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Effect of powerful pulsed and continuous ion beams on the Al-Cu-Mg alloy structure

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Abstract. The paper considers the results of an electron microscopy study of the VD1 alloy of the Al-Cu-Mg system after cold working and subsequent irradiation with a powerful pulsed ion beam (70% C^+ + 30% H^+, E = 180 keV) in the pulsed-periodic mode (τ = 80 ns, f = 0.1 Hz, j = 200 A/cm^2, F = $1{\cdot}10^{14}$ cm^{-2}) and under the conditions of the generation of only one pulse (τ = 180 ns, j = 100 A/cm^2, F = $2{\cdot}10^{15}$ cm^{-2}). It is established that this irradiation noticeably affects the microstructure of the cold-worked 3 mm thick sheets of VD1 alloy. The initial cellular dislocation structure transforms into a subgrain one. The intensity of structural transformations in the alloy increases with ion current density of a pulse. A similar transformation of a dislocation structure over the entire thickness of the sample is observed under irradiation with continuous Ar^+ ion beams (E = 20-40 keV) with not high fluences (10^{15}-10^{16} cm^{-2}).

1. Introduction

The nature of *long-range effect* under both continuous and pulsed ion implantation is still under investigation. The exposure of powerful ion beams (with the ion energy is 10^5-$3{\cdot}10^5$ eV, the energy density in the pulse is 1-3 J/cm^2, and the pulse duration is ~100 ns) on metal materials leads to changes in the structural state of its surface layers, the thickness of which exceeds the projective ion range by 2-3 orders of magnitude and the layer thickness heated during pulse action exceeds it by 1-2 orders of magnitude [1-3]. The changes at large depths are associated with quenching effects due to the rapid (>10^9 K/s) cooling of the heated layer and waves of mechanical stresses (thermoelastic waves) formed due to thermoelastic processes and recoil momentum during the pulsed evaporation of the surface layer of the target. Such waves can strongly affect the structure and properties of materials and lead to the formation of various radiation and deformation defects.

It is established that structural-phase transformations under irradiation with not only a *powerful pulsed* but *continuous* beams of midenergy (from a few tens to several hundred keV) ions take place not only in the ion penetration zone, but also in the region that exceeds the projected ranges of ions by more than a factor of 10^3-10^4 [4-13]. To explain the nature of these long range effects under continuous ion irradiation, a hypothesis has been proposed, which is associated with the propagation of intense post-cascade solitary waves resulted from the evolution of dense cascades of atomic collisions [14, 15] and are able to restructure the metastable media [10, 16].

In connection with this, it is of interest to compare the influence of the pulse-repetitive and continuous ion beams on the structure and properties of the alloy at similar fluences, as well as to compare these results with the effect of a single powerful ion pulse when the fluence of implanted ions is minimal and cannot play a noticeable role in changing the composition of the surface layer.

An electron-microscopy examination of the exposure of nanosecond pulses (with a high current density in the pulse) on the structure and phase composition of the VD1 alloy of the Al-Cu-Mg system were performed with the goal to compare the results with previously obtained data on the influence of continuous Ar^+ ion beams with an energy of 20-40 keV on structural-phase state of the VD1 alloy [11-13].

2. Experimental

The samples to be investigated were cut from cold-worked VD1 alloy (Al - 1.84 Cu, 0.79 Mg, 0.29 Mn, wt %) sheets ~3 mm thick (ε = 60%) fabricated at the Kamensk-Ural'skii metallurgical works. The sheets were cladded with technically pure aluminum from each side. The thickness of the clad layer was 60 µm.

The VD1 alloy samples were irradiated from one side by a powerful ion beam (70% C^+ + 30% H^+) under conditions of single-pulse generation and in a pulse-repetitive mode (at a pulse repetition rate of f = 0.1 Hz) using a TEMP accelerator (Tomsk Polytechnical University) at a pulse duration τ = 80 ns. The ion energy was 180 keV. In the case of a single pulse, the ion current density was 200 A/cm^2 that corresponds to a fluence of $1 \cdot 10^{14}$ cm^{-2}. The pulse-repetitive mode irradiation was performed at an ion current density of 100 A/cm^2 to a fluence of $2 \cdot 10^{15}$ cm^{-2}. The average temperature of the samples during irradiation did not exceed 30°C.

The electron microscopy analysis was carried out by the method of thin foils using a JEM-200 CX transmission electron microscope. TEM examination was carried out in a cross section and in the section parallel to the irradiated surface at a distance of ~150 µm from it.

