Supplementary material

1. Competing mechanisms: strengthening and softening

The lack of strength increase despite such substantial grain refinement is explained by the competition between two oppositely directed processes.

1. Strengthening via grain refinement (Hall–Petch effect)

Refining the grain size from ≈25 μm to ≈2 μm would be expected to provide significant strengthening according to the Hall–Petch relationship [30]. Grain-boundary strengthening is one of the primary mechanisms for increasing the strength of aluminum alloys subjected to severe plastic deformation. The increase in total grain boundary area creates effective barriers to dislocation motion, thereby raising the flow stress.

2. Softening due to coagulation of $Al_3(Sc, Zr)$ particles

During high-temperature deformation ($325°C \approx 0.6T_m$), coagulation (coarsening) of nanoscale $Al_3(Sc, Zr)$ particles occurs [31], particularly near grain boundaries. Initially coherent particles with a size of several nanometers provide effective dispersion strengthening via the Orowan or Mott-Nabarro mechanism [30, 32, 33]. However, during prolonged holding and deformation at elevated temperatures, the particles lose coherency and coarsen, leading to a reduction in the contribution of dispersion strengthening. The kinetics of $Al_3(Sc, Zr)$ coarsening at elevated temperatures are described in detail in [31, 34 – 36].

Thus, the reduction in dispersion strengthening due to particle coarsening offsets the strengthening from grain refinement, and the strength remains at the initial level.

2. Enhancing ductility: the role of high-angle grain boundaries and structural homogeneity

The increase in ductility from 28% to 38% while maintaining strength is an unusual result, associated with the specific features of the formed microstructure.

1. High fraction of high-angle grain boundaries (HAB ≈ 78%)

The formation of a structure with predominantly high-angle grain boundaries (misorientation >15°) provides several mechanisms for enhancing ductility:

– *Activation of multiple slip systems.* High-angle grain boundaries, unlike low-angle ones, effectively transmit stresses and promote the activation of slip systems in neighboring grains, ensuring a more uniform distribution of deformation [30, 37, 38].

– *Grain boundary sliding (GBS).* In ultrafine-grained aluminum alloys, the contribution of GBS at room temperature is enhanced, which contributes to additional deformation capacity [30, 39, 40].

– *Reduction of stress concentration.* The uniform distribution of grains with equilibrium high-angle grain boundaries reduces local stress concentration and suppresses premature fracture [41].

2. Structural homogeneity and facilitation of strain transfer

The uniform distribution of grains with a size of about 2 μm and a narrow size distribution (structural homogeneity) creates favorable conditions for deformation kinetics [42]. In such a structure, strain transfer from grain to grain is facilitated, since there are no large grains acting as stress concentrators and no regions with poorly deformable low-angle boundaries. This promotes more uniform flow of the material and increases the overall deformation capacity [30, 43, 44].

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