Grain refinement in semi-solid metal processing : Current status and recent development

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ABSTRACT

Metal casting has become increasingly significant in the manufacture of industrial components. Aluminium alloys have become a typical metal casting material due to their lightweight, excellent corrosion resistance, improved mechanical properties, and excellent electrical conductivity. Grain refinement is a preferred method for improving the strength and flexibility of metallic materials by modifying the size of the grain structure using various processes. As a result, aluminium grain refinement is regarded an essential method in the aluminium processing industry. Grain refinement involves severe plastic deformation, quick solidification, and the addition of an inoculant. This paper discusses semi-solid metal processing (SSMP) research that enhances material properties using the grain refinement technique. The effect of different grain refinement techniques to the microstructure formation is also highlighted. The importance of the fine equiaxed globular microstructure in SSMP areas is explained. This study is expected to help the researcher establish the most effective grain refining technique in SSMP.

KEYWORDS

Globular microstructure; Grain refinement; Grain refiner; Rapid solidification; Semi-solid metal processing; Severe plastic deformation

REFERENCES

1. Czerwinski F (2017) “An overview of thixoforming process,”. https://doi.org/10.1088/1757-899X/257/1/012053.

2. Razak NA, Ahmad AH, Rashidi MM (2020) Thermal proile and microstructure of wrought aluminium 7075 for semi-solid metal processing. Int J Automot Mech Eng 17(2):7842–7850. https://doi.org/10.15282/ijame.17.2.2020.03.0584

3. de Figueredo A, N A D C (2001) Association, Science and tech-nology of semi-solid metal processing LK - https://ump.on. World cat. org/oclc/248922398. Rosemont, Ill. SE - Getr. Zählung [circa140 Seiten]: North American Die Casting Association

4. Miller WS, Zhuang L, Bottema J, Wittebrood AJ, De SmetP, Haszler A, Vieregge A (2000) Recent development in aluminium alloys for the automotive industry. Mater Sci Eng A 280:37–49. https://doi.org/10.1016/S0921-5093(99)00653-X

5. Guan R, Lou H, Huang H, Liang X, Xiao X (2020) Development of aluminum alloy materials: current status, trend, and prospects. Chinese J Eng Sci 22(5):68. https:// doi.org/10.15302/jsscae2020.05.013

6. Guan R-G, Tie D (2017) A review on grain reinement of aluminum alloys : progresses, Challenges and prospects. Acta Metall Sin (English Lett) 30(5):409–432. https://doi.org/10.1007/ s40195017-0565-8

7. Chang Z, Su N, Wu Y, Lan Q, Peng L, Ding W (2020) Semisolid rheoforming of magnesium alloys: a review. Mater Des 195:108990. https://doi.org/10.1016/j.matdes.2020.108990

8. Jiang J, Zhang Y, Wang Y, Xiao G, Liu Y, Zeng L (2020) Microstructure and mechanical properties of thixoforged complex box-type component of 2A12 aluminum alloy. Mater Des 193:108859. https://doi.org/10.1016/j.matdes.2020.108859

9. Rosso M, Peter I, Torino P (2013) New frontiers for thixoforming. Int J Microstruct Mater Prop 8:113

10. Salleh MS, Omar MZ, Syarif J, Mohammed MN (2013) An overview of semisolid processing of aluminium alloys. ISRN Mater Sci 2013:679820. https://doi.org/10.1155/2013/679820

11. Ahmad AH, Naher S, Brabazon D (2014) The efect of direct thermal method, temperature and time on microstructure of a cast aluminum alloy. Mater Manuf Process 29(2):134–139. https://doi.org/10.1080/10426914.2013.822980

12. Lee S-H, Saito Y, Sakai T, Utsunomiya H (Feb. 2002) Microstructures and mechanical properties of 6061 aluminum alloy processed by accumulative roll-bonding. Mater Sci Eng A 325:228–235. https://doi.org/10.1016/S0921-5093(01)01416-2

13. Rovira MM, Lancini BC, Robert MH (1999) Thixo-forming of Al–Cu alloys. J Mater Process Technol 92–93:42–49. https://doi.org/10.1016/S0924-0136(99)00220-4