3. Results

The VD1 alloy in the initial cold-worked state is characterized by a dislocation cellular structure with narrow boundaries between the cells (Figure 1*a*). The cell boundaries are dense dislocation tangles. The diameter of the cells is 0.5-2 µm. Inside the cells the dislocation networks are observed (Figure 1*b*). Some regions in the sample exhibit subgrain structure (Figure 1*c*), but the fraction of such regions is relatively small. Slip bands 0.3-0.5 µm wide (Figure 1*d*) are observed in the cross section of the sample. The bands contain randomly distributed dislocation tangles.

The study of the phase composition of the alloy has shown the clusters of equiaxed Al_8Fe_2Si particles ~50-100 nm in diameter (Figures 1*c*, 1*d*) inside the cells along both longitudinal and transverse sections of the alloy sample. Figure 1*e* illustrates an electron diffraction pattern with reflections from that phase.

Irradiation with single pulses. The investigation of the longitudinal section of the VD1 alloy sample at a distance of 150 µm from the irradiated surface after one-sided irradiation with *single pulses* of 70% C^+ + 30% H^+ ions at the ion current density j = 200 A/cm^2 (fluence of 10^{14} cm^{-2} per pulse) revealed almost complete transformation of the cell structure into a subgrain one over the examined section (Figure 2). Subgrains formed have an equiaxed shape and an average diameter of 1-3 µm. The subgrains are almost free of dislocations. The signs of the cellular structure, namely, imperfect subgrain boundaries, have been retained only in several regions of the sample, which occupy the insignificant volume of the sample.

Some subgrains, similar to the initial state, include a small number of equiaxed Al_8Fe_2Si particles ~100 nm in diameter.

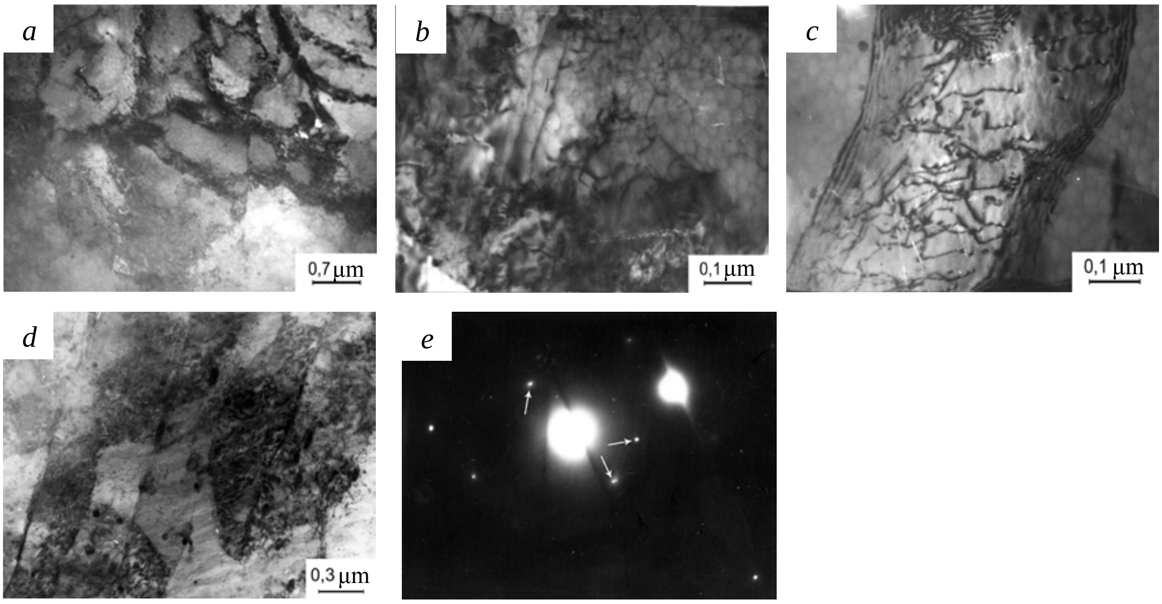


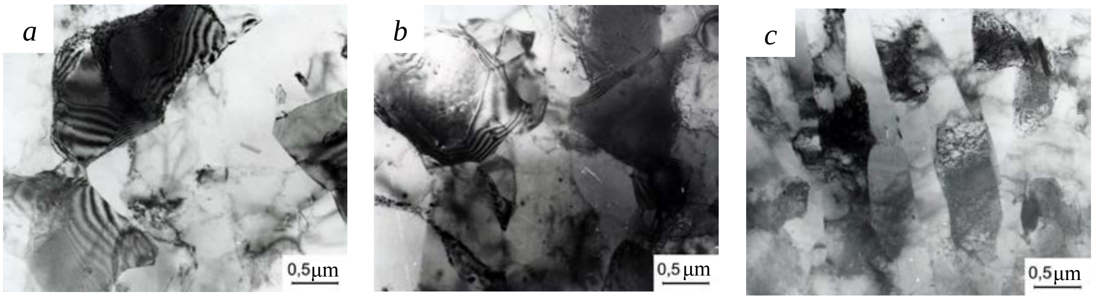
Figure 1. Microstructure of the VD1 alloy in the initial cold-worked state: *a*-*c* – longitudinal section of the sample: *a*, *b* – cellular structure; *c* – subgrain structure; *d* – slip bands in the cross section; *e* – electron diffraction pattern with reflections from the Al_8Fe_2Si phase.

The investigation of the cross section of the sample confirmed that irradiation in the *single pulse* mode caused the transition of the structure from cellular to the subgrain one over the entire sample volume (Figure 2*a*). For example, elongated or equiaxed-shaped subgrains are observed inside slip bands near the irradiated surface. They are particularly free of dislocations (Figure 2*c*). The opposite surface of the sample 3 mm thick also have slip bands (which contain individual subgrains) free of randomly distributed dislocations, but they are narrower then those observed on irradiated surfase. The subgrains exhibit either the finest subgrains or they are separated into individual fragments by cell boundaries (Figure 2*d*). Thus, irradiation affected the structure of the VD1 alloy over the entire depth of the sample, but this effect decreased with distance from the irradiated surface.

Pulse-repetitive mode. Irradiation of the sample in the pulse-repetitive mode at a lower ion current density j = 100 A/cm^2 and a higher fluence $2\cdot10^{15}$ cm^{-2} resulted in the formation of a mixed structure in the alloy: in some regions, a cellular structure dominates (Figure 3*a*), in other, subgrain one (Figure 3*b*), whereas the signs of the both structures are observed in the third regions (Figure 3*c*). The average diameter of subgrains varies from 0.5 to 1.5 μm and is comparable with the cell diameter.

The figures demonstrate a small number of equiaxed Al_8Fe_2Si particles ~100 nm in diameter in several subgrains.

Slip bands are clearly observed in the cross section of the sample. The bands become narrower at a distance from the irradiated surface (Figures 3*d*, 3*e*). Similar to that in longitudinal section, the mixed structure is observed in the bands located near the irradiated surface (Figure 3*d*): some of them contain fine subgrains, whereas others are fragmented into separate blocks by dense dislocation tangles. There are almost no subgrains within slip bands near the opposite surface, whereas dislocation tangles are wider. However, this structure is more perfect as compared with that of the deformed state. Our results confirmed the effect of irradiation over the entire depth of the sample 3 mm thick.



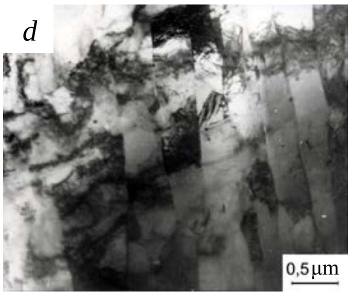


Figure 2. Subgrain structure in the VD1 alloy after pulsed irradiation with 70% C^+ + 30% H^+ ions at E = 180 keV, j = 200 A/cm^2, F = 10^{14} cm^{-2}: a, b – longitudinal section of the sample; c, d − cross section of the sample: c − near the irradiated surface, d − near the unirradiated surface.

