THE EFFECT OF PROCESSING PARAMETERS ON MICROSTRUCTURE AND MECHANICAL PROPERTIES OF ALUMINIUM 6061 SEMISOLID METAL BILLET

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I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

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ABSTRAK

Tesis ini mempersembahkan dapatan kerja kajian mengenai kesan parameter Pemprosesan Logam Separa Pepejal (PLSP) pada aluminium bilet yang dihasilkan dengan menggunakan Kaedah Haba Langsung (KHL)). Gabungan suhu tuangan telah ditetapkan pada suhu 640 °C, 660 °C dan 680 °C dengan masa pegangan 20 s, 40 s dan 60 s. Tiga sampel dihasilkan untuk setiap kombinasi pemprosesan. Logam aluminium lebur dituangkan ke dalam acuan tembaga silinder dengan kombinasi suhu tuangan dan masa pegangan yang berbeza sebelum dilindapkejutkan ke dalam air yang bersuhu bilik. Ketumpatan, kekuatan tegangan utama dan kekuatan Vickers bilet PLSP setelah melalui proses KHL diperiksa. Nilai ketumpatan untuk setiap sampel yang dihasilkan diantara 2.527 g/cm^3 dan 2.701 g/cm^3. Sampel 6 dengan suhu tuangan 660 ° C dan masa pegangan 60 s mempunyai nilai ketumpatan tertinggi iaitu 2.701 g/cm^3. Ini menunjukkan bahawa sampel 6 mempunyai kandungan keliangan terendah dalam bilet PLSP. Hasil ujian tegangan juga menunjukkan bahawa nilai ujian tegangan utama adalah diantara 65.39 MPa dan 146.797 MPa, sementara nilai ujian kekuatan vickers adalah diantara 65.85 HV dan 86.5 HV. Sampel dengan suhu tuangan di atas sedikit suhu lebur aluminium 6061 mengakibatkan kandungan keliangan menurun, manakala kekuatan tegangan dan nilai kekerasan meningkat. Sampel 4 dengan suhu tuangan 660 °C dan masa pegangan 20 s menghasilkan ukuran struktur bulat dan kecil dari kawasan fasa primer iaitu 2547.87 μm^2. Hasil kajian menunjukkan bahawa akibat daripada proses penyejukan secara pantas bagi aloi aluminium 6061, lebih banyak struktur bulat diperoleh. Kecepatan haba yang keluar dari aloi akan merencatkan pembentukan struktur dendritik sehingga mengubahnya menjadi struktur bulat untuk pemprosesan PLSP. Suhu tuangan yang lebih rendah meningkatkan pembentukan nukleasi semasa proses penyejukan, sehingga menghasilkan struktur bulat yang lebih banyak dan ukuran butiran yang lebih kecil. Penemuan kajian ini meningkatkan pemahaman yang lebih baik mengenai tingkah laku bilet aluminium 6061 PLSP. Penemuan ini boleh memberi kefahaman sifat aluminium 6061 yang lebih baik terutamanya dalam industri pembuatan.