14. Jiang J, Atkinson HV, Wang Y (2017) Microstructure and mechanical properties of 7005 aluminum alloy components formed by thixoforming. J Mater Sci Technol 33(4):379–388. https://doi.org/10.1016/j.jmst.2016.07.014

15. Hultquist G, Leygraf C (1980) Materials science and engineering : an introduction. Mater Sci Eng An Introd 42(1):181

16. Backerud L, Chai G Tamminen J (1990) Solidiication characteristics of aluminium alloys. Vol 2 foundry alloys. American Foundrymans Society/Skanaluminium

17. Zaid AIO (2016) Efect of molybdenum addition to ZA22 grain reined by Ti+B on its metallurgical and mechanical characteristics.Int J Sci Eng Res 7(4):591–595. https://doi.org/10.14299/ijser.2016.04.006
18. Lloyd DJ (Jan. 1994) Particle reinforced aluminium and magnesium matrix composites. Int Mater Rev 39(1):1–23. https://doi.org/10.1179/imr.1994.39.1.1
19. Kashyap KT, Chandrashekar T (2001) Effects and mechanisms of grain refinement in aluminium alloys. Bull Mater Sci 24(4):345–353.https://doi.org/10.1007/BF02708630
20. Al-Qawabah SMA, Zaid AIO (2016) Diferent methods for grain reinement of materials. Int J Sci Eng Res 7(7):1133–1140
21. Chokshi AH, Rosen A, Karch J, Gleiter H (1989) On the validity of the hall-petch relationship In nanocrystalline materials. Scr Metall 23(10):1679–1683. https://doi.org/10.1016/0036-9748(89)90342-6
22. Granger DA, Liu J (1983) The occurrence, efect, and control of twinned columnar growth In aluminum alloys. JOM J Miner Met Mater Soc 35(6):54–59. https:// doi.org/10.1007/BF03338303
23. Easton MA, Qian M, St John DH (2011) "Grain reinement in
alloys: novel approaches," Encycl Mater Sci Technol, pp. 1–7.
https://doi.org/10.1016/b978-0-08-043152-9.02259-4
24. Ferrante M, Freitas E (Nov.1999) Rheology and microstructural development of a Al–4wt%Cu alloy in the semi-solid state. Mater Sci Eng A 271:172–180. https://doi.org/10.1016/S0921-5093(99)00226-9
25. Edalati K et al (2022) Nanomaterials by severe plastic deformation : review of historical Developments and recent advances.Mater Res Lett 10(4):163–256. https://doi.org/10.1080/21663831.2022.2029779
26. Kulczyk M, Zysk B, Lewandowska M, Kurzydlowski KJ (2010) Grain reinement in CuCrZr by SPD processing. Phys Status Solidi Appl Mater Sci 207(5):1136–1138. https://doi.org/10.1002/pssa. 200983378
27. Boris B, Straumal R, Kulagin L. Klinger (2022) Structure refinement and fragmentation of precipitates under severe plastic deformation : a review. Materials(Basel) 15:2. https://doi.org/10.3390/ma15020601
28. Kumar S, Ranjan V, Tripathy S (2022) "Materials today : proceedings study of severe plastic deformations of metallic materials : -a move towards amorphization," Mater Today Proc,no. xxxx, pp.2–8.https://doi.org/10.1016/j.matpr.2022.02.244
29. Xu C, Horite Z, Furukawa M, Langdon TG (2004) Using equalchannel angular pressing for the Production of superplastic aluminum and magnesium alloys. J Mater Eng Perform 13(6):683–690. https://doi.org/10.1361/10599490421385
30. Molnár P, Jäger A, Lejcek P (2012) Efect of temperature on grain reinement of Mg-3Al-1Zn alloy processed by equal channel angular pressing. Acta Phys Pol A 122(3):461–464. https://doi.org/10.12693/APhysPolA.122.461
31. Valiev RZ, Ivanisenko YV, Rauch EF, Baudelet B (1996) Structure and deformation behaviour of Armco iron subjected to severe plastic deformation. Acta Mater 44(12):4705–4712. https:// doi. Org/10.1016/S1359-6454(96)00156-5
32. Langdon TG (2007) "The principles of grain reinement in equalchannel angular pressing," vol.462, pp. 3–11. https://doi.org/10.1016/j.msea.2006.02.473

33. Valiev RZ, Langdon TG (2006) “Principles of equal-channel angular pressing as a processing tool for grain reinement,” vol. 51, pp. 881–981. https://doi.org/10.1016/j.pmatsci.2006.02.003
34. Valiev RZ, Korznikov AV, Mulyukov RR (1993) Structure and properties of ultraine-grained materials produced by severe plastic deformation. Mater Sci Eng A 168(2):141–148. https:// doi.org/10.1016/0921-5093(93)90717-S
35. Furukawa M, Horita Z, Nemoto M, Langdon TG (2001) Review:processing of metals by equal-channel angular pressing. J Mater Sci 36:2835–2843. https://doi.org/10.1023/A:1017932417043
36. Moradi M, Nili-Ahmadabadi M, Heidarian B, Parsa MH (2008) Study of ECAP processing routes on semi-solid microstructure evolution of A356 alloy. Solid State Phenom 141–143:397–402. https://doi.org/10.4028/www.scientiic.net/ssp.141-143.397
37. Ashouri S, Nili-Ahmadabadi M, Moradi M, Iranpour M (2008) Semi-solid microstructure evolution during reheating of aluminum A356 alloy deformed severely by ECAP.J Alloys Compd 466(1–2):67–72.https://doi.org/10.1016/j.jallcom.2007.11.010
38. Proni CTW, Torres LV, Haghayeghi R, Zoqui EJ (2016) Materials characterisation ECAP : an a lternative route for producing AlSiCu for use in SSM processing. Mater Charact 118:252–262. https://doi.org/10.1016/j.matchar.2016.06.002
39. Toofaninejad M, Nili-Ahmadabadi M, Shirazi H (2014) Microstructural evolution of semi-solid type 304 stainless steel deformed severely by ECAP. Solid State Phenom 217–218:99–104. https://doi.org/10.4028/www.scientiic.net/SSP.217-218.99
40. Lin HQ, Wang JG, Wang HY, Jiang QC (2007) Efect of predeformation on the globular grains in AZ91D alloy during strain induced melt activation (SIMA) process.J Alloys Compd 431(1):141–147. https://doi.org/10.1016/j.jallcom.2006.05.067
41. Saito Y, Utsunomiya H, Tsuji N, Sakai T (1999) “Novel ultra-high straining process for bulk materials-development of the accumulative roll-bonding (ARB) process,”vol. 47,no.2
42. Gupta A, Chandrasekhar B, Saxena KK (2021) Efect of equalchannel angular pressing on mechanical properties : an overview. Mater Today Proc 45:5602–5607. https://doi .org/10.1016/j.matpr.2021.02.317
43. T suji N, Saito Y, Utsunomiya H, Tanigawa S (1999) Ultra-inegrained bulk steel produced by accumulative roll-bonding (ARB) process. United States. https:// doi.org/10.1016/S1359-6462(99)00015-9
44. Ghalehbandi SM, Malaki M, Gupta M (2019) Accumulative roll bonding—a review. Appl Sci 9(17):3627. https://doi.org/10.3390/app9173627
45. T suji N, Saito Y, Lee S-H, Minamino Y (2003) ARB (Accumulative Roll-Bonding) and other new Techniques to produce bulk ultrafine grained materials. Adv Eng Mater 5:338–344. https://doi. org/10.1002/adem.200310077
46. Jamaati R, Amirkhanlou S, Toroghinejad MR, Niroumand B (2011) Signiicant improvement of semi-solid microstructure and mechanical properties of A356 alloy by ARB process. Mater Sci Eng A 528(6):2495–2501. https://doi.org/10.1016/j. msea.2010.11.086
47. Jamaati R, Amirkhanlou S, Toroghinejad MR, Niroumand B (2012) Comparison of the microstructure and mechanical properties of as-cast A356/SiC MMC processed by ARB and CAR methods. J Mater Eng Perform 21(7):1249–1253. https://doi.org/10.1007/s11665-011-0045-7
48. Huang X, T suji N, Hansen N, Minamino Y (2003) Microstructural evolution During accumulative roll-bonding of commercial purity aluminum. Mater Sci Eng A 340:265–271. https://doi.org/10.1016/S0921-5093(02)00182-X

49. Edalati K, Horita Z (2016) A review on high-pressure torsion (HPT) from 1935 to 1988. Mater Sci Eng A 652:325–352. https://doi.org/10.1016/j.msea.2015.11.074
50. Sakai G, Horita Z, Langdon TG (2005) Grain reinement and superplasticity in an aluminum alloy processed by high-pressure torsion. Mater Sci Eng 393:344–351. https://doi.org/10.1016/j.msea.2004.11.007
51. Wang X, Nie M, Ting C, Cai S, Gao N (2015) Microhardness and corrosion properties of hypoeutectic Al – 7Si alloy processed by high-pressure torsion. Mater Des 83:193–202. https://doi.org/10.1016/j.matdes.2015.06.018
52. KrutsuwanNuphairode C, Fadhlina Mohamed I, Lamin F, W. Fathul Hakim Wan Zamri, M. Zaidi Omar, and Z. Horita (2020) The evolvement of mechanical properties and microstructure of commercial aluminum alloy 6061 via high-pressure torsion. JKejuruter 32(3):531–538
53. Zhang X, Huang LK, Zhang B, Chen YZ, Liu F (2020) Microstructural evolution and strengthening mechanism of an Al–Si–Mg alloy processed by high-pressure torsion with diferent Heat treatments. Mater Sci Eng A 794(December 2019):139932. https://doi.org/10.1016/j.msea.2020.139932
54. Kawasaki M, Langdon TG (2008) The signiicance of strain reversals during processing by high pressure torsion. Mater Sci Eng 498:341–348. https://doi.org/10.1016/j.msea.2008.08.021
55. Zhil yaev AP, Langdon TG (2008) "Progress in materials science using high-pressure torsion for metal processing : fundamentals and applications," vol. 53, no. March, pp. 893–979. https://doi. org/10.1016/j.pmatsci.2008.03.002
56. Giordano L, Ramous E (1986) Rapid solidiication of surface lay ers melted by CW Laser BT - laser surface treatment of metals. In : Draper CW, Mazzoldi P (eds). Springer Netherlands, Dordrecht, pp 483–495
57. Dorin T, Vahid A, Lamb J (2018) Aluminium lithium alloys. In: Lumley RN (ed) Fundamentals of aluminium metallurgy. Woodhead Publishing, pp 387–438. https://doi.org/10.1016/B978-0-081020630.00011-4
58. Yu W et al (2021) 2022 "Solute inverse segregation behavior in twin roll casting of an Al-Cu alloy." Scr Mater 213(April 2021):114592. https://doi.org/10.1016/j.script amat.2022.114592
59. Zhang W, Ju D, Zhao H, Hu X, Yao Y, Zhang Y (2015) A decoupling control model on perturbation method for twin-roll casting magnesium alloy sheet. J Mater Sci Technol 31(5):517–522. https://doi.org/10.1016/j.jmst.2015.01.005
60. Javaid A, Czerwinski F (2021) Progress in twin roll casting of magnesium alloys : a review. J Magnes Alloy 9(2):362–391.https://doi.org/10.1016/j.jma.2020.10.003
61. Barekar NS, Dhindaw BK (2014) "Twin-roll casting of aluminum alloys – an overview twin-roll casting of aluminum alloys – an overview,"vol. 6914. https://doi.org/10.1080/10426914.2014.912307.
62. Wang H, Zhou L, Zhang Y, Cai Y, Zhang J (2016) Journal of Materials Processing Technology Efects of twin-roll casting process on the microstructure and sheet metal forming behavior of 7050 aluminum alloy. J Mater Process Tech 233:186–191. https://doi.org/10.1016/j.jmatprotec.2016.02.016
63. Yun M, Lokyer S, Hunt J. D (2000) "Twin roll casting of aluminium alloys," vol. 280,pp.116–123
64. Li B, Lavernia EJ (2016) Spray forming of MMCs, reference module in materialsscience and materials engineering. Elsevier. https://doi.org/10.1016/B978-0-12-803581-8.03884-4

65. Shen J, Zeng S, Jiang Z, Cui C, Li Q (1994) Pressure characteristics at the tip of the metal delivery tube in a spray deposition process. In Advanced materials. Elsevier, pp 725–729. https://doi.org/10.1016/B978-0-444-81991-8.50177-1
66. Boe ttinger WJ, Banerjee DK (2014) 7 - Solidiication. In: Laughlin DE, Hono K (eds) Physical metallurgy, 5th edn. Elsevier, Oxford, pp 639–850. https://doi.org/10.1016/B978-0-444-537706.00007-1
67. Srivastava VC, Mandal GK, Ciftci N, Uhlenwinkel V, Mädler L (2017) Processing of high-entrop AlCoCr0.75Cu0.5FeNi alloy by spray forming. J Mater Eng Perform 26(12):5906–5920. https://doi.org/10.1007/s11665-017-3071-2
68. Grant PS (1995) Spray forming. Prog Mater Sci 39(4):497–545. https://doi.org/10.1016/0079-6425(95)00004-6
69. Doher ty RD (2001) Spray casting: fundamentals. In Encyclopedia of materials: science and technology.Elsevier, Oxford, pp 8776–8779. https://doi.org/10.1016/B0-08-043152-6/01573-4
70. Mehmood A, Shah M, Sheikh NA, Qayyum JA, Khushnood S (2016) Grain reinement of ASTM A356 aluminum alloy using sloping plate process through gravity die casting. Alexandria Eng J 55(3):2431–2438. https://doi.org/10.1016/j.aej.2016.03.016
71. Quested TE (2004) Understanding mechanisms of grain refinement of aluminium alloys By inoculation. Mater Sci Technol 20(11):1357–1369. https://doi.org/10.1179/026708304225022359
72. Murty BS, Kori SA, Chakraborty M (2002) Grain reinement of aluminium and its alloys by heterogeneous nucleation and alloying. Int Mater Rev 47(1):3–29. https://doi.org/10.1179/095066001225001049
73. Pandee P, Patakham U, Limmaneevichitr C (2017) Microstructural evolution and mechanical properties of Al-7Si-0.3Mg alloys with erbium additions. J Alloys Compd 728:844–853. https://doi.org/10.1016/j.jallcom.2017.09.054
74. Hu X, Jiang F, Ai F, Yan H (2012) Efects of rare earth Er additions on microstructure development and mechanical properties of die-cast ADC12 aluminum alloy. J Alloys Compd 538:21–27. https://doi.org/10.1016/j.jallcom.2012.05.089
75. Bozorgi S, Anders K, Baumgartner I (2019) Microstructures and mechanical properties of Er modiied AA7075 alloy. Int J Cast Met Res 32(1):15–20. https://doi.org/10.1080/13640461.2018.1500123
76. Peeratatsuwan C, Pandee P, Patakham U, Limmaneevichitr C (2021) Efect of erbium on the rheocast quality index of A356 semi-solid feedstock. Mater Sci Technol (United Kingdom) 37(4):424–438. https://doi.org/10.1080/02670836.2021.1908727
77. Birol Y (2012) Efect of silicon content in grain reining hypoeutectic Al-Si foundry alloys with boron and titanium additions. Mater Sci Technol 28(4):385–389. https://doi.org/10.1179/1743284711Y.0000000049
78. Chen Z, Kang H, Hua Fan G, Li JH (2016) Grain reinement of hypoeutectic Al-Si alloys with boron. Acta Mater 120:168–178. https://doi.org/10.1016/j.actamat.2016.08.045
79. Xu Q, Ding X, Chen C, Zhou J, Xue F, Chen Q (2021) Role of erbium in microstructure and mechanical properties of Sn58Bi42 solder alloy. Mater Lett 305(August):130745. https://doi.org/10. 1016/j.matlet.2021.130745

80. Joy D, Aravindakshan R, Varrma NS (2021) Efect of zirconium additions on microstructure and mechanical properties of hot rolled Al-Mg alloys. Mater Today Proc 47:5098–5103. https://doi.org/10.1016/j.matpr.2021.05.284
81. Salleh MS, Omar MZ, Syarif J (2015) The efects of Mg addition on the microstructure and mechanical properties of thixoformed Al-5%Si-Cu alloys. J Alloys Compd 621:121–130. https://doi.org/10.1016/j.jallcom.2014.09.152
82. Peeratatsuwan C, Pandee P, Patakham U, Limmaneevichitr C (2021) Microstructure and rheological properties of a semi-solid A356 with erbium addition. J Rare Earths. https://doi.org/10.1016/j.jre.2021.06.011
83. Alhawari KS, Omar MZ, Ghazali MJ, Salleh MS, Mohammed MN (2016) Dry sliding wear behaviour of thixoformed hypoeutectic Al-Si-Cu alloy with diferent amounts of magnesium. Compos Interfaces 23(6):519–531. https://doi.org/10. 1080/09276 440.2016.1164496
84. Liu Z, Qiu D, Wang F, Taylor JA, Zhang M (2015) Grain refinement of cast zinc throughmagnesium inoculation: characterization and mechanism. Mater Charact 106:1–10. https://doi.org/10.1016/j. matchar.2015.05.011
85. Gandel DS, Birbilis N, Easton MA, Gibson MA (2010) Inluence of manganese, zirconium and iron on the corrosion of magnesium. Australas Corros Assoc Preston, VIC 8:1–11
86. Edgar R, Schmid R, Grobner J (2006) Magnesium alloys and their applications
87. Cao P, Qian M, Stjohn DH (2006) Efect of manganese on grain reinement of Mg-Al based alloys. Scr Mater 54(11):1853–1858. https://doi.org/10.1016/j.script amat.2006.02.020
88. Zhao T, Hu Y, He B, Zhang C, Zheng T, Pan F (2019) Efect of manganese on microstructure and properties of Mg-2Gd magnesium alloy. Mater Sci Eng A 765(1):138292. https://doi.org/10.1016/j.msea.2019.138292
89. Yu Z, Tang A, He J (2018) Efect of high content of manganese on microstructure, texture and mechanical properties of magnesium alloy. Mater Charact 136:310–317. https://doi.org/10.1016/j.match ar.2017.12.029
90. Chaturvedi V, Sharma A, Pandel U (Apr. 2017) Efect of mechanical vibrations on grain refinement of AZ91 Mg alloy. Mater Res Express 4(4):46501.https://doi.org/10.1088/2053-1591/aa64f5
91. Taghavi F, Saghaian H, Kharrazi Y (May 2009) Study on the efect of prolonged mechanical vibration on the grain refinement and density of A356 aluminum alloy. Mater Des - MATER Des 30:1604–1611. https://doi.org/10.1016/j.matdes.2008.07.032
92. Jiang W, Chen X, Wang B, Fan Z, Wu H (2016) Efects of vibration frequency on microstructure, mechanical properties, and fracture behavior of A356 aluminum alloy obtained by expendable pattern shell casting. Int J Adv Manuf Technol 83(1–4):167–175.https://doi.org/10.1007/s00170 015-7586-0
93. Limmanee vichitr C, Pongananpanya S, Kajornchaiyakul J (2009) Metallurgical structure of A356 aluminum alloy solidiied under mechanical vibration: an investigation of alternative semi-solid casting routes. Mater Des 30(9):3925–3930. https://doi.org/10.1016/j.matdes.2009.01.036
94. Guo HM, Zhang AS, Yang XJ, Yan MM (2014) Grain refinement of Al-5%Cu aluminum alloy under mechanical vibration using meltable vibrating probe. Oral Oncol 50(10):2489–2496. https://doi.org/10.1016/S1003-6326(14)63375-6