

Supplementary Material

The impact of direct current electro-treatment on the microstructure and mechanical behavior of cold-rolled 2014 aluminum alloys

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Supplementary Information on Steady-state Temperature Estimations during Electro-treatment Using Finite Element Simulation

During electro-treatment at each current density, a K-type thermocouple was used to monitor temperature variations, and the steady-state temperatures were recorded. To validate the accuracy of these measurements, steady-state temperatures were also simulated using finite element analysis (FEA) in Ansys ICEPAK. A constant current boundary condition was applied at the Cu electrode interfaces to model direct current flow. Natural convection with a heat transfer coefficient of $10 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}$ was imposed on all outermost exposed surfaces of the setup to account for air cooling [29]. Temperature-dependent material properties, including electrical resistivity, thermal conductivity, and specific heat capacity, were incorporated to improve thermophysical accuracy. The model employed an unstructured hexahedral mesh comprising about 1.26 million elements and 1.3 million nodes. The maximum element size was limited to 12 mm, with minimum gap constraints of 0.2 mm in the X and Z directions and 0.1 mm in the Y direction. Local mesh refinement was introduced at the electrode/specimen interfaces, and the mesh assemblies separately option was enabled to maintain thermal continuity across material boundaries [S1].

- [S1] X. Tian, H. Zhang, Z. Qu, S. Ai, An efficient finite element mesh generation methodology based on μ CT images of multi-layer woven composites, *Compos. Part Appl. Sci. Manuf.* 184 (2024) 108255. <https://doi.org/10.1016/j.compositesa.2024.108255>

Supplementary Information on Determination of Cleanup Procedures for the EBSD Post-processing

Prior to standard EBSD quantitative analyses, we evaluated grain-dilation cleanup procedures to reduce undesirable isolated misindexed pixels (e.g., “random-orientation crosses” inside initially unindexed interiors) while preserving true grain morphology. The standard settings of EBSD post-processing parameters were tolerance angle of 5° , minimum grain size of $1\ \mu\text{m}$, grains required to span multiple rows setting, and single iteration setting [29]. Direct comparisons of the EBSD IPF maps before (raw data) and after cleanup (Fig. S1) showed that under the cold-rolled, $1.4 \times 10^4\ \text{A/cm}^2$ for 1 h, and $1.6 \times 10^4\ \text{A/cm}^2$ for 1 h conditions, the operation produced “random-orientation crosses” inside initially unindexed interiors, which is recognized as over-cleanup/neighbor correlation rather than true grain morphologies. Therefore, in the manuscript, these three conditions were presented from raw and uncleaned orientation grids for all quantitative analyses. Under the $1.8 \times 10^4\ \text{A/cm}^2$ for 1 h and $2.0 \times 10^4\ \text{A/cm}^2$ for 1 h conditions, the residual unindexed pixels were confined to grain boundaries, and no artifacts were observed; therefore, these two conditions were presented after one grain-dilation iteration with the parameters above.

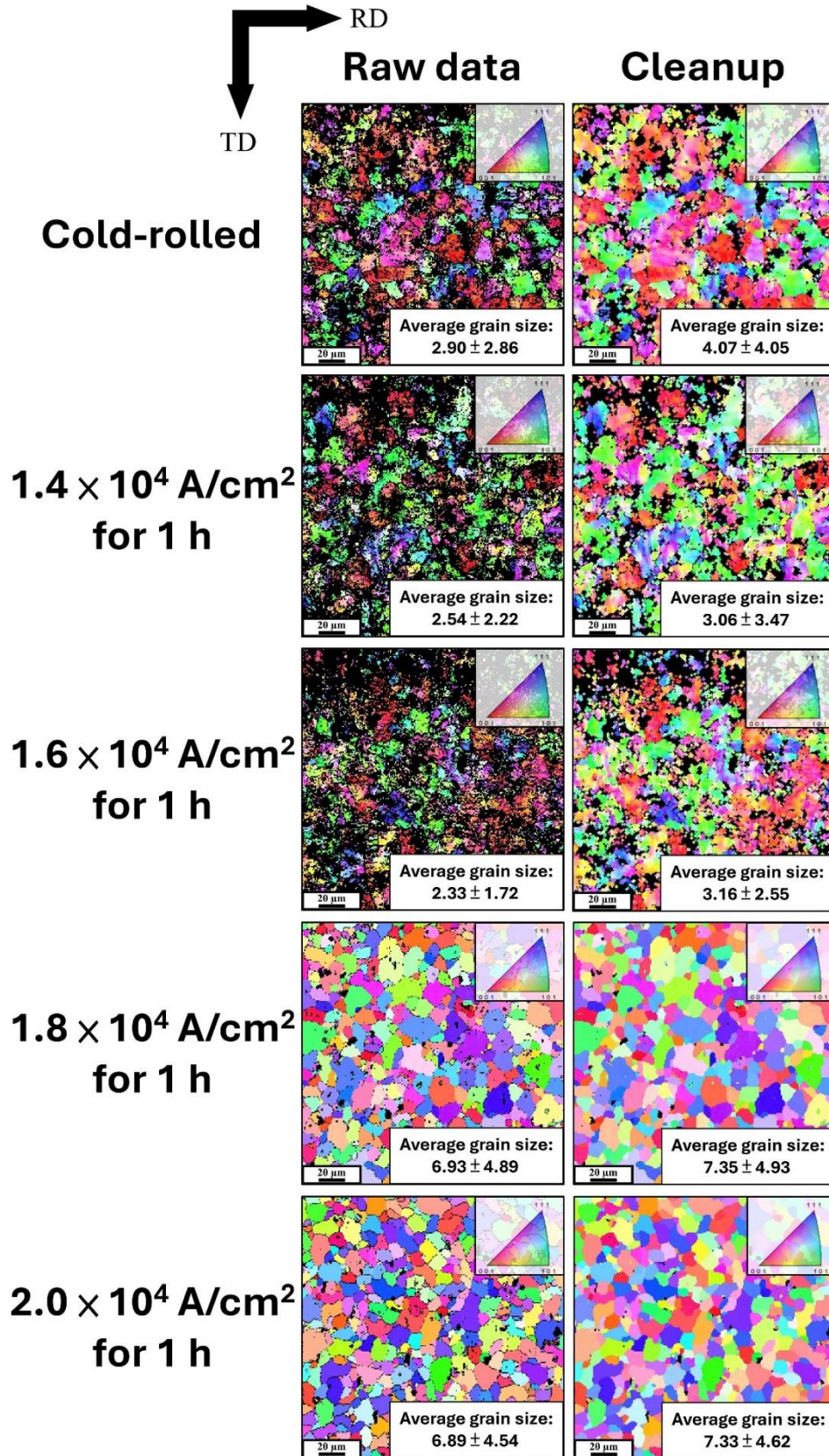


Fig. S1. Direct comparisons of the EBSD IPF maps before (raw data) and after cleanup using the grain dilation method for the cold-rolled AA2014 strips before and after the ET at $1.4 \times 10^4 \text{ A/cm}^2$, $1.6 \times 10^4 \text{ A/cm}^2$, $1.8 \times 10^4 \text{ A/cm}^2$, and $2.0 \times 10^4 \text{ A/cm}^2$ for 60 minutes.

Supplementary Information on Grain Size Distribution: Average Grain size and Standard Deviation

Fig. S2 presents the grain size distribution charts of the AA2014-CR strips before and after the ET at different current densities ($1.4\text{--}2.0 \times 10^4 \text{ A/cm}^2$) for 60 minutes. Under the cold-rolled condition and those treated at relatively low current densities of 1.4 and $1.6 \times 10^4 \text{ A/cm}^2$ (Fig. S2(a)-(c)), the grain distribution was dominated by uniformly small grains, with minimum grain sizes measured as 1.27 , 1.28 , and $1.28 \mu\text{m}$, respectively. When recrystallization occurred above $1.8 \times 10^4 \text{ A/cm}^2$, the grain distributions widely spread, revealing different degrees of recrystallization of grains. All the minimum grain sizes measured exceed the step size applied in this study ($0.8 \mu\text{m}$).

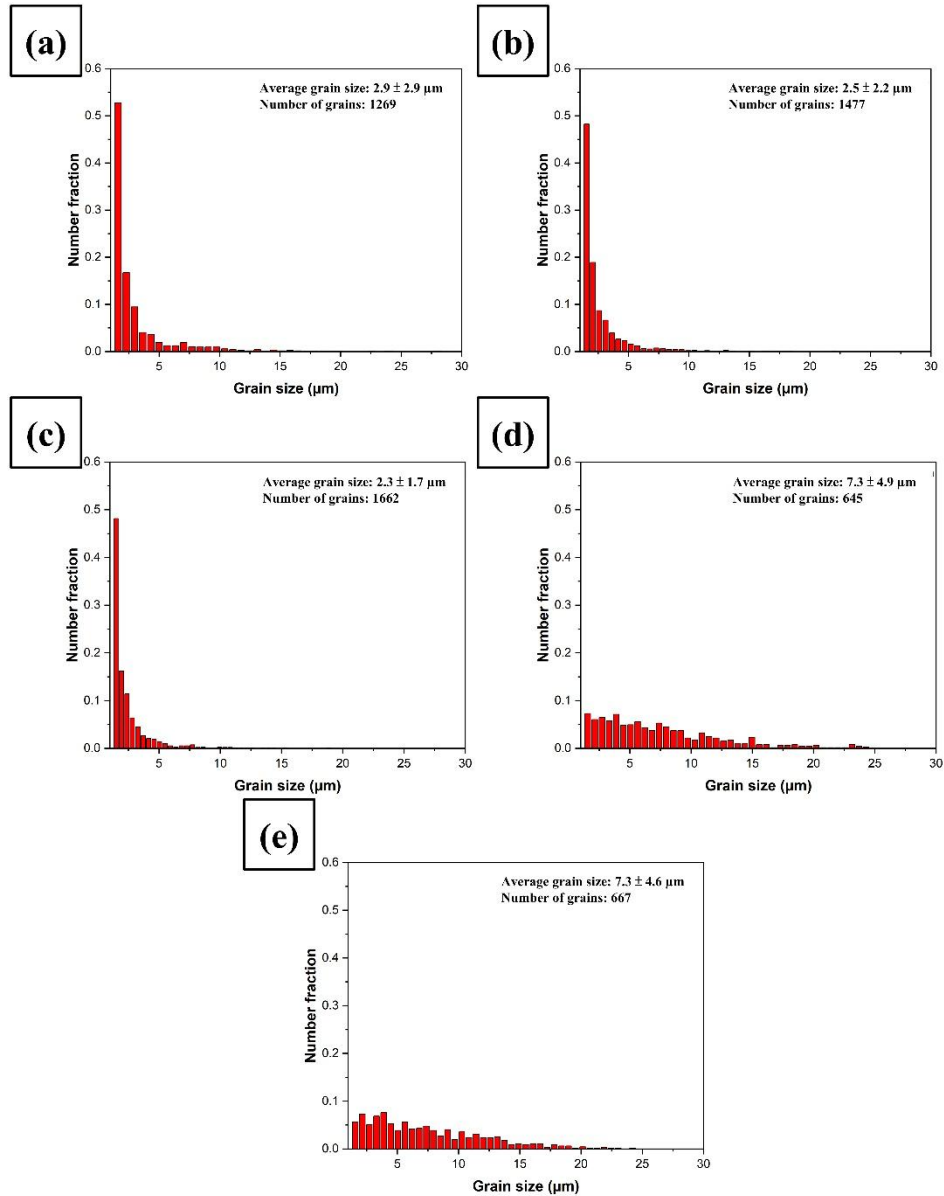


Fig. S2. Grain size distribution charts of the AA2014-CR strips before and after the ET at different current densities for 60 minutes: (a) cold-rolled benchmark; (b) $1.4 \times 10^4 \text{ A/cm}^2$; (c) $1.6 \times 10^4 \text{ A/cm}^2$; (d) $1.8 \times 10^4 \text{ A/cm}^2$; (e) $2.0 \times 10^4 \text{ A/cm}^2$.