ABSTRACT

This thesis presents the experimental works on the effects of the semisolid metal (SSM) processing parameters on the aluminium feedstock billets produced by the direct thermal method (DTM). The combinations of pouring temperatures were fixed at 640 °C, 660 °C, and 680 °C with holding times of 20 s, 40 s, and 60 s, respectively. Three samples were produced for each of the combinations. The SSM feedstock billets were prepared by using DTM, in which 6061 molten metal was poured into a cylindrical copper mould with a different combination of pouring temperature and holding time before being solidified into room temperature water. The porosity content, ultimate tensile st1rength, and Vickers hardness were examined for the feedstock billets after the DTM process. There were differences in density value for each sample which occurred between 2.527 g/cm^3 and 2.701 g/cm^3. Sample 6 with a pouring temperature of 660 °C and holding time of 60 s has the highest density value, which was 2.701 g/cm^3. This indicated that sample 6 has the lowest porosity content within the feedstock billets. The tensile test results showed that the ultimate tensile test values were between 65.39 MPa and 146.797 MPa, while the Vickers hardness test values were between 65.85 HV and 86.5 HV. In the sample with pouring temperature slightly above the aluminium 6061 liquidus temperature, the porosity content had decreased; tensile strength and hardness values had increased. Sample 4 with a pouring temperature of 660 °C and holding time of 20 s produced globular and small grain size for the primary phase area, which was 2547.87 μm^2. Results show that, due to the rapid cooling condition of the molten 6061 inside the copper mould, more globular microstructures were obtained. The faster the heat is convicted out from the molten alloy will retard the formation of dendritic microstructure, thus transforming it into globular microstructure for SSM processing. The lower pouring temperature enhances the formation of nucleation during the solidification process, thus producing more globular microstructure and smaller grain size. The findings of this experimental works enhance a better understanding of the behaviour of aluminium alloy 6061 SSM feedstock billets. These findings could lead to better information on the formability behaviour of aluminium alloy 6061, mainly in the manufacturing industry.

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LIST OF SYMBOLS

°C	degree Celsius
s	Second
%	Percentage
Mg_2Si	Magnesium Silicide
Mg	Magnesium
Si	Silicon
Cu	Copper
Cr	Chromium
Al	Aluminium
Mn	Manganese
HB	Brinell Hardness
MPa	Mega Pascal
µm	Micro meter
ρf	Density of feedstock
Wf	Weight of feedstock
Ww	Weight of water
ρw	Density of water
SiC	Silica Carbide
HV	Vickers Hardness
rpm	Revolutions per minute

LIST OF ABBREVIATIONS

SSMP	Semi Solid Metal Processing
SSM	Semi Solid Metal
MIT	Massachusetts Institute of Technology
DTM	Direct Thermal Method
MHD	Magnetohydrodynamic
HPDC	High Pressure Die Casting
ITT	International Telephone and Telegraph
NRC	New Rheocasting
DAQ	data acquisition
ASTM	American society for testing and materials
SEM	Scanning Electron Microscope
EDXS	Energy-dispersive X-ray Spectroscopy
CNC	Computer numerical control

REFERENCES

Abdulrazaq, M. N. (2014). An Overview of Semisolid Procesing of Aluminium Alloys. International Scholarly Research Notices.

Abramov, V. (1998). Solidification of aluminium alloys under ultrasonic irradiation using water-cooled resonator. Material Design, 18, 323–326.

Abubakre, O. K., Mamaki, U. P., & Muriana, R. A. (2009). Investigation of the Quenching Properties of Selected Media on 6061 Aluminum Alloy. Journal of Minerals and Materials Characterization and Engineering, 08(04), 303–315. https://doi.org/10.4236/jmmce.2009.84027

Ahmad, A. H. (2015). Effect of Temporal Thermal Field on Quality of Semi-solid Metal Formed Components.

Ahmad, A. H., Naher, S., & Brabazon, D. (2014). The effect of direct thermal method, temperature and time on microstructure of a cast aluminum alloy. Materials and Manufacturing Processes, 29(2), 134–139. https://doi.org/10.1080/10426914.2013.822980

Ahmad, A H, Naher, S., & Brabazon, D. (2014). Direct Thermal Method of Aluminium 7075. 939, 400–408. https://doi.org/10.4028/www.scientific.net/AMR.939.400

Ahmad, Asnul Hadi, Naher, S., Aqida, S. N., & Brabazon, D. (2014). Routes to Spheroidal Starting Material for Semisolid Metal Processing. https://doi.org/10.1016/B978-0-08-096532-1.00515-X

Ahmad, Asnul Hadi, Naher, S., & Brabazon, D. (2014). Direct Thermal Method of Aluminium 7075. Advanced Materials Research, 939, 400–408. https://doi.org/10.4028/www.scientific.net/AMR.939.400

Ahmad, Asnul Hadi, Naher, S., & Brabazon, D. (2014). The Effect of Direct Thermal Method , Temperature and Time on Microstructure of a cast aluminium alloy. (March). https://doi.org/10.1080/10426914.2013.822980

