Ultra-severe plastic deformation for room-temperature superplasticity and superfunctionality

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Keywords: Severe Plastic Deformation (SPD), High-Pressure Torsions (HPT), Superplasticity, Strain Rate Sensitivity, Functional Properties

Abstract. Ultra-severe plastic deformation (ulta-SPD) is a terminology used for the introduction of extremely large shear strains (over 1000) to material so that the thickness of sheared phases geometrically reaches the subnanometer level. Under such extreme shearing conditions, new nanostructured phases with unique properties are formed even from the immiscible systems. Various metallic alloys and ceramics were developed by this concept for different applications such as room-temperature superplasticity, room-temperature hydrogen storage, photocatalytic hydrogen production, photocatalytic carbon dioxide conversion, etc. This article reviews recent advances regarding ultra-SPD with a focus on low-temperature superplasticity, which was reported for the first time at room temperature in aluminum and magnesium alloys.

Introduction

Severe plastic deformation (SPD) is a popular technology to introduce large plastic strain in a workpiece [1,2]. There are various SPD methods such as high-pressure torsion (HPT), equal-channel angular pressing (ECAP) and accumulative roll-bonding (ARB) [3,4]. The main target to employ SPD is the generation of ultrafine grains (UFG) [5,6]. Formation of such UFG structures leads to strengthening and enhanced functional properties [7,8]. A review paper written by 49 experts in SPD referred to these SPD-processed UFG materials as superfunctional materials due to their excellent functional properties [9]. SPD has been used since ancient times, but its scientific principles were documented by Bridgman in the 1930s [10,11], Segal et al. in the 1970s [12], and Valiev et al. in the 1980s [13]. For the latest progress in the SPD field, the readers are referred to review papers published in a special issue of Materials Transactions [14].

Ultra-SPD is one of the new directions which is getting attention to synthesize new materials with promising properties [15]. This manuscript reviews recent advances in the application of ultra-SPD with a focus on room-temperature superplasticity, which could be realized for the first time in aluminum and magnesium alloys by ultra-SPD [16,17].

Ultra-Severe Plastic Deformation

The concept of ultra-SPD was suggested in 2017 as an attempt to find a strategy to synthesize new materials [18]. Ultra-SPD is defined as SPD processing in which the shear strain is drastically increased so that the thickness of sheared phases reaches the subnanometer level, as schematically shown in Fig. 1a [15]. The necessary shear strain depends on the size of phases and their co-deformation, but the applied shear strain is at least 1000 [15]. Besides the objective of material synthesis, ultra-SPD has also raised questions regarding the behavior of metallic materials in the steady state, where the strength is supposed to remain constant with increasing shear strain [19].

High-Pressure Torsion for Ultra-Severe Plastic Deformation

Ultra-SPD studies use HPT, a process schematically shown in Fig. 1b. The method, in which a disc [20] or ring [21] is strained under pressure by torsion, has some merits for ultra-SPD. First, shear strain in HPT ($\gamma = 2\pi rN/h$; γ: shear strain, r: radial distance from the rotation center, N: rotation numbers, h: thickness of disc- or ring-shaped specimen) can be increased with almost no limits by increasing the rotation numbers [9-11]. Second, pressure in HPT is high, and thus it is applicable to hard metals (Hf [22], Mo [23], W [24]), glasses [25-27], semiconductors (Si [28,29], Ge [30,31]), oxides (TiO_2 [32], ZrO_2 [33], $BiTaO_3$ [34]), and multi-component alloys (intermetallics [35-37], single-phase high-entropy alloys [38-40], dual-phase high-entropy alloys [41-43]). Third, it is applicable for cold consolidation of powders [44-46], because of high pressure/strain and minor temperature rise [47,48]. Fourth, the method uses the advantages of high pressure/strain to control phase transformations [49-51]. Fifth, the method continuously applies strain, resulting in a high concentration of defects [52-54] and ultra-fast dynamic interdiffusion [55-57].

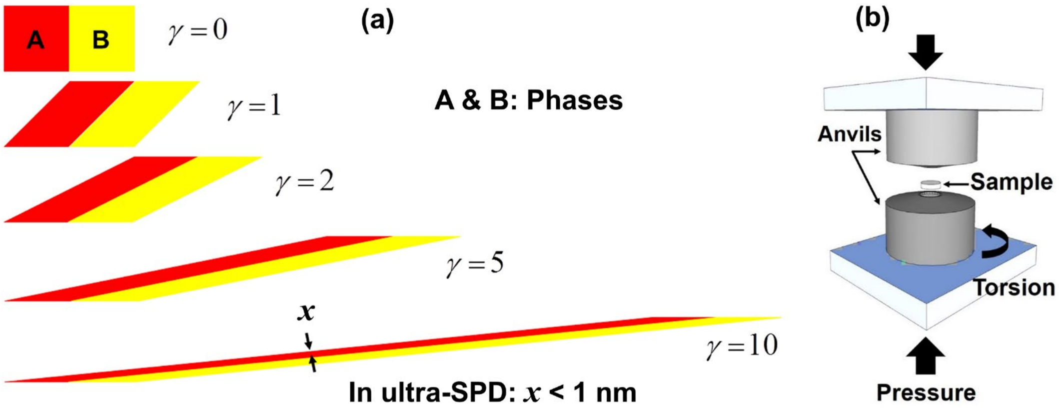

Fig. 1. (a) Schematic illustration of (a) ultra-SPD, and (b) HPT.

Main Findings by Ultra-Severe Plastic Deformation

Ultra-SPD is promising to synthesize a variety of materials including conventional binary/ternary alloys [15], intermetallic compounds [18], high-entropy alloys [18], hydrides [58], and high-entropy ceramics [59]. Such materials show promising properties like high strength, room-temperature superplasticity, hydrogen storage, biocompatibility, superconductivity, thermal stability, and photocatalysis, as reviewed in [60]. A summary of materials processed by ultra-SPD and their characteristics are given in Table 1 [61-88]. These properties are briefly summarized below, but room-temperature superplasticity is discussed in the next section.

SPD-processed materials usually show low thermal stability due to a large fraction of defects [89-93], but the materials processed by ultra-SPD can have high thermal stability. For example, the application of ultra-SPD to produce supersaturated Al-Ca [69], Al-Fe [70], Al-Zr [75], and Al-La-Ce [76] alloys, leads not only to high thermal stability but also to age hardening.

Ultra-SPD is effective in the stabilization of phases that do not exist in the phase diagram such as BCC, HCP and FCC phases in the immiscible Mg-Ti [62], Mg-Zr [63] and Mg-Hf [64] systems.

Table 1. Summary of the application of ultra-SPD to various materials.

Alloy	Shear Strain	Characteristics	Ref.
Mg–Li	7800	Superplasticity at room temperature	[16]
Mg_2X (X: 21 elements)	5500	Storing hydrogen	[61]
Mg–Ti	5500	Storing hydrogen	[62]
Mg–Zr	55000	Storing hydrogen in new phases	[63]
Mg–Hf	3900	Biocompatible new phases	[64]
Mg–V–Cr	50000	Storing hydrogen	[65]
Mg_4NiPd	59000	Storing hydrogen at room temperature	[66]
MgTiVCrFe	12000	Storing hydrogen	[67]
$MgTiH_4$	17000	Storing hydrogen	[68]

Al–Ca	39000	Thermal stability	[69]
Al–Fe	39000	Thermal stability	[70]
AlNi	4700	Enhanced microhardness	[71]
Al_3Ni	4700	Enhanced microhardness	[72,73]
Al–Cu	3900	Quick interdiffusion	[74]
Al–Zn	7800	Superplasticity at room temperature	[17]
Al–Zr	39000	Thermal stability and age hardening	[75]
Al–La–Ce	39000	Thermal stability and age hardening	[76]
TiAl	2000	Enhanced strength/plasticity	[77]
TiV	5500	Storing hydrogen with no activation treatment	[78]
Ti-Nb	5900	Biocompatibility with good strength/elasticity	[79]
TiZrHfNbTa	2000	Biocompatibility with good strength/elasticity	[80]
$TiZHfNbTaO_{11}$	7800	Photocatalytic H_2 evolution and CO_2 conversion	[81,82]
$TiZrHfNbTaO_6N_3$	3900	Photocatalytic H_2 evolution and CO_2 conversion	[83,84]
$TiZrNbTaWO_{12}$	3900	Photocatalytic O_2 evolution	[85]
FeNi	3900	Quick phase transition	[86]
Ni_2AlTi	4700	Enhanced microhardness	[87]
Nb-Ti	3900	Superconductivity	[88]

Intermetallic compounds with nanograin sizes are of interest, but these materials should be produced by two-step procedures like high-temperature sintering of nanipowders [93-96]. However, ultra-SPD is a single-step process to produce bulk nano-intermetallics like Mg_2X (X: other elements) for hydrogen storage [61], AlNi [71] and Al_3Ni [72,73] with high hardness, TiAl with high strength and plasticity [77], $L1_0$-FeNi [86] and Ni_2AlTi [87].

Orthopedic materials should have biocompatibility, high strength and low elastic modulus. Ti-based biomaterials suffer from low strength and high modulus [97], but SPD can improve their strength [98-101]. Ultra-SPD was successfully used to synthesize alloys with a good combination of high strength and low elastic modulus from the Ti-Zr-Hf-Nb-Ta biocompatible system [79,80].

Nanostructured Nb-Ti superconductors are commercially fabricated by several repetitions of wire drawing and long-time annealing [102-105]. Ultra-SPD followed by short annealing is a fast method to produce such superconductors with properties comparable with commercial ones [88].

The design and synthesis of magnesium alloys that can reversibly store hydrogen at room temperature is a long-term challenge [106,107]. Ultra-SPD not only contributed to the synthesis of various hydrogen-storing compounds such as Mg_2X intermetallics (X: other elements) [61], immiscible Mg–Ti [62,68], Mg–Zr [63] and Mg–Hf [66] alloys, ternary Mg–V–Cr alloy [65] and high-entropy MgVTiCrFe alloy [67], but also it introduced Mg4Ni1pd as the first Mg-based material with reversible hydrogen storage performance at room temperature [66].

Ultra-SPD introduced the first high-entropy photocatalysts for hydrogen and oxygen production from water splitting as well as for CO_2 conversion. The high-entropy oxides $TiZrHfNbTaO_{11}$ [81,82] and $TiZrNbTaWO_{12}$ [85] and the high-entropy oxynitride $TiZrHfNbTaO_6N_3$ [83,84] are the first high-entropy photocatalysts with high activity.

Room-Temperature Superplasticity

Superplasticity is defined as the capability of a material for large tensile deformations over 400%. Such elongations can be achieved at homologous temperatures over 0.5, where grain-boundary sliding is dominant. Superplasticity is quantified by the creep equation with a strain rate sensitivity of ~0.5 [108]. The equation suggests two solutions to achieve low-temperature superplasticity: (i) grain size reduction which was used to attain low-temperature superplasticity by SPD processing [109-111]; and (ii) acceleration of grain boundary diffusion by grain boundary engineering, which was used to attain room-temperature superplasticity in Mg-Li and Al-Zn by ultra-SPD [16,17].

The application of ultra-SPD (200 HPT turns) to a two-phase Mg-8wt.%Li alloy (Mg-rich α phase + Li-rich β) resulted in 440% elongation at room temperature (Fig. 2a) with a strain-rate sensitivity of 0.37 (Fig. 2b) [16]. However, the extrusion and SPD process for 5 HPT turns did not lead to such an elongation in agreement with earlier studies [112]. Superplastic deformation after ultra-SPD is promising because room temperature corresponds to a homologous temperature of 0.35 for the alloy. Room-temperature superplasticity occurs due to fast grain-boundary diffusion by increasing the fraction of α/β interphase boundaries and the segregation of lithium along the α/α grain boundaries, as shown in Fig. 2d using high-angle annular dark-field (HAADF) image and in Figs. 2d and 2e using energy-filtered transmission electron microscopy (EFTEM).