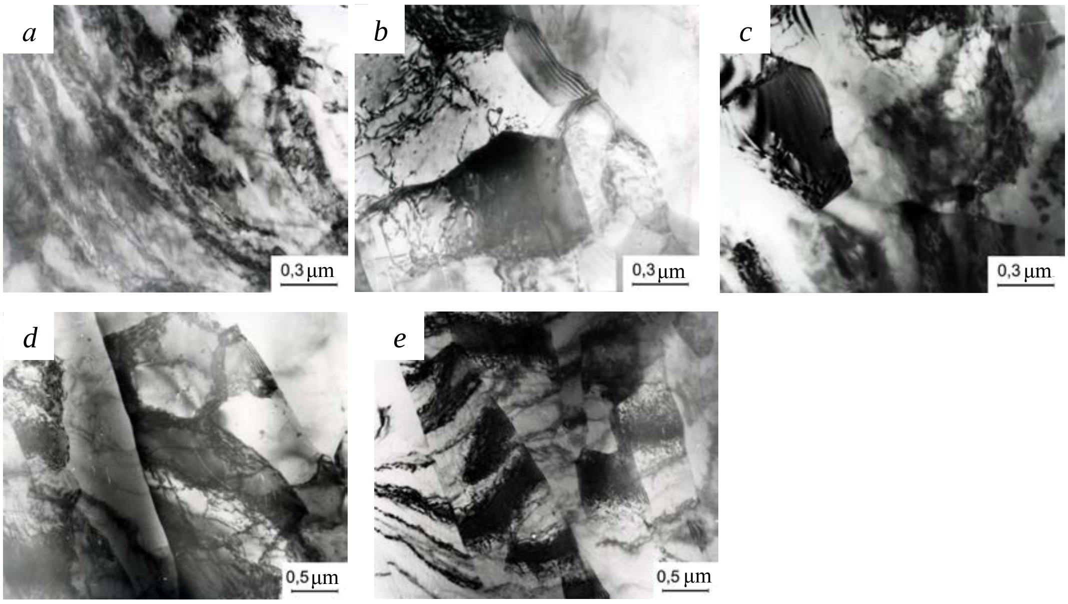


Figure 3. Microstructure of the VD1 alloy after pulsed irradiation with 70% C^+ + 30% H^+ ions at E = 180 keV, j = 200 A/cm^2, F = 10^{15} cm^{-2}: *a-c* – longitudinal section of the sample, *d*, *e* – cross section of the sample: *d* – near the irradiated surface, *e* – near the unirradiated surface.

Continuous mode. It was established previously in [11-13] that the effect of continuous Ar^+ ion beams with an energy of 20-40 keV on the cold-worked VD1 alloy also led to the transformation of the structure from cellular dislocation to subgrain at relativity low fluences (10^{15}-10^{16} cm^{-2}) and to the formation of a coarse-grained structure with a grain size of more than 10 μm at elevated fluences (~ 10^{17} cm^{-2}). Furthermore, at elevated fluences, supersaturated solid solution decomposition was observed in the alloy with the precipitation of hardening θ'(θ'') phase ($CuAl_2$). The above structural changes occur with a high rate (during a few seconds or *tens of seconds* of irradiation) over the entire sample volume 3 mm thick, which exceeds the projective Ar^+ ion range by a factor of more than tens of thousands. The average projected *range* of Ar^+ ions with an energy of 40 keV in the studied alloys is ~40 nm, according to calculations. There is no a prolonged holding of samples at elevated temperatures, as in the case of conventional furnace annealing [11-13].

Thus, under the effect of powerful nanosecond pulsed ion beams (70% C^+ + 30% H^+, E = 180 keV, j = 200 A/cm^{-2}, F = 10^{14} cm^{-2}), the transformation of the dislocation structure is observed over the entire sample volume of the cold-worked VD1 alloy of the Al-Cu-Mg system, which is similar to that occurring under irradiation of this alloy with continuous ion beams (Ar^+, E = 20-40 keV, j = 150-400 μA/cm^2) at comparable fluences (10^{15}-10^{16} cm^{-2}) [11-13]. Irradiation in the pulse-repetitive mode at a lower ion current density has a slightly less effect on the state of the alloy.

4. Summary

Thus, irradiation with single and repetitive pulses of 70% C^+ + 30% H ions substantially affects the microstructure of the cold-worked VD1 alloy. The initial cellular dislocation structure of the alloy transforms into the subgrain structure. The influence that the ion current density has on the degree of transformation of the initial structure of the alloy was found. More intense structural changes took place under the effect of a single pulse with a higher ion current density (j = 200 A/cm^2), despite a lower value of fluence of – 10^{14} см$^{-2}$ (at j = 100 A/cm^2, samples were irradiated to a fluence of $2\cdot10^{15}$ cm^{-2}).

The electron microscopy study of the VD1 alloy samples in both the section parallel to the irradiated surface at a distance of ~150 μm from it and the transverse section indicates that the depth of the effect of pulsed powerful ion beams exceeds the projective ion paths in this alloy by a factor of more than 1000. The initial cellular dislocation structure transforms into a subgrain one. A similar transformation of a dislocation structure is observed under irradiation of this alloy with continuous Ar^+ ion beams with small fluences (10^{15}-10^{16} cm^{-2}) [11-13].

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