Ahmad, Asnul Hadi, Naher, S., & Brabazon, D. (2015). Mechanical Properties of Thixoformed 7075 Feedstock Produced via the Direct Thermal Method. https://doi.org/10.4028/www.scientific.net/KEM.651-653.1569

Akhtar, S., Arnberg, L., Timelli, G., Bonollo, F., & Di Sabatino, M. (2011). A comparative study of defects and mechanical properties in high pressure die cast and gravity die cast aluminium alloys. Foundry Trade Journal International, 185(3690), 348–356.

Anson, J. P., & Gruzleski, J. E. (1999). Quantitative discrimination between shrinkage and gas microporosity in cast aluminum alloys using spatial data analysis. Materials Characterization, 43(5), 319–335. https://doi.org/10.1016/S1044-5803(99)00059-5

Aruri, D., Adepu, K., Adepu, K., & Bazavada, K. (2013). Wear and mechanical properties of 6061-T6 aluminum alloy surface hybrid composites [(SiC + Gr) and (SiC + Al 2 O 3)]. Integrative Medicine Research, 2(4), 362–369. https://doi.org/10.1016/j.jmrt.2013.10.004

Avalle, M., Belingardi, G., Cavatorta, M. P., & Doglione, R. (2002). Casting defects and fatigue strength of a die cast aluminium alloy: A comparison between standard specimens and production components. International Journal of Fatigue, 24(1), 1–9. https://doi.org/10.1016/S0142-1123(01)00112-8

Aziz Ahamed, A. K. M., Kato, H., Kageyama, K., & Komazaki, T. (2006). Acoustic visualization of cold flakes and crack propagation in aluminum alloy die-cast plate. Materials Science and Engineering A, 423(1–2), 313–323. https://doi.org/10.1016/j.msea.2006.02.042

Benjunior, B., Ahmad, A. H., & Rashidi, M. M. (2020). Direct thermal method pouring temperature and holding time effect on aluminium alloy 6061 microstructure. IOP Conference Series: Materials Science and Engineering, 788(1). https://doi.org/10.1088/1757-899X/788/1/012017

Benjunior, B., Ahmad, A. H., Rashidi, M. M., & Reza, M. S. (2017). Effect of Different Cooling Rates Condition on Thermal Profile and Microstructure of Aluminium 6061. Procedia Engineering, 184, 298–305. https://doi.org/10.1016/j.proeng.2017.04.098

Bochao, L., Youngkoo, P., & Hongsheng, D. (2011). Effects of rheocasting and heat treatment on microstructure and mechanical properties of A356 alloy. Materials Science & Engineering A, 528(3), 986–995. https://doi.org/10.1016/j.msea.2010.09.059

Browne, D. J., Hussey, M. J., Carr, A. J., & Brabazon, D. (2003a). Direct thermal method : new process for development of globular alloy microstructure. (May 2014). https://doi.org/10.1179/136404603225007854

Browne, D. J., Hussey, M. J., Carr, A. J., & Brabazon, D. (2003b). Direct thermal method: New process for development of globular alloy microstructure. International Journal of Cast Metals Research, 16(4), 418–426. https://doi.org/10.1080/13640461.2003.11819618

Cabibbo, M., Spigarelli, S., & Evangelista, E. (2002). A TEM investigation on the effect of semisolid forming on precipitation processes in an Al-Mg-Si Alloy. Materials Characterization, 49(3), 193–202. https://doi.org/10.1016/S1044-5803(02)00325-X

Cardoso, E., Atkinson, H., & Jones, H. (2004). Microstructural Evolution of A356 During NRC Processing. Proceedings of the 8th International Conference on Semi-Solid Processing of Alloys and Composites, S2P 2004.

