtained from the microscope, and our model from ANSYS, one can precisely define the boundary of the pore formation region for No. 2. At the same time, a theoretical analysis of the triaxial stresses distribution shows that UFG samples demonstrate higher values of the triaxial stresses in comparison with CG samples of the same geometry. Furthermore, this analysis indicates that UFG samples have higher critical stress values than CG samples [4]. The results of quantitative analysis of the pore sizes formed at the fracture region of the tensioned samples are presented in table 3. The pore size changes from CG to UFG range by more than 3 times.

Conclusion
The triaxial stresses distribution is uniform in the samples without a groove. The groove leads to a concentration of the triaxial stresses (i.e., increased values of hydrostatic stresses) in the groove area. The nature of the triaxial stresses distribution is defined by mechanical behavior of a material (i.e., its microstructure and aging state) and the groove geometry. In addition, the grain size in a material affects the size of the obtained pores. The pore size changes from CG to UFG range by more than 3 times. The minimal value of the triaxial stresses, 331 MPa, refers to CG sample with geometry No. 1, while the maximal value of the triaxial stresses,
944 MPa (ANSYS), is achieved in UFG sample. The use of the Argon model and the results of a theoretical study of the triaxial stresses distribution in the samples during the tests made it possible to determine the critical stresses in case of pores $\sigma_r \approx 550$ MPa (equation (1)) for CG state of the sample No. 2. The analysis also suggests that the critical stress value during the pore formation in UFG material has higher values.

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References

[1] Argon A S, Im J, and Needleman A 1975 Distribution of plastic strain and negative pressure in necked steel and copper bars Metallurg. Trans. A 6 815
[2] Valiev R Z and Alexandrov I V 2000 Nanostructured Materials Produced by Severe Plastic Deformation (Moscow: Logos)
[3] Magomedova D K and Murashkin M Yu 2018 Influence of grain size and second phase particles on the process of the void initiation J. Phys. Conf. Ser. 991 012055
[4] Magomedova D K, Murashkin M Yu, and Efimov M A 2018 Technique development for conducting mechanical tests to study the pore formation process in case of material fracture AIP Conference Proceedings 1959 070021