

Supplementary Materials

Role of Mn in partitioning behavior and precipitation evolution in multicomponent Fe-Cu-based steels

Nianshuang Qiu^{1,2,3}, Sonia Guehairia², Peter Hedström², Zhuang Shen^{1,3}, Linlin Zhao⁴, Xiaowei Zuo^{1,3}, Tao Zhou²

¹Dongguan Key Laboratory of Interdisciplinary Science for Advanced Materials and Large-scale Scientific Facilities, School of Physical Sciences, Great Bay University, and Great Bay Institute for Advanced Study, Dongguan 523000, Guangdong, China.

²Department of Materials Science and Engineering, KTH Royal Institute of Technology, Stockholm SE-100 44, Sweden.

³Key Laboratory of Electromagnetic Processing of Materials (Ministry of Education), and School of Metallurgy, Northeastern University, Shenyang 110819, Liaoning, China.

⁴HBIS Material Technology Research Institute, HBIS Group, Shijiazhuang 050023, Hebei, China.

Correspondence to: Dr. Xiaowei Zuo, Dongguan Key Laboratory of Interdisciplinary Science for Advanced Materials and Large-scale Scientific Facilities, School of Physical Sciences, Great Bay University, and Great Bay Institute for Advanced Study, Dongguan 523000, Guangdong, China. E-mail: zuoxw@gbu.edu.cn; Dr. Tao Zhou, Department of Materials Science and Engineering, KTH Royal Institute of Technology, Stockholm SE-100 44, Sweden. E-mail: taozhou@kth.se

Nanoindentation load-depth and stress-strain curves for the three steels aged for 1 h are shown in Fig. S1. At an indentation depth of 4000 nm, Cu-0Mn steel reaches a peak load of ~600 mN, Cu-4Mn steel reaches ~950 mN (+58%), and CuNiAl-4Mn steel reaches ~1000 mN, reflecting progressively enhanced hardness and plastic deformation resistance with Mn addition and alloying complexity. Nanoindentation-derived yield strengths follow the same trend: ~820 MPa for Cu-0Mn, ~1300 MPa for Cu-4Mn, and ~1600 MPa for CuNiAl-4Mn. The higher yield strength in Mn-containing steels produces a smaller plastic zone and steeper strain gradient at the onset of indentation, requiring greater load at equivalent depth. The nanoindentation stress values are systematically higher than those from room-temperature tensile testing, consistent with the well-known constraint effect inherent to indentation-based measurements.

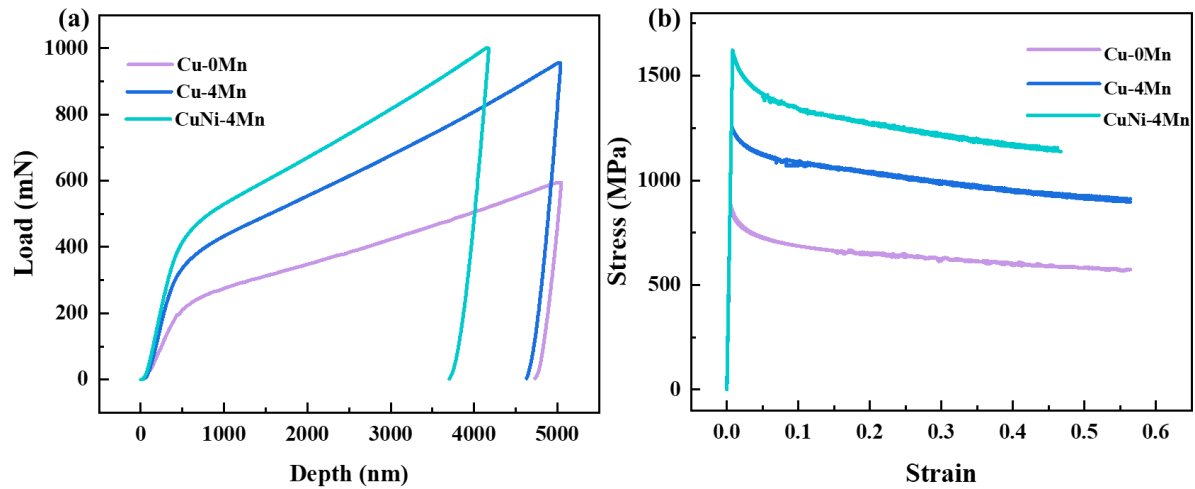


Fig. S1 (a) Nanoindentation load-depth curves of 1 h aged samples, (b) Nanoindentation stress-strain curves of 1 h aged samples.

