Reviews on Advanced Materials and Technologies, 2024, vol. 6, no. 3, pp. 120–131
DOI: 10.17586/2687-0568-2024-6-3-120-131

Hydrogen-Enhanced Martensitic Transformation and Twinning under Rolling of AISI 321 Austenitic Stainless Steel

Elena G. Astafurova, Evgenii V. Melnikov, Sergey V. Astafurov

Laboratory of Physics of Hierarchical Structures in Metals and Alloys, Institute of Strength Physics and Materials Science SB RAS, 2/4 Akademicheskii prospekt, 634055, Tomsk, Russia

Received: September 20, 2024 Corresponding author: Elena G. Astafurova

Abstract. In this paper, we study the effect of hydrogen pre-charging (in a 1N H_2SO_4 solution with a $CS(NH_2)_2$ as a recombination potion, at current densities of 10, 100 and 200 mA/cm^2, for 5 hours) on the microstructure and phase composition of a type AISI 321 austenitic stainless steel during room-temperature rolling. Hydrogen pre-charging enhances the contribution of mechanical twinning to the fragmentation of the structure and assists to γ→α' and γ→ε transformations during rolling. Both, twinning and martensitic transformations, are dependent on hydrogen pre-charging regime: an increase in a current density during pre-charging of the specimens causes a decrease in the thickness of twin plates, increases the density of twin boundaries and fraction of α'-martensite in the structure of the rolled specimens. The formation of a high density of $\Sigma 3^n$ boundaries (twin and ε-martensite) prevents the formation of a misoriented grain structure in austenite during rolling of steel specimens. Hydrogen pre-charging provides faster kinetics of γ→α' phase transformation in metastable steel AISI 321 during rolling.

Acknowledgements. This research was funded by the Government research assignment for ISPMS SB RAS, project FWRW-2022-0005. The study was conducted using the equipment of ISPMS SB RAS ("Nanotech" center) and center for collective use "Diagnostics of the Structure and Properties of Nanomaterials" (Belgorod State University).

Citation: Rev. Adv. Mater. Technol., 2024, vol. 6, no. 3, pp. 120–131

View online: https://doi.org/10.17586/2687-0568-2024-6-3-120-131

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

REFERENCES

[1] K.H. Lo, C.H. Shek, J.K.L. Lai, Recent developments in stainless steels, *Mater. Sci. Eng. R*, 2009, vol. 65, no. 4–6, pp. 39–104.

[2] T. Michler, C. San Marchi, J. Naumann, S. Weber, M. Martin, Hydrogen environment embrittlement of stable austenitic steels, *Int. J. Hydr. Energy*, 2012, vol. 37, no. 21, pp. 16231–16246.

[3] R.A. Oriani, A mechanistic theory of hydrogen embrittlement of steels, *Ber. Bunsengesellsch. Phys. Chem.*, 1972, vol. 76, no. 8, pp. 848–857.

[4] M. Nagumo, *Fundamentals of hydrogen embrittlement*, Springer, Singapore, 2016.

[5] S. Lynch, Hydrogen embrittlement phenomena and mechanisms, *Corros. Rev.*, 2012, vol. 30, no. 3–4, pp. 105–123.

[6] H.K. Birnbaum, P. Sofronis, Hydrogen-enhanced localized plasticity–a mechanism for hydrogen-related fracture, *Mater. Sci. Eng. A*, 1994, vol. 176, no. 1–2, pp. 191–202.

[7] P.J. Ferreira, I.M. Robertson, H.K. Birnbaum, Hydrogen effects on the character of dislocations in high-purity aluminium, *Acta Mater.*, 1999, vol. 47, no. 10, pp. 2991–2998.

[8] P. Rozenak, L. Levin, D. Eliezer, Hydrogen effects on phase transformations in austenitic stainless steels, *J. Mater. Sci.*, 1984, vol. 19, no. 2, pp. 567–573.

[9] E.G. Astafurova, E.V. Melnikov, S.V. Astafurov, I.V. Ratochka, I.P. Mishin, G.G. Maier, V.A. Moskvina, G.N. Zakharov, A.I. Smirnov, V.A. Bataev, Hydrogen embrittlement effects on austenitic stainless steels with ultrafine-grained structure of different morphology, *Phys. Mesomech.*, 2019, vol. 22, pp. 313–326.

[10] J. Morisawa, M. Kodama, S. Nishimura, K. Asano, K. Nakata, S. Shima, Effects of hydrogen on mechanical properties in irradiated austenitic stainless steels, *J. Nuclear Mater.*, 1994, vol. 212–215, pp. 1396–1400.

[11] L.R. Queiroga, G.F. Marcolino, M. Santos, G. Rodrigues, C. Eduardo dos Santos, P. Brito, Influence of machining parameters on surface roughness and susceptibility to hydrogen embrittlement of austenitic stainless steels, *Int. J. Hydr. Energy.*, 2019, vol. 44, no. 54, pp. 29027–29033.

[12] S. Weber, M. Martin, W. Theisen, Impact of heat treatment on the mechanical properties of AISI 304L austenitic stainless steel in high-pressure hydrogen gas, *J. Mater. Sci.*, 2012, vol. 47, no. 16, pp. 6095–6107.

[13] D.P. Abraham, C.J. Altstetter, The effect of hydrogen on the yield and flow stress of an austenitic stainless steel, *Metall. Mater. Trans. A*, 1995, vol. 26, no. 11, pp. 2849–2858.

[14] D.P. Abraham, C.J. Altstetter, Hydrogen-enhanced localization of plasticity in an austenitic stainless steel, *Metall. Mater. Trans. A*, 1995, vol. 26, no. 11, pp. 2859–2871.

[15] M. Koyama, E. Akiyama, T. Sawaguchi, K. Ogawa, I.V. Kireeva, Y.I. Chumlyakov, K. Tsuzaki, Hydrogen assisted quasi-cleavage fracture in a single crystalline type 316 austenitic stainless steel, *Corros. Sci.*, 2013, vol. 75, pp. 345–353.

[16] Y. Mine, Z. Horita, Y. Murakami, Effect of hydrogen on martensite formation in austenitic stainless steels in high-pressure torsion, *Acta Mater.*, 2009, vol. 57, no. 10, pp. 2993–3002.

[17] Y. Mine, C. Narazaki, K. Murakami, S. Matsuoka, Y. Murakami, Hydrogen transport in solution-treated and pre-strained austenitic stainless steels and its role in hydrogen-enhanced fatigue crack growth, *Int. J. Hydr. Energy*, 2009, vol. 34, no. 2, pp. 1097–1107.

[18] A.F. Padilha, R.L. Plaut, P.R. Rios, Annealing of cold-worked austenitic stainless steels. *ISIJ Int.*, 2003, vol. 43, no. 2, pp. 135–143.

[19] V. Shrinivas, S.K. Varma, L.E. Murr, Deformation-induced martensitic characteristics in 304 and 316 stainless steels during room-temperature rolling, *Metall. Mater. Trans. A*, 1995, vol. 26, no. 3, pp. 661–671.

[20] E. Astafurova, A. Fortuna, E. Melnikov, S. Astafurov, The effect of strain rate on hydrogen-assisted deformation behavior and microstructure in AISI 316L austenitic stainless steel, *Materials*, 2023, vol. 16, no. 8, art. no. 2983.

[21] Y. Yagodzinskyy, O. Todoshchenko, S. Papula, H. Hänninen, Hydrogen solubility and diffusion in austenitic stainless steels studied with thermal desorption spectroscopy, *Steel Res. Int.*, 2011, vol. 82, no .1, pp. 20–25.

[22] D.B. Williams, C.B. Carter, *Transmission Electron Microscopy. Textbook for Materials Science*, Springer, New York, USA, 2009.
[23] I. Shakhova, V. Dudko, A. Belyakov, K. Tsuzaki, R. Kaibyshev, Effect of large strain cold rolling and subsequent annealing on microstructure and mechanical properties of an austenitic stainless steel, *Mater. Sci. Eng. A*, 2012, vol. 545, pp. 176–186.
[24] C. Donadille, R. Valle, P. Dervin, R. Penelle, Development of texture and microstructure during cold-rolling and annealing of f.c.c. alloys: example of an austenitic stainless steel, *Acta Metall.*, 1989, vol. 37, no. 6, pp. 1547–1571.
[25] O.V. Rybalchenko, D.V. Prosvirnin, A.A. Tokar, V.P. Levin, M.R. Tyutin, G.I. Raab, L.R. Botvina, S.V. Dobatkin, Effect of ECAP on structural, mechanical and functional characteristics of the austenitic Cr-Ni-Ti steels, *J. Phys.: Conf. Ser.*, 2018, vol. 1134, art. no. 012049.
[26] S.V. Dobatkin, O.V. Rybalchenko, N.A. Enikeev, A.A. Tokar, M.M. Abramova, Formation of fully austenitic ultrafine-grained high strength state in metastable Cr–Ni–Ti stainless steel by severe plastic deformation, *Mater. Lett.*, 2016, vol. 166, pp. 276–279.
[27] A.K. De, J.G. Speer, D.K. Matlock, D.C. Murdock, M.C. Mataya, R.J. Comstock, Deformation-induced phase transformation and strain hardening in type 304 austenitic stainless steel, *Metal. Mater. Trans. A*, 2006, vol. 37, no. 6, pp. 1875–1886.
[28] E.I. Galindo-Nava, P.E.J. Rivera-Díaz-del-Castillo, Understanding martensite and twin formation in austenitic steels: A model describing TRIP and TWIP effects, *Acta Mater.*, 2017, vol. 128, pp. 120–134.
[29] C. Zhang, H. Zhi, S. Antonov, L. Chen, Y. Su, Hydrogen-enhanced densified twinning (HEDT) in a twinning-induced plasticity (TWIP) steel, *Scr. Mater.*, 2021, vol. 190, pp. 108–112.
[30] M. Koyama, N. Terao, K. Tsuzaki, Revisiting the effects of hydrogen on deformation-induced γ-ε martensitic transformation, *Mater. Lett.*, 2019, vol. 249, pp. 197–200.
[31] J.S. Aristeidakis, G.N. Haidemenopoulos, Constitutive and transformation kinetics modeling of ε-, α′-martensite and mechanical twinning in steels containing austenite. *Acta Mater.*, 2022, vol. 228, art. no. 117757.
[32] E.G. Astafurova, M.S. Tukeeva, G.G. Maier, E.V. Melnikov, H.J. Maier, Microstructure and mechanical response of single-crystalline high-manganese austenitic steels under high-pressure torsion: The effect of stacking-fault energy, *Mater. Sci. Eng. A*, 2014, vol. 604, pp. 166–175.
[33] I.V. Kireeva, Y.I. Chumlyakov, Effect of nitrogen and stacking-fault energy on twinning in $[\bar{1}11]$ single crystals of austenitic stainless steels, *Phys. Metals Metallogr.*, 2009, vol. 108, no. 3, pp. 298–309.
[34] I.V. Kireeva, Y.I. Chumlyakov, Orientation dependence of the γ-ε martensitic transformation in single crystals of austenitic stainless steels with low stacking fault energy, *Phys. Metals Metallogr.*, 2006, vol. 101, no. 2, pp. 186–203.
[35] X.-S. Yang, S. Sun, T.-Y. Zhang, The mechanism of bcc α′ nucleation in single hcp ε laths in the fcc γ → hcp ε → bcc α′ martensitic phase transformation, *Acta Mater.*, 2015, vol. 95, pp. 264–273.
[36] M.J. Sohrabi, M. Naghizadeh, H. Mirzadeh, Deformation-induced martensite in austenitic stainless steels: A review, *Archiv. Civ. Mech. Eng.*, 2020, vol. 20, no. 4, art. no. 124.
[37] V.A. Polyanskiy, A.K. Belyaev, E.L. Alekseeva, A.M. Polyanskiy, D.A. Tretyakov, Yu.A. Yakovlev, Phenomenon of skin effect in metals due to hydrogen absorption, *Continuum Mech. Thermodyn.*, 2019, vol. 31, no. 6, pp. 1961–1975.
[38] E. Owczarek, T. Zakroczymski, Hydrogen transport in a duplex stainless steel, *Acta Mater.*, 2000, vol. 48, no. 12, pp. 3059–3070.
[39] V. Olden, C. Thaulow, R. Johnsen, Modelling of hydrogen diffusion and hydrogen induced cracking in supermartensitic and duplex stainless steels, *Mater. Des.*, 2008, vol. 29, no. 10, pp. 1934–1948.
[40] H. Zhan, Y. Li, W. Liang, L. Zheng, Observation of diffusion channel and hydrogen trap in 304 austenitic stainless steel, *Mater. Lett.,* 2021, vol. 290, art. no. 129453.
[41] I.M. Robertson, The effect of hydrogen on dislocation dynamics, *Eng. Fra. Mech.*, 2001, vol. 68, no. 6, pp. 671–692.