Carr, A. J., Browne, D. J., Hussey, M. J., Lumsden, N., & Scanlan, M. (2007). Modelling and experimental development of the direct thermal method of rheocasting. International Journal of Cast Metals Research, 20(6), 325–332. https://doi.org/10.1179/136404608X286147

Chayong, S., Atkinson, H. V., & Kapranos, P. (2005). Thixoforming 7075 aluminium alloys. Materials Science and Engineering A, 390(1–2), 3–12. https://doi.org/10.1016/j.msea.2004.05.004

Czerwinski, F. (2018). Thermomechanical Processing of Metal Feedstock for Semisolid Forming: A Review. Metallurgical and Materials Transactions B, 49(6), 3220–3257. https://doi.org/10.1007/s11663-018-1387-4

Davis, J. R. (2001). Aluminum and Aluminum Alloys. 351–416. https://doi.org/10.1361/autb2001p351

Davis, J. R. (2004). Tensile Testing. https://doi.org/10.1361/ttse2004p001

Dispinar, D., & Campbell, J. (2006). Use of bifilm index as an assessment of liquid metal quality. International Journal of Cast Metals Research, 19(1), 5–17. https://doi.org/10.1179/136404606225023300

Doutre, I. D., & Hay, G. (2002). (12) United States Patent (10) Patent No .: 2(12).

Fan, Z. (2002). Semisolid metal processing. International Materials Reviews, 47(2), 49–85. https://doi.org/10.1179/095066001225001076

Fang, X., Wu, S., Lü, S., Wang, J., & Yang, X. (2017). Microstructure evolution and mechanical properties of quasicrystal-reinforced Mg-Zn-Y alloy subjected to ultrasonic vibration. Materials Science and Engineering A, 679(September 2016), 372–378. https://doi.org/10.1016/j.msea.2016.10.035

Ferrante, M., & Freitas, E. (1999). Rheology and microstructural development of a Al–4wt%Cu alloy in the semi-solid state. Materials Science and Engineering: A, 271, 172–180. https://doi.org/10.1016/S0921-5093(99)00226-9

Fiorese, E., Bonollo, F., Timelli, G., Arnberg, L., & Gariboldi, E. (2015). New classification of defects and imperfections for aluminum alloy castings. International Journal of Metalcasting, 9(1), 55–66. https://doi.org/10.1007/BF03355602

Flemings, M. (1991). Behavior of Metal Alloys in the Semisolid State. Metallurgical and Materials Transactions A-Physical Metallurgy and Materials Science - METALL MATER TRANS A, 22, 957–981. https://doi.org/10.1007/BF02661090

Flemings, M. C. (1974). Solidification processing. Metallurgical Transactions, 5(10), 2121–2134. https://doi.org/10.1007/BF02643923

Flemings, M C, Riek, R. G., & Young, K. P. (1976). Rheocasting. Materials Science and Engineering, 25, 103–117. https://doi.org/https://doi.org/10.1016/0025-5416(76)90057-4

Flemings, Merton C. (1991). Behavior of metal alloys in the semisolid state. Metallurgical Transactions B, 22(3), 269–293. https://doi.org/10.1007/BF02651227

Garrison, W. M., & Moody, N. R. (1987). Ductile fracture. Journal of Physics and Chemistry of Solids, 48(11), 1035–1074. https://doi.org/10.1016/0022-3697(87)90118-1

Gupta, A. K., Lloyd, D. J., & Court, S. A. (2001). Precipitation hardening in Al – Mg – Si alloys with and without excess Si. 316, 11–17.

Haga, T., & Kapranos, P. (2002). Simple rheocasting processes. Journal of Materials Processing Technology, 130–131, 594–598. https://doi.org/10.1016/S0924-0136(02)00819-1

Haga, T., & Suzuki, S. (2001). Casting of aluminum alloy ingots for thixoforming using a cooling slope. Journal of Materials Processing Technology - J MATER PROCESS TECHNOL, 118, 169–172. https://doi.org/10.1016/S0924-0136(01)00888-3

Haghayeghi, R., Zoqui, E. J., Halvaee, A., & Emamy, M. (2005). An investigation on semi-solid Al-7Si-0.3Mg alