Reviews on Advanced Materials and Technologies, 2026, vol. 8, no. 1, pp. 15–21
DOI: 10.17586/2687-0568-2026-8-1-15-21

Composition Undulation Induced Strain Hardening in Fine-Grained FCC Alloys

A.G. Sheinerman [1,2]

[1] Institute for Problems in Mechanical Engineering, Russian Academy of Sciences, Bolshoi pr., V.O., 61, St. Petersburg 199178, Russia
[2] Saint Petersburg State University, Universitetskaya nab., 7/9, St. Petersburg, 199034 Russia

Received: November 24, 2025 Corresponding author: A.G. Sheinerman

Abstract. A model is suggested that describes tensile plastic deformation of fine-grained FCC alloys with three-dimensional composition undulation. Within the model, composition undulation is approximated by spherical inclusions, which envelope the region of highest and lowest solute concentration. It is assumed that these inclusions can increase the yield strength due to their misfit stresses and, in addition, initiate the cross-slip of screw dislocations that otherwise tend to move in a planar mode. The initiation of additional dislocation slip systems reduces the dislocation mean slip path, which increases the dislocation density, enhances strain hardening and thereby increases the ultimate strength and ductility of alloys. It is demonstrated that the maximum ultimate strength can be achieved either at low or at high values of the composition undulation wavelength, while the uniform elongation slightly decreases with an increase in the composition undulation wavelength.

Acknowledgements. The author acknowledges the financial support of the Russian Science Foundation (grant 24-21-00034).

Citation: Rev. Adv. Mater. Technol., 2026, vol. 8, no. 1, pp. 15–21

View online: https://doi.org/10.17586/2687-0568-2026-8-1-15-21

View Table of Contents: https://reviewsamt.com/issues

REFERENCES

1. H. Li, H. Zong, S. Li, S. Jin, Y. Chen, M.J. Cabral, B. Chen, Q. Huang, Y. Chen, Y. Ren, K. Yu, S. Han, X. Ding, G. Sha, J. Lian, X. Liao, E. Ma, J. Sun. Uniting tensile ductility with ultrahigh strength via composition undulation. *Nature*, 2022, vol. 604, pp. 273–279.
2. R.O. Ritchie. The conflicts between strength and toughness. *Nature Materials*, 2011, vol. 10, pp. 817–822.
3. E.P. George, D. Raabe, R.O. Ritchie. High-entropy alloys. *Nature Reviews Materials*, 2019, vol. 4, pp. 515–534.
4. W. Zhang, P.K. Liaw, Y. Zhang. Science and technology in high-entropy alloys. *Science China Materials*, 2018, vol. 61, pp. 2–22.
5. H. Wang, B.S. Dong, Z.B. Chen, J.Q. Liu, N. Haghdadi, R.Q. Lu, S. Primig, Z.Y. Wang, Z.X. Pan, H.J. Li, S.P. Ringer, X.Z. Liao. Effect of compositional heterogeneity on the mechanical properties of a single-phase Cu–9Al alloy with different grain sizes. *Acta Materialia*, 2024, vol. 263, art. no. 119531.
6. Z. Li, S. Zhao, R.O. Ritchie, M.A. Meyers. Mechanical properties of high-entropy alloys with emphasis on face-centered cubic alloys. *Progress in Materials Science*, 2019, vol. 102, pp. 296–345.
7. Z. An, S. Mao, T. Yang, C.T. Liu, B. Zhang, E. Ma, H. Zhou, Z. Zhang, L. Wang, X. Han. Spinodal-modulated solid solution delivers a strong and ductile refractory high-entropy alloy. *Materials Horizons*, 2021, vol. 8, no. 3, pp. 948–955.
8. H. Guan, H. Xie, Z.-P. Luo, W.-K. Bao, Z.-S. You, Z. Jin, H.-J. Jin. Ultrastrong spinodoid alloys enabled by electrochemical dealloying and refilling. *Proceedings of the National Academy of Sciences of the USA*, 2023, vol. 120, no. 1, art. no. e2214773120.
9. B. Gwalani, V. Soni, O.A. Waseem, S.A. Mantri, R. Banerjee. Laser additive manufacturing of compositionally graded AlCrFeMoVx (x = 0–1) high-entropy alloy system. *Optics and Laser Technology*, 2019, vol. 113, pp. 330–337.
10. E. Ma, X. Wu. Tailoring heterogeneities in high-entropy alloys to promote strength–ductility synergy. *Nature Communications*, 2019, vol. 10, art. no. 3563.
11. Q.J. Li, H. Sheng, E. Ma. Strengthening in multi-principal element alloys with local-chemical-order roughened dislocation pathways. *Nature Communications*, 2019, vol. 10, art. no. 3563.
12. Q. Ding, Y. Zhang, X. Chen, X. Fu, D. Chen, S. Chen, L. Gu, F. Wei, H. Bei, Y. Gao, M. Wen, J. Li, Z. Zhang, T. Zhu, R.O. Ritchie, Q. Yu. Tuning element distribution, structure and properties by composition in high-entropy alloys. *Nature*, 2019, vol. 574, pp. 223–227.
13. Y. Ikeda, B. Grabowski, F. Körmann. Ab initio phase stabilities and mechanical properties of multicomponent alloys: A comprehensive review for high-entropy alloys and compositionally complex alloys. *Materials Characterization*, 2019, vol. 147, pp. 464–511.
14. J. Zhu, L. Sun, D. Li, L. Zhu, X. He. Compositional undulation induced strain hardening and delocalization in multi-principal element alloys. *International Journal of Mechanical Sciences*, 2023, vol. 241, art. no. 107931.
15. Y.-C. Wu, J.-L. Shao. FCC–BCC phase transformation induced simultaneous enhancement of tensile strength and ductility at high strain rate in high-entropy alloy. *International Journal of Plasticity*, 2023, vol. 169, art. no. 103730.
16. A.M. Smirnov, A.G. Sheinerman, X.T. Li, Z.J. Zhang. Modeling strength and ductility of alloys with intragrain compositional inhomogeneities. *International Journal of Plasticity*, submitted.
17. S.-D. Kim, S.-J. Park, J.H. Jang, J. Moon, H.-Y. Ha, C.-H. Lee, H. Park, J.-H. Shin, T.-H. Lee. Strain hardening recovery mediated by coherent precipitates in lightweight steel. *Scientific Reports*, 2021, vol. 11, art. no. 14468.
18. A.J. Ardell. Precipitation hardening. *Metallurgical Transactions A*, 1985, vol. 16, pp. 2131–2165.
19. G.I. Taylor. The mechanism of plastic deformation of crystals. Part I. Theoretical. *Proceedings of the Royal Society A*, 1934, vol. 145, pp. 362–387.
20. Y. Estrin, H. Mecking. A unified phenomenological description of work hardening and creep based on one-parameter models. *Acta Metallurgica*, 1984, vol. 32, no. 1, pp. 57–70.

21. M.E. Kassner, K. Kyle. Taylor hardening in five power law creep of metals and class M alloys. In: M.A. Meyers, M. Sarikaya, R.O. Ritchie (Eds.). *Nano and Microstructural Design of Advanced Materials*. Elsevier, 2003, pp. 255–271.
22. W.J. Poole, J.D. Embury, D.J. Lloyd. Work hardening in aluminum alloys. In: R. Lumley (Ed.). *Fundamentals of Aluminum Metallurgy: Production, Processing and Applications*. Woodhead Publishing, 2011, pp. 307–344.
23. H. Mecking, U.F. Kocks. Kinetics of flow and strain-hardening. *Acta Metallurgica*, 1981, vol. 29, no. 11, pp. 1865–1875.
24. R. Schouwenaars. Calculating the grain size effect during strain hardening through a probabilistic analysis of the mean slip distance in polycrystals. *International Journal of Plasticity*, 2024, vol. 178, art. no. 104012.
25. S.V. Bobylev, A.G. Sheinerman, X.T. Li, Z.J. Zhang. Modeling of strength and ductility of metal alloy/graphene composites containing precipitates. *International Journal of Solids and Structures*, 2024, vol. 296, art. no. 112843.
26. A.A. Fedorov, M.Yu. Gutkin, I.A. Ovid'ko. Triple junction diffusion and plastic flow in fine-grained materials. *Scripta Materialia*, 2002, vol. 47, no. 1, pp. 51–55.
27. A. Considère. Mémoire sur l'emploi du fer et de l'acier dans les constructions. *Annales des Ponts et Chaussées*, 1885, vol. 9, pp. 574–775.
28. H. Park, F. Haftlang, Y. Heo, J. Seol, Z. Wang, H. Kim. Periodic spinodal decomposition in double-strengthened medium-entropy alloy. *Nature Communications*, 2024, vol. 15, art. no. 5757.