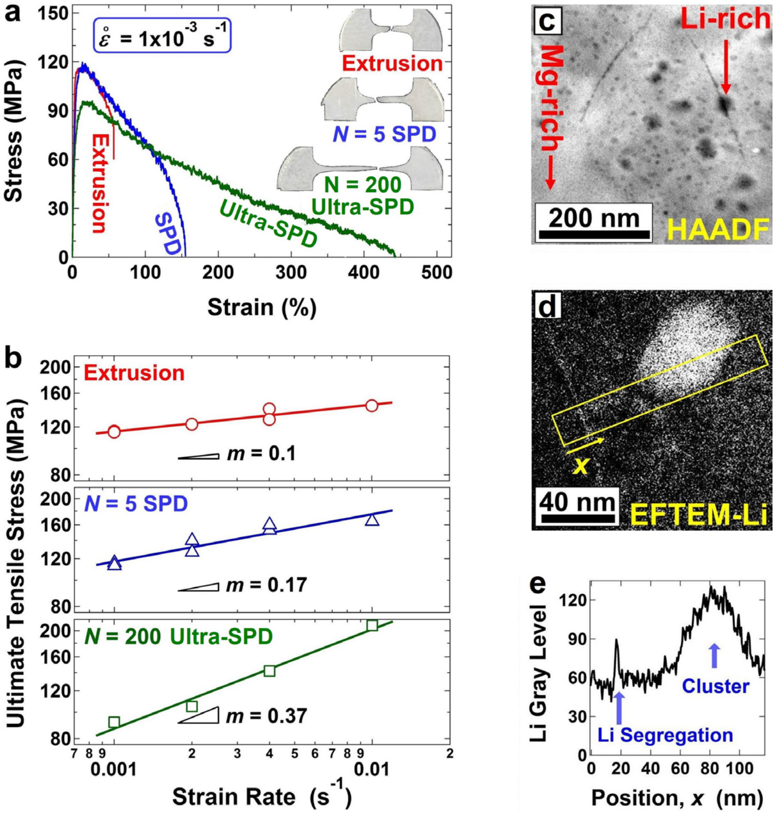

Fig. 2. (a) Stress-strain curves, (b) ultimate tensile strength versus strain rate for Mg-Li alloy processed by extrusion, SPD with 5 HPT turns and ultra-SPD with 200 HPT turns (m: strain-rate sensitivity). (c) HAADF image, (d) EFTEM-Li image and (e) gray level versus position shown in (b) for Mg-Li after ultra-SPD [16].

Ultra-SPD (200 HPT turns) was applied to an Al-30at%Zn alloy with two phases of Al-rich α and Zn-rich η [17]. The tensile behavior of the material was examined after ultra-SPD and after 100 days of aging at room temperature. As shown in Fig. 3a, the homogenized sample shows limited plasticity, but elongation is 480% after ultra-SPD and 330% after aging. It should be noted that this alloy did not show room-temperature superplasticity after SPD using 20 HPT turns [113]. The strain-rate sensitivity for ultra-SPD-processed samples reached a high value of 0.41, as shown in Fig. 3b. Superplasticity after ultra-SPD at room temperature (i.e. the homologous temperature of 0.36) is due to fast grain-boundary diffusion by increasing the fraction of α/η. interphase boundaries and the segregation of zinc along the α/α grain boundaries, as shown in Fig. 3c and 3d using HAADF image and in Figs. 3e and 3f using energy-dispersive X-ray spectroscopy (EDS).

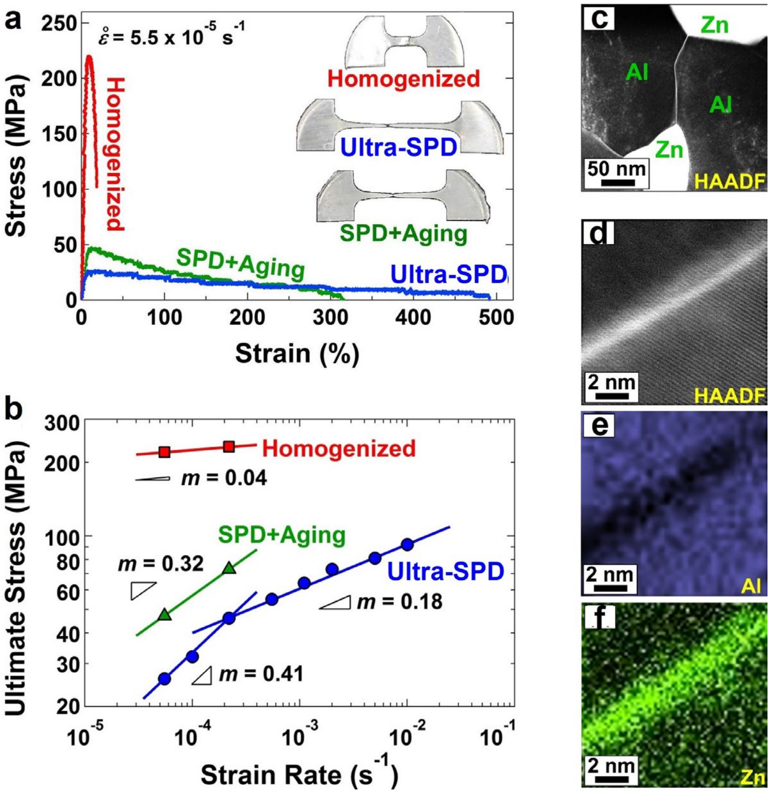

Fig. 3. (a) Stress-strain curves, (b) ultimate tensile strength versus strain rate for Mg-Li alloy processed by homogenization, ultra-SPD with 200 HPT turns and ultra-SPD followed by 100 day aging (m: strain-rate sensitivity). (c, d) HAADF images, and (e, f) EDS elemental mappings of region in

Summary

The concept of ultra-SPD is effective to develop various superfunctional materials for energy, electrical and biomedical applications. One of the interesting results achieved by ultra-SPD is the development of first room-temperature-superplastic aluminum and magnesium alloys.

References

[1] R.Z. Valiev, R.K. Islamgaliev, I.V. Alexandrov, Bulk nanostructured materials from severe plastic deformation, Prog. Mater. Sci. 45 (2000) 103-189. https://doi.org/10.1016/S0079-6425(99)00007-9

[2] R.Z. Valiev, Y. Estrin, Z. Horita, T.G. Langdon, M.J. Zehetbauer, Y.T. Zhu, Producing bulk ultrafine-grained materials by severe plastic deformation, JOM 58(4) (2006) 33-39. https://doi.org/10.1007/s11837-006-0213-7

[3] A. Azushima, R. Kopp, A. Korhonen, D.Y. Yang, F. Micari, G.D. Lahoti, P. Groche, J. Yanagimoto, N. Tsuji, A. Rosochowski, A. Yanagida, Severe plastic deformation (SPD) processes for metals, CRIP Ann. Mauuf. Technol. 57 (2008) 716-735. https://doi.org/10.1016/j.cirp.2008.09.005

[4] V. Segal, Review: modes and processes of severe plastic deformation (SPD), Materials 11 (2018) 1175. https://doi.org/10.3390/ma11071175

[5] R. Pippan, S. Scheriau, A. Taylor, M. Hafok, A. Hohenwarter, A. Bachmaier, Saturation of fragmentation during severe plastic deformation, Annu. Rev. Mater. Res. 40 (2010) 319-343. https://doi.org/10.1146/annurev-matsci-070909-104445

[6] M.J. Starink, X.C. Cheng, S. Yang, Hardening of pure metals by high-pressure torsion: A physically based model employing volume-averaged defect evolutions, Acta Mater. 61 (2013) 183-192. https://doi.org/10.1016/j.actamat.2012.09.048

[7] M. Zehetbauer, R. Grossinger, H. Krenn, M. Krystian, R. Pippan, P. Rogl, T. Waitz, R. Wurschum, Bulk nanostructured functional materials by severe plastic deformation, Adv. Eng. Mater. 12 (2010) 692-700. https://doi.org/10.1002/adem.201000119

[8] Y. Estrin, A. Vinogradov, Extreme grain refinement by severe plastic deformation: a wealth of challenging science, Acta Mater. 61 (2013) 782-817. https://doi.org/10.1016/j.actamat.2012.10.038

[9] K. Edalati, A. Bachmaier, V.A. Beloshenko, Y. Beygelzimer, V.D. Blank, W.J. Botta, K. Bryła, J. Čížek, S. Divinski, N.A. Enikeev, Y. Estrin, G. Faraji, R.B. Figueiredo, M. Fuji, T. Furuta, T. Grosdidier, J. Gubicza, A. Hohenwarter, Z. Horita, J. Huot, Y. Ikoma, M. Janeček, M. Kawasaki, P. Krǎl, S. Kuramoto, T.G. Langdon, D.R. Leiva, V.I. Levitas, A. Mazilkin, M. Mito, H. Miyamoto, T. Nishizaki, R. Pippan, V.V. Popov, E.N. Popova, G. Purcek, O. Renk, Á. Révész, X. Sauvage, V. Sklenicka, W. Skrotzki, B.B. Straumal, S. Suwas, L.S. Toth, N. Tsuji, R.Z. Valiev, G. Wilde, M.J. Zehetbauer, X. Zhu, Nanomaterials by severe plastic deformation: review of historical developments and recent advances, Mater. Res. Lett. 10 (2022) 163-256. https://doi.org/10.1080/21663831.2022.2029779

[10] P.W. Bridgman, Effects of high shearing stress combined with high hydrostatic pressure, Phys. Rev. 48 (1935) 825-847. https://doi.org/10.1103/PhysRev.48.825

[11] K. Edalati, Z. Horita, A review on high-pressure torsion (HPT) from 1935 to 1988, Mater. Sci. Eng. A 652 (2016) 325-352. https://doi.org/10.1016/j.msea.2015.11.074

[12] V.M. Segal, V.I. Reznikov, A.E. Drobyshevskiy, V.I. Kopylov, Plastic working of metals by simple shear, Russ. Metall. 1 (1981) 99-105.

[13] R.Z. Valiev, O.A. Kaibyshev, R.I. Kuznetsov, R.S. Musalimov, N.K. Tsenev, Low-temperature superplasticity of metallic materials, Dokl. Akad. Nauk. SSSR 301 (1988) 864-866.

[14] K. Edalati, Z. Horita, Special issue on severe plastic deformation for nanomaterials with advanced functionality, Mater. Trans. 60 (2019) 1103. https://doi.org/10.2320/matertrans.MPR2019904

[15] K. Edalati, T. Masuda, M. Arita, M. Furui, X. Sauvage, Z. Horita, R.Z. Valiev, Room-temperature superplasticity in an ultrafine-grained magnesium alloy, Sci. Rep. 7 (2017) 2662. https://doi.org/10.1038/s41598-017-02846-2

[16] K. Edalati, Z. Horita, R.Z. Valiev, Transition from poor ductility to room-temperature superplasticity in a nanostructured aluminum alloy, Sci. Rep. 8 (2018) 6740. https://doi.org/10.1038/s41598-018-25140-1

[17] K. Edalati, Metallurgical alchemy by ultra-severe plastic deformation via high-pressure torsion process, Mater. Trans. 60 (2019) 1221-1229. https://doi.org/10.2320/matertrans.MF201914

[18] K. Edalati, R. Uehiro, K. Fujiwara, Y. Ikeda, H.W. Li, X. Sauvage, R.Z. Valiev, E. Akiba, I. Tanaka, Z. Horita, Ultra-severe plastic deformation: evolution of microstructure, phase transformation and hardness in immiscible magnesium-based systems, Mater. Sci. Eng. A 701 (2017) 158-166. https://doi.org/10.1016/j.msea.2017.06.076

[19] J.G. Sevillano, Dynamic steady state by unlimited unidirectional plastic deformation of crystalline materials deforming by dislocation glide at low to moderate temperatures, Metals 10 (2020) 66. https://doi.org/10.3390/met10010066

[20] A.P. Zhilyae, T.G. Langdon, Using high-pressure torsion for metal processing: fundamentals and applications, Prog. Mater. Sci. 53 (2008) 893-979. https://doi.org/10.1016/j.pmatsci.2008.03.002

[21] K. Edalati, Z. Horita, Scaling-up of high pressure torsion using ring shape, Mater. Trans. 50 (2009) 92-95. https://doi.org/10.2320/matertrans.MD200822

[22] K. Edalati, Z. Horita, Y. Mine, High-pressure torsion of hafnium, Mater. Sci. Eng. A 527 (2010) 2136-2141. https://doi.org/10.1016/j.msea.2009.11.060

[23] S. Lee, K. Edalati, Z. Horita, Microstructures and mechanical properties of pure V and Mo processed by high-pressure torsion, Mater. Trans. 51 (2010) 1072-1079. https://doi.org/10.2320/matertrans.M2009375

[24] L. Chen, L. Ping, T. Ye, L. Lingfeng, X. Kemin, Z. Meng, Observations on the ductility and thermostability of tungsten processed from micropowder by improved high-pressure torsion, Rare Met. Mater. Eng. 45 (2016) 3089-3094. https://doi.org/10.1016/S1875-5372(17)30059-0

[25] K. Edalati, Y. Yokoyama, Z. Horita, High-pressure torsion of machining chips and bulk discs of amorphous Zr50Cu30Al10Ni10, Mater. Trans. 51 (2010) 23-26. https://doi.org/10.2320/matertrans.MB200914

[26] Y.B. Wang, D.D. Qu, X.H. Wang, Y. Cao, X.Z. Liao, M. Kawasaki, S.P. Ringer, Z.W. Shan, T.G. Langdon, J. Shen, Introducing a strain-hardening capability to improve the ductility of bulk metallic glasses via severe plastic deformation, Acta Mater. 60 (2012) 253-260. https://doi.org/10.1016/j.actamat.2011.09.026

[27] Á. Révész, Z. Kovács, Severe plastic deformation of amorphous alloys, Mater. Trans. 60 (2019) 1283-1293. https://doi.org/10.2320/matertrans.MF201917

[28] V.D. Blank, M.Y. Popov, B.A. Kulnitskiy, The effect of severe plastic deformations on phase transitions and structure of solids, Mater. Trans. 60 (2019) 1500-1505. https://doi.org/10.2320/matertrans.MF201942

[29] Y. Ikoma, K. Hayano, K. Edalati, K. Saito, Q. Guo, Z. Horita, Phase transformation and nanograin refinement of silicon by processing through high-pressure torsion, Appl. Phys. Lett. 101 (2012) 121908. https://doi.org/10.1063/1.4754574

[30] K. Edalati, Z. Horita, Correlations between hardness and atomic bond parameters of pure metals and semi-metals after processing by high-pressure torsion, Scr. Mater. 64 (2011) 161-164. https://doi.org/10.1016/j.scriptamat.2010.09.034

[31] Y. Ikoma, Severe plastic deformation of semiconductor materials using high-pressure torsion, Mater. Trans. 60 (2019) 1168-1176. https://doi.org/10.2320/matertrans.MF201907

[32] H. Razavi-Khosroshahi, K. Edalati, M. Arita, Z. Horita, M. Fuji, Plastic strain and grain size effect on high-pressure phase transformations in nanostructured TiO2 ceramics, Scr. Mater. 124 (2016) 59-62. https://doi.org/10.1016/j.scriptamat.2016.06.022

[33] Q. Wang, K. Edalati, Y. Koganemaru, S. Nakamura, M. Watanabe, T. Ishihara, Z. Horita, Photocatalytic hydrogen generation on low-bandgap black zirconia (ZrO2) produced by high-pressure torsion, J. Mater. Chem. A 8 (2020) 3643-3650. https://doi.org/10.1039/C9TA11839J

[34] K. Edalati, M. Arimura, Y. Ikoma, T. Daio, M. Miyata, D.J. Smith, Z. Horita, Plastic deformation of BaTiO3 ceramics by high-pressure torsion and changes in phase transformations, optical and dielectric properties, Mater. Res. Lett. 3 (2015) 216-221. https://doi.org/10.1080/21663831.2015.1065454

[35] J.Y. Huang, Y.T. Zhu, X.Z. Liao, R.Z. Valiev, Amorphization of TiNi induced by high-pressure torsion, Phil. Mag. Lett. 84 (2004) 183-190. https://doi.org/10.1080/09500830310001657353

[36] C. Gammer, C. Mangler, H.P. Karnthaler, C. Rentenberger, Growth of nanosized chemically ordered domains in intermetallic FeAl made nanocrystalline by severe plastic deformation, Scr. Mater. 65 (2011) 57-60. https://doi.org/10.1016/j.scriptamat.2011.03.002

[37] D.G. Morris, M.A. Muñoz-Morris, Microstructural refinement in alloys and intermetallics by severe plastic deformation, J. Alloys. Compd. 536 (2012) S180-S185. https://doi.org/10.1016/j.jallcom.2011.10.069

[38] A. Kilmametov, R. Kulagin, A. Mazilkin, S. Seils, T. Boll, M. Heilmaier, H. Hahn, High-pressure torsion driven mechanical alloying of CoCrFeMnNi high entropy alloy, Scr. Mater. 158 (2019) 29-33. https://doi.org/10.1016/j.scriptamat.2018.08.031
[39] J. Gubicza, A. Heczel, M. Kawasaki, J.K. Han, Y. Zhao, Y. Xue, S. Huang, J.L. Lábár, Evolution of microstructure and hardness in Hf25Nb25Ti25Zr25 high-entropy alloy during high-pressure torsion, J. Alloys Compd. 788 (2019) 318-328. https://doi.org/10.1016/j.jallcom.2019.02.220
[40] W. Skrotzki, A. Pukenas, E. Odor, B. Joni, T. Ungar, B. Völker, A. Hohenwarter, R. Pippan, E.P. George, Microstructure, texture, and strength development during high-pressure torsion of CrMnFeCoNi high-entropy alloy, Crystals 10 (2020) 336. https://doi.org/10.3390/cryst10040336
[41] P. Edalati, R. Floriano, Y. Tang, A. Mohammadi, K. Danielle Pereira, A. Ducati Luchessi, K. Edalati, Ultrahigh hardness and biocompatibility of high-entropy alloy TiAlFeCoNi processed by high-pressure torsion, Mater. Sci. Eng. C 112 (2020) 110908. https://doi.org/10.1016/j.msec.2020.110908
[42] P. Edalati, A. Mohammadi, M. Ketabchi, K. Edalati, Ultrahigh hardness in nanostructured dual-phase high-entropy alloy AlCrFeCoNiNb developed by high-pressure torsion, J. Alloys Compd. 884 (2021) 161101. https://doi.org/10.1016/j.jallcom.2021.161101
[43] P. Edalati, A. Mohammadi, M. Ketabchi, K. Edalati, Microstructure and microhardness of dual-phase high-entropy alloy by high-pressure torsion: twins and stacking faults in FCC and dislocations in BCC, J. Alloys Compd. 894 (2022) 162413. https://doi.org/10.1016/j.jallcom.2021.162413
[44] A.P. Zhilyaev, G. Ringot, Y. Huang, J.M. Cabrera, T.G. Langdon, Mechanical behavior and microstructure properties of titanium powder consolidated by high-pressure torsion, Mater. Sci. Eng. A 688 (2017) 498-504. https://doi.org/10.1016/j.msea.2017.02.032
[45] K. Edalati, Z. Horita, H. Fujiwara, K. Ameyama, Cold consolidation of ball-milled titanium powders using high-pressure torsion, Metall. Mater. Trans. A 41 (2010) 3308-3317. https://doi.org/10.1007/s11661-010-0400-6
[46] S. Panda, J.J. Fundenberger, Y. Zhao, J. Zou, L.S. Toth, T. Grosdidier, Effect of initial powder type on the hydrogen storage properties of high-pressure torsion consolidated Mg, Int. J. Hydrog. Energy 42 (2017) 22438-22448. https://doi.org/10.1016/j.ijhydene.2017.05.097
[47] R.B. Figueiredo, P.H.R. Pereira, M.T.P. Aguilar, P.R. Cetlin, T.G. Langdon, Using finite element modeling to examine the temperature distribution in quasi-constrained high-pressure torsion. Acta Mater. 60 (2012) 3190-3198. https://doi.org/10.1016/j.actamat.2012.02.027
[48] K. Edalati, Y. Hashiguchi, P.H.R. Pereira, Z. Horita, T.G. Langdon, Effect of temperature rise on microstructural evolution during high-pressure torsion, Mater. Sci. Eng. A 714 (2018) 167-171. https://doi.org/10.1016/j.msea.2017.12.095
[49] K. Edalati, S. Toh, M. Arita, M. Watanabe, Z. Horita, High-pressure torsion of pure cobalt: hcp-fcc phase transformations and twinning during severe plastic deformation, Appl. Phys. Lett. 102 (2013) 181902. https://doi.org/10.1063/1.4804273
[50] V.I. Levita,: High-pressure phase transformations under severe plastic deformation by torsion in rotational anvils, Mater. Trans. 60 (2019) 1294-1301. https://doi.org/10.2320/matertrans.MF201923
[51] A. Mazilkin, B. Straumal, A. Kilmametov, P. Straumal, B. Baretzky, Phase transformations induced by severe plastic deformation, Mater. Trans. 60 (2019) 1489-1499. https://doi.org/10.2320/matertrans.MF201938
[52] X. Sauvage, A. Duchaussoy, G. Zaher, Strain induced segregations in severely deformed materials, Mater. Trans. 60 (2019) 1151-1158. https://doi.org/10.2320/matertrans.MF201919

[53] J. Gubicza, Lattice defects and their influence on the mechanical properties of bulk materials processed by severe plastic deformation, Mater. Trans. 60 (2019) 1230-1242. https://doi.org/10.2320/matertrans.MF201909
[54] J. Čížek, M. Janeček, T. Vlasák, B. Smola, O. Melikhova, R.K. Islamgaliev, S.V. Dobatkin, The development of vacancies during severe plastic deformation, Mater. Trans. 60 (2019) 1533-1542. https://doi.org/10.2320/matertrans.MF201937
[55] G. Wilde, S. Divinski, Grain boundaries and diffusion phenomena in severely deformed materials, Mater. Trans. 60 (2019) 1302-1315. https://doi.org/10.2320/matertrans.MF201934
[56] A. Bachmaier, R. Pippan, High-pressure torsion deformation induced phase transformations and formations: new material combinations and advanced properties, Mater. Trans. 60 (2019) 1256-1269. https://doi.org/10.2320/matertrans.MF201930
[57] J.K. Han, J.I. Jang, T.G. Langdon, M. Kawasaki, Bulk-state reactions and improving the mechanical properties of metals through high-pressure torsion, Mater. Trans. 60 (2019) 1131-1138. https://doi.org/10.2320/matertrans.MF201908
[58] K. Edalati, E. Akiba, Z. Horita, High-pressure torsion for new hydrogen storage materials, Sci. Technol. Adv. Mater. 19 (2018) 185-193. https://doi.org/10.1080/14686996.2018.1435131
[59] S. Akrami, P. Edalati, M. Fuji, K. Edalati, High-entropy ceramics: review of principles, production and applications, Mater. Sci. Eng. R 146 (2021) 100644. https://doi.org/10.1016/j.mser.2021.100644
[60] K. Edalati, Superfunctional materials by ultra-severe plastic deformation, Materials 16 (2023) 587. https://doi.org/10.3390/ma16020587
[61] H. Emami, K. Edalati, A. Staykov, T. Hongo, H. Iwaoka, Z. Horita, E. Akiba, Solid-state reactions and hydrogen storage in magnesium mixed with various elements by high-pressure torsion: experiments and first-principles calculations, RCS Adv. 6 (2016) 11665-11674. https://doi.org/10.1039/C5RA23728A
[62] K. Edalati, H. Emami, A. Staykov, D.J. Smith, E. Akiba, Z. Horita, Formation of metastable phases in magnesium-titanium system by high-pressure torsion and their hydrogen storage performance, Acta Mater. 50 (2015) 150-156. https://doi.org/10.1016/j.actamat.2015.07.060
[63] K. Edalati, H. Emami, Y. Ikeda, H. Iwaoka, I. Tanaka, E. Akiba, Z. Horita, New nanostructured phases with reversible hydrogen storage capability in immiscible magnesium-zirconium system produced by high-pressure torsion, Acta Mater. 108 (2016) 293-303. https://doi.org/10.1016/j.actamat.2016.02.026
[64] E.I. Lopez-Gomez, K. Edalati, D.D. Coimbroo, F.J. Antiqueira, G. Zepon, J.M. Cubero-Sesin, W.J. Botta, FCC phase formation in immiscible Mg-Hf (magnesium-hafnium) system by high-pressure torsion, AIP Adv. 10 (2020) 055222. https://doi.org/10.1063/5.0009456
[65] K. Fujiwara, R. Uehiro, K. Edalati, H.W. Li, R. Floriano, E. Akiba, Z. Horita, New Mg-V-Cr BCC alloys synthesized by high-pressure torsion and ball milling, Mater. Trans. 59 (2018) 741-746. https://doi.org/10.2320/matertrans.M2018001
[66] K. Edalati, R. Uehiro, Y. Ikeda, H.W. Li, H. Emami, Y. Filinchuk, M. Arita, X. Sauvage, I. Tanaka, E. Akiba, Z. Horita, Design and synthesis of a magnesium alloy for room temperature hydrogen storage, Acta Mater. 149 (2018) 88-96. https://doi.org/10.1016/j.actamat.2018.02.033
[67] M.O. de Marco, Y. Li, H.W. Li, K. Edalati, R. Floriano, Mechanical synthesis and hydrogen storage characterization of MgVCr and MgVTiCrFe high-entropy alloy, Adv. Eng. Mater. 22 (2020) 1901079. https://doi.org/10.1002/adem.201901079
[68] K. Kitabayashi, K. Edalati, H.W. Li, E. Akiba, Z. Horita, Phase transformations in MgH2-TiH2 hydrogen storage system by high-pressure torsion process, Adv. Eng. Mater. 22 (2020) 1900027. https://doi.org/10.1002/adem.201900027

[69] X. Sauvage, F. Cuvilly, A. Russell, K. Edalati, Understanding the role of Ca segregation on thermal stability, electrical resistivity and mechanical strength of nanostructured aluminum, Mater. Sci. Eng. A 798 (2020) 140108. https://doi.org/10.1016/j.msea.2020.140108

[70] A. Duchaussoy, X. Sauvage, K. Edalati, Z. Horita, G. Renou, A. Deschamps, F. De Geuser, Structure and mechanical behavior of ultrafine-grained aluminum-iron alloy stabilized by nanoscaled intermetallic particles, Acta Mater. 167 (2019) 89-102. https://doi.org/10.1016/j.actamat.2019.01.027

[71] K. Edalati, S. Toh, M. Watanabe, Z. Horita, In-situ production of bulk intermetallic-based nanocompsites and nanostructured intermetallics by high-pressure torsion, Scr. Mater. 66 (2012) 386-389. https://doi.org/10.1016/j.scriptamat.2011.11.039

[72] A. Alhamidi, K. Edalati, Z. Horita, Production of nanograined intermetallics using high-pressure torsion, Mater. Res. 16 (2013) 672-678. https://doi.org/10.1590/S1516-14392013005000057

[73] A. Alhamidi, K. Edalati, Z. Horita, Effect of temperature on solid-state formation of bulk nanograined intermetallics during high-pressure torsion, Philos. Mag. 94 (2014) 876-887. https://doi.org/10.1080/14786435.2013.868945

[74] K. Oh-ishi, K. Edalati, H.S. Kim, K. Hono, Z. Horita, High-pressure torsion for enhanced atomic diffusion and promoting solid-state reactions in aluminum-copper system, Acta Mater. 61 (2013) 3482-3489. https://doi.org/10.1016/j.actamat.2013.02.042

[75] A. Mohammadi, N.A. Enikeev, M.Y. Murashkin, M. Arita, K. Edalati, Developing age-hardenable Al-Zr alloy by ultra-severe plastic deformation: significance of supersaturation, segregation and precipitation on hardening and electrical conductivity, Acta Mater. 203 (2021) 116503. https://doi.org/10.1016/j.actamat.2020.116503

[76] A. Mohammadi, N.A. Enikeev, M.Y. Murashkin, M. Arita, K. Edalati, Examination of inverse Hall-Petch relation in nanostructured aluminum alloys by ultra-severe plastic deformation, J. Mater. Sci. Technol. 91 (2021) 78-89. https://doi.org/10.1016/j.jmst.2021.01.096

[77] K. Edalati, S. Toh, H. Iwaoka, M. Watanabe, Z. Horita, D. Kashioka, K. Kishida, H. Inui, Ultrahigh strength and high plasticity in TiAl intermetallics with bimodal grain structure and nanotwins, Scr. Mater. 67 (2012) 814-817. https://doi.org/10.1016/j.scriptamat.2012.07.030

[78] K. Edalati, H. Shao, H. Emami, H. Iwaoka, Z. Horita, E. Akiba, Activation of titanium-vanadium alloy for hydrogen storage by introduction of nanograins and edge dislocations using high-pressure torsion, Int. J. Hydrog. Energy 41 (2016) 8917-8924. https://doi.org/10.1016/j.ijhydene.2016.03.146

[79] A. Campos-Quirós, J.M. Cubero-Sesín, K. Edalati, Synthesis of nanostructured biomaterials by high-pressure torsion: effect of niobium content on microstructure and mechanical properties of Ti-Nb alloys, Mater. Sci. Eng. A 795 (2020) 139972. https://doi.org/10.1016/j.msea.2020.139972

[80] J. González-Masís, J.M. Cubero-Sesin, A. Campos-Quirós, K. Edalati, Synthesis of biocompatible high-entropy alloy TiNbZrTaHf by high-pressure torsion, Mater. Sci. Eng. A 825 (2021) 141869. https://doi.org/10.1016/j.msea.2021.141869

[81] P. Edalati, Q. Wang, H. Razavi-Khosroshahi, M. Fuji, T. Ishihara, K. Edalati, Photocatalytic hydrogen evolution on a high-entropy oxide, J. Mater. Chem. A 8 (2020) 3814-3821. https://doi.org/10.1039/C9TA12846H

[82] S. Akrami, Y. Murakami, M. Watanabe, T. Ishihara, M. Arita, M. Fuji, K. Edalati, Defective high-entropy oxide photocatalyst with high activity for CO2 conversion, Appl. Catal. B 303 (2022) 120896. https://doi.org/10.1016/j.apcatb.2021.120896

[83] P. Edalati, X.F. Shen, M. Watanabe, T. Ishihara, M. Arita, M. Fuji, K. Edalati, High-entropy oxynitride as low-bandgap and stable photocatalyst for hydrogen production, J. Mater. Chem. A 9 (2021) 15076-15086. https://doi.org/10.1039/D1TA03861C
[84] S. Akrami, P. Edalati, Y. Shundo, M. Watanabe, T. Ishihara, M. Fuji, K. Edalati, Significant CO2 photoreduction on a high-entropy oxynitride, Chem. Eng. J. 449 (2022) 137800. https://doi.org/10.1016/j.cej.2022.137800
[85] P. Edalati, Y. Itagoe, H. Ishihara, T. Ishihara, H. Emami, M. Arita, M. Fuji, K. Edalati, Visible-light photocatalytic oxygen production on a high-entropy oxide with multiple-heterojunction introduction, J. Photochem. Photobiol. A 433 (2022) 114167. https://doi.org/10.1016/j.jphotochem.2022.114167
[86] S. Lee, K. Edalati, H. Iwaoka, Z. Horita, T. Ohtsuki, T. Ohkochi, M. Kotsugi, T. Kojima, M. Mizuguchi, K. Takanashi, Formation of FeNi with L10-ordered structure using high-pressure torsion, Philos. Mag. Lett. 94 (2014) 639-646. https://doi.org/10.1080/09500839.2014.955546
[87] K. Edalati, T. Daio, Z. Horita, K. Kishida, H. Inui, Evolution of lattice defects, disordered/ordered phase transformations and mechanical properties in Ni-Al-Ti intermetallics by high-pressure torsion, J. Alloys Compd. 563 (2013) 221-228. https://doi.org/10.1016/j.jallcom.2013.02.128
[88] K. Edalati, T. Daio, S. Lee, Z. Horita, T. Nishizaki, T. Akune, T. Nojima, T. Sasaki, High strength and superconductivity in nanostructured niobium-titanium alloy by high-pressure torsion and annealing: significance of elemental decomposition and supersaturation, Acta Mater. 80 (2014) 149-158. https://doi.org/10.1016/j.actamat.2014.07.065
[89] J. Cubicza, N.Q. Chinh, J.L. Labar, Z. Hegedus, T.G. Langdon, Principles of self-annealing in silver processed by equal-channel angular pressing: the significance of a very low stacking fault energy, Mater. Sci. Eng. A 527 (2010) 752-760. https://doi.org/10.1016/j.msea.2009.08.071
[90] V.V. Popov, E.N. Popova, D.D. Kuznetsov, A.V. Stolbovskii, V.P. Pilyugin, Thermal stability of nickel structure obtained by high-pressure torsion in liquid nitrogen, Phys. Met. Metallogr. 115 (2014) 682-691. https://doi.org/10.1134/S0031918X14070060
[91] Y. Huang, S. Sabbaghianrad, A.I. Almazrouee, K.J. Al-Fadhalah, S.N. Alhajeri, T.G. Langdon, The significance of self-annealing at room temperature in high purity copper processed by high-pressure torsion, Mater. Sci. Eng. A 656 (2016) 55-66. https://doi.org/10.1016/j.msea.2016.01.027
[92] J.A. Muñoz, O.F. Higuera, A.H. Expósito, A. Boulaajaj, R.E. Bolmaro, F.D. Dumitru, P.R. Calvillo, A.M. Jorge Jr, J.M. Cabrera, Thermal stability of ARMCO iron processed by ECAP, Int. J. Adv. Manufact. Technol. 98 (2018) 2917-2932. https://doi.org/10.1007/s00170-018-2353-7
[93] H. Gleiter, Nanocrystalline materials, Prog. Mater. Sci. 33 (1989) 223-315. https://doi.org/10.1016/0079-6425(89)90001-7
[94] J.A. Haber, J.L. Crane, W.E. Buhro, C.A. Frey, S.M.L. Sastry, J.J. Balbach, M.S. Conradi, Chemical synthesis of nanocrystalline titanium and nickel aluminides from the metal chlorides and lithium aluminum hydride, Adv. Mater. 8 (1996) 163-166. https://doi.org/10.1002/adma.19960080215
[95] Y.B. Pithawalla, M.S. El-Shall, S.C. Deevi, Synthesis and characterization of nanocrystalline iron aluminide particles, Intermetallics 8 (2000) 1225-1231. https://doi.org/10.1016/S0966-9795(00)00076-5
[96] S. Suryanarayana, Mechanical alloying and milling, Prog. Mater. Sci. 46 (2001) 1-184. https://doi.org/10.1016/S0079-6425(99)00010-9
[97] M. Long, H.J. Rack, Titanium alloys in total joint replacement - a materials science perspective, Biomaterials. 19 (1998) 1621-1639. https://doi.org/10.1016/S0142-9612(97)00146-4

[98] R. Valiev, I.P. Semenova, E. Jakushina, V.V. Latysh, H.J. Rack, T.C. Lowe, J. Petruželka, L. Dluhoš, D. Hrušák, J. Sochová, Nanostructured SPD processed titanium for medical implants, Mater. Sci. Forum 584-586 (2008) 49-54. https://doi.org/10.4028/www.scientific.net/MSF.584-586.49

[99] Y. Estrin, H.E. Kim, R. Lapovok, H.P. Ng, J.H. Jo, Mechanical strength and biocompatibility of ultrafine-grained commercial purity titanium, BioMed Res. Int. 2013 (2013) 914764. https://doi.org/10.1155/2013/914764

[100] A.P. Zhilyaev, Y. Huang, J.M. Cabrera, T.G. Langdon, Influence of inhomogeneity on mechanical properties of commercially pure titanium processed by HPT, Defect Diffus. Forum 385 (2018) 284-289. https://doi.org/10.4028/www.scientific.net/DDF.385.284

[101] T.C. Lowe, R.Z. Valiev, X. Li, B.R. Ewing, Commercialization of bulk nanostructured metals and alloys, MRS Bull. 46 (2021) 265-272. https://doi.org/10.1557/s43577-021-00060-0

[102] C. Meingast, D.C. Larbalestier, Quantitative description of a very high critical current density Nb-Ti superconductor during its final optimization strain. II. Flux pinning mechanisms, J. Appl. Phys. 66 (1989) 5971-5983. https://doi.org/10.1063/1.343625

[103] L.D. Cooley, P.D. Jablonski, P.J. Lee, D.C. Larbalestier, Strongly enhanced critical current density in Nb 47 wt.% Ti having a highly aligned microstructure, Appl. Phys. Lett. 58 (1991) 2984-2986. https://doi.org/10.1063/1.104689

[104] R.W. Heussner, P.D. Jablonski, P.J. Lee, D.C. Larbalestier, Properties of rod-based artificial pinning center Nb-Ti superconductors, IEEE Trans. Appl. Supercon. 5 (1995) 1705-1708. https://doi.org/10.1109/77.402905

[105] V.A. Beloshenko, V.V. Chishko, Deformation-heat treatment of Nb-Ti superconductors using severe plastic deformation methods, Phys. Met. Metallogr. 114 (2013) 992-1002. https://doi.org/10.1134/S0031918X13090032

[106] I.P. Jain, C. Lal, A. Jain, Hydrogen storage in Mg: a most promising material, Int. J. Hydrogen Energy 35 (2010) 5133-5144. https://doi.org/10.1016/j.ijhydene.2009.08.088

[107] Á. Révész, M. Gajdics, High-pressure torsion of non-equilibrium hydrogen storage materials: a review, Energies 14 (2021) 819. https://doi.org/10.3390/en14040819

[108] T.G. Langdon, Seventy-five years of superplasticity: historic developments and new opportunities, J. Mater. Sci. 44 (2009) 5998-6010. https://doi.org/10.1007/s10853-009-3780-5

[109] R.Z. Valiev, M.Y. Murashkin, A. Kilmametov, B. Straumal, N.Q. Chinh, T.G. Langdon, Unusual super-ductility at room temperature in an ultrafine-grained aluminum alloy, J. Mater. Sci. 45 (2010) 4718-4724. https://doi.org/10.1007/s10853-010-4588-z

[110] M. Kawasaki, T.G. Langdon, The contribution of severe plastic deformation to research on superplasticity, Mater. Trans. 60 (2019) 1123-1130. https://doi.org/10.2320/matertrans.MF201915

[111] M. Demirtas, G. Purcek, Room temperature superplaticity in fine/ultrafine grained materials subjected to severe plastic deformation, Mater. Trans. 60 (2019) 1159-1167. https://doi.org/10.2320/matertrans.MF201922

[112] R. Wu, Y. Yan, G. Wang, L.E. Murr, W. Han, Z. Zhang, M. Zhang, Recent progress in magnesium-lithium alloys, Int. Mater. Rev. 60 (2015) 65-100. https://doi.org/10.1179/1743280414Y.0000000044

[113] A. Alhamidi, K. Edalati, Z. Horita, S. Hirosawa, K. Matsuda, D. Terada, Softening by severe plastic deformation and hardening by annealing of aluminum-zinc alloy: significance of elemental and spinodal decompositions, Mater. Sci. Eng. A 610 (2014) 17-27. https://doi.org/10.1016/j.msea.2014.05.026