STEM characterization of Cu precipitate distribution in the three steels is shown in Fig. S2. In Cu-0Mn steel, precipitates are uniformly distributed within grains (Fig. S2a), with coarser particles (6–10 nm) preferentially located at grain boundaries and dislocations. These regions

serve as fast diffusion pathways, promoting early nucleation and accelerated local coarsening [1]. B2-ordered precipitates are clearly identified along the $[110]$ zone axis (Fig. S2b), consistent with the known nucleation behavior of Cu phases in the α -Fe matrix [2]. In Cu-4Mn steel, pronounced precipitate coarsening is observed, with average intragranular sizes reaching 16–20 nm and strong precipitate-dislocation interactions evident (Fig. S2c–d). STEM imaging along the $[1\bar{1}1]$ zone axis confirms that these large precipitates have adopted a 9R structure (Fig. S2d), consistent with the sequential $\text{BCC} \rightarrow 9\text{R} \rightarrow \text{FCC}$ structural transformation known to occur with extended aging [3,4]. This confirms that Mn substantially accelerates Cu precipitate coarsening kinetics. In CuNiAl-4Mn steel, intragranular precipitates range from 7–14 nm, which are finer than in Cu-4Mn but coarser than in Cu-0Mn (Fig. S2e), confirming that Ni and Al partially counteract the Mn-driven coarsening. Both B2 and FCC Cu phases are identified in this steel (Fig. S2f–g), indicating that Mn, Ni, and Al together exert a significant combined influence on precipitate size, spatial distribution, structural evolution, and coarsening behavior.

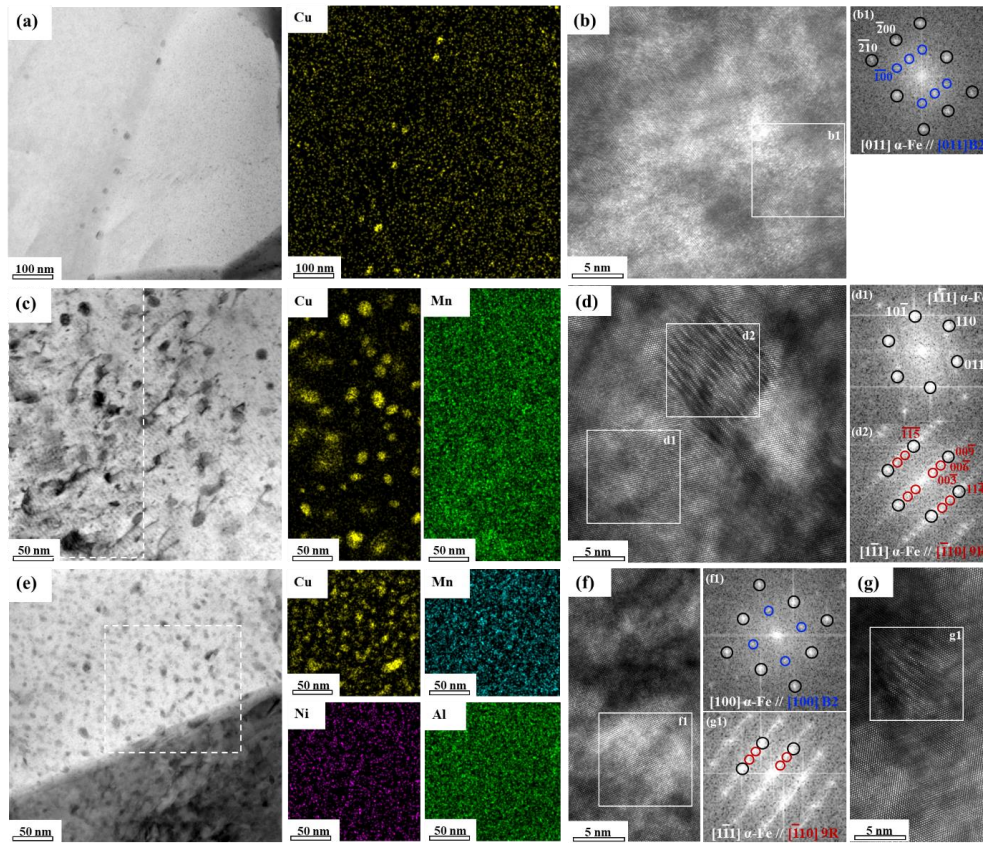


Fig. S2 STEM imaging and EDS analysis, and SAED patterns after aged at 500 °C for 1 h, (a, b) Cu-steel, SAED patterns with zone [011]; (c, d) Cu-4Mn steel, SAED patterns with zone [1 $\bar{1}$ 1]; (e, f, g) CuNi-4Mn steel, (f) SAED patterns with zone [100] and (g) SAED patterns with zone [1 $\bar{1}$ 1].

References

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