Mechanical properties and peculiar features of energy dissipation of ultrafine-grained aluminum alloys under dynamic deformation

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Abstract. This paper presents experimental results on the thermodynamics of deformation process and mechanical behavior of the ultrafine grained aluminum alloys under dynamic compression. Dynamic compression tests were performed on a Hopkinson-Kolsky split bar at the strain rate of \(10^3\) s\(^{-1}\) with simultaneously recording the surface temperature of samples by an infrared camera. Energy dissipation ability was determined for ultrafine-grained alloys. An inverse strain rate dependency of dynamic yield strength was observed in the ultrafine-grained Al-Zn-Mg-Cu alloy (A7075).

1. Introduction

For many years the ultrafine-grained (UFG) and nanostructured materials attract enhanced attention of researches from different fields of science because of the unique structural states and, therefore, unusual physico-mechanical properties of these materials. The paper is focused on high strength aluminum commercial alloys developed for aircraft and space industry. The mechanical properties of such materials under extreme loading conditions (for example, high-strain rate deformation, shock-wave loading and high pressure action) are of great interest for their application. The paper presents experimental data on dynamic compression tests of the ultrafine-grained Al-Zn-Mg-Cu (A7075) and Al-Mn (A3003) alloys together with the results of infrared scanning in the course of deformation process. The Hopkinson-Kolsky split bar was used for compression tests. The infrared camera has allowed to register the temperature field on the sample’s surfaces and in accord with these data the dissipated and the stored energies were evaluated. Also, structural investigations of the samples before and after dynamic compression were carried out. The
obtained results were put to comparison with those for coarse grained (CG) conventional materials of the same chemical composition.

The UFG structures in the alloys were formed via high strain rate shear deformation using dynamic channel angular pressing (DCAP) [1]. The strain rate in the DCAP experiments has reached $10^5 \text{ s}^{-1}$. Deformation process duration is estimated as about 50 µs.

Different DCAP conditions such as strain rate and accumulated strain (depending on the initial velocity of the sample, $V$, and the number of pressing cycles, $N$, respectively) have provided for the formation of several structural states in the alloys. These structural states differed in a grain size, which was in the range of 200-500 nm, in an internal stress (dislocation density), grain boundary states (equilibrium, nonequilibrium), and a fracture of recrystallized structure. The mentioned structural features affect mechanical behavior and dissipation energy values. Each of the parameters is given to consideration in this paper.

2. Materials and experimental techniques

The objects of the present investigation are the UFG and CG aluminum alloys A7075 and A3003. Chemical compositions of the alloys are listed in the table 1. The samples with UFG structure were produced by DCAP at different deformation conditions (tab. 2).

Table 1. Chemical composition of the alloys investigated, wt, %

| Alloy  | Al   | Mn   | Zn   | Mg   | Cu   | Si    | Fe | Cr | Others |
|-------|------|------|------|------|------|-------|----|----|--------|
| A3003 | base | 1.0-1.5 | 0.1 | - | 0.05-0.2 | 0.6 | 0.7 | - | 0.15 |
| A7075 | base | 0.2-0.6 | 5.0-7.0 | 1.8-2.8 | 1.4-2.0 | 0.5 | 0.5 | 0.1-0.25 | 0.25 |

Table 2. DCAP deformation conditions

| Alloy  | $V$, m/s | $N$ |
|-------|----------|-----|
| A3003 | 150      | 1   |
|       | 300      | 4   |
| A7075 | 150      | 1   |
|       |          | 2   |

In the traditional Hopkinson – Kolsky method (fig. 1) [2], a sample is placed between two measuring bars. By the plunger accelerated by the gas gun, a one-dimensional elastic compression wave is actuated in the tested sample. The sample undergoes elastic-plastic deformation, but the bars are deformed elastically during compression. Elastic deformation impulses in the bars are registered by piezoelectric sensors. Then the stress, strain, and strain rate can be determined as functions of time (1)-(3). Excluding the time as a parameter, one can plot a stress-strain diagram ($\sigma_n(\varepsilon_n)$).
\[
\sigma_n(t) = \frac{EA}{A_0} \varepsilon^n(t), \\
\varepsilon_n(t) = -2c \int_0^t \varepsilon^k(t) dt, \\
\dot{\varepsilon}_n(t) = -2c \varepsilon^k(t),
\]

where \( E \) is the Young's modulus of the material of the bars, \( A \) is the cross section area of the bars, \( A_0 \) and \( L_0 \) are the cross section area and the length of the sample, respectively. Dynamic compression was provided at strain rates of 4 and \( 6 \times 10^3 \) s\(^{-1}\).

Figure 1. The scheme of Hopkinson-Kolsky method. 1 – gas gun, 2 – plunger, 3 – entry bar, 4 – sample, 5 – exit bar.

The regularities of energy dissipation during deformation were investigated using infrared thermography. The infrared camera FLIR SC 5000 was used for in-situ measurements of the temperature distribution on the surface of the samples. The camera has spectral range of 3-5 µm, temperature sensitivity of 0.025 K, and spatial resolution of 0.2 mm. Frequency shooting was of 3 kHz. Having the data on mean temperature of the sample, the dissipation energy and storage energy can be evaluated [3]. Considering that under dynamic loading the heat loss during the exchange with the environment is negligible, than the fraction of dissipated energy can be defined as

\[
\beta_d = E_d / E_1,
\]

where \( E_1 \) is the energy expended on the deformation of the sample, \( E_2 \) is the energy converted into heat.

An investigation of fine structure of the samples was performed by using the transmission electron microscope (TEM) Philips CM-30 at accelerating voltage of 300 kV. The average crystallite size was calculated over dark field patterns. The X-ray diffraction analysis was carried out in Co K\(_\alpha\) radiation on the θ-θ diffractometer D8 Advance Bruker AXS. Based on the effect of line broadening, the mean square lattice microdistortion \( \left\langle \varepsilon^2 \right\rangle^{1/2} \) was determined, and the lattice dislocations density \( \rho_d \) was also evaluated. Hardness and microhardness measurements were carried out.
3. Experimental results and discussion

3.1. Grain size and internal stress

In the Al-Zn-Mg-Cu alloy processed by DCAP one can observe the developing of a fragmentation process with growth in the accumulated strain. Profile changes of grain size distributions (fig. 2 b, c) are indicative of continuous grain refinement.

![Figure 2. A7075 alloy. a – TEM pattern of the structure after 2 cycles of DCAP; b, c - grain size distribution of the samples after 1 and 2 DCAP cycles respectively.](image)

The level of internal stresses that was evaluated from X-ray diffraction data (mean square lattice microdistortion $\langle \varepsilon^2 \rangle^{1/2}$) increases as well as lattice dislocation density (fig. 3). The formed structure is nonequilibrium (fig. 2a). The large fraction of grain boundaries is characteristic of high-angle nonequilibrium boundaries as judged by a high density of grain boundary defects.

![Figure 3. Mean square lattice microdistortion changes and lattice dislocation density for A7075 alloy deformed by 1 and 2 cycles of DCAP.](image)

The fraction of the energy dissipated during dynamic compression was calculated for the UFG and CG alloys. There is strong increasing in the dissipation energy value depending on preliminarily accumulated strain (fig. 4a). The more the amount of structural defects (lattice dislocations, grain boundary defects, grain boundary volume), the more the dissipated energy of the material. Aluminum alloys in the UFG state have greater dissipation ability than the CG
ones. Such difference in the dissipation energy between UFG and CG alloys is
due to structural relaxation processes, such as dynamic recovery and dynamic
recrystallization. According to TEM investigations, X-ray diffraction analysis,
and hardness measurements, these processes arise in the samples having
nonequilibrium fragmented structure. And the more the amount of structural
defects, the more the intensity of the relaxation process. On the other hand, in
the CG samples having subgrains with a size of 1.5-2 µm, such deformation leads
to the subgrain refinement. The subgrain size becomes equal to 300 nm.
However, low angle crystallite boundaries are prevailing.

The UFG and CG alloys are characterized by differing mechanical
behavior. So, the CG Al-Mn alloy has normal strain rate dependence of yield
strength. The UFG Al-Zn-Mg-Cu alloy has inverse dependence. The yield stress
value decreases with increasing strain rate (fig. 4b).

3.2. Grain boundaries state and recrystallized structure

Previously the behavior of the UFG materials with a nonequilibrium
structure was discussed. The effects of the grain boundaries condition (states)
and the fraction of recrystallized grains on the thermodynamics of the
deformation process was studies on the example of the Al-Mn alloy (A3003).

During DCAP, the dynamic recrystallization in this alloy develops owing
to high dislocation mobility and the absence of the second phase precipitates. The
UFG structure of the Al-Mn alloy transforms depending on DCAP deformation
conditions. Thus at V=150 m/s and N=1, UFG structures having the grain size of
500 nm and the defective boundaries of crystallites forms due to the
fragmentation process (fig. 5a). At V=300 m/s and N=4 the structure with
equilibrium grain boundaries forms as a result of dynamic recrystallization (fig.
5c).
It is shown that the fragmented structure is characterized by higher dissipation ability than that of a recrystallized one. Thus, the fraction of dissipated energy is 0.56 for the fragmented structure and 0.49 for the recrystallized structure. At the same time, the fragmented structure transforms to the dynamic recovered structure (more equilibrium state) and the recrystallized one transforms to the mixed structure, that gives evidence of a new stage of the fragmentation (fig. 5 b, d). Namely, within the grains we observe a high number density of dislocations and newly formed low angle boundaries.

4. Conclusions
Based on obtained experimental data it was established that the fraction of dissipated energy in UFG alloys is essentially higher in comparison with CG analogs. The dynamic deformation causes structural relaxation processes in the
UFG alloys with nonequilibrium structure, whereas in the alloys with recrystallized structure the processes of the fragmentation and defects accumulation are at an advantage. The UFG Al-Zn-Mg-Cu alloy reveals anomalous strain rate dependency of dynamic yield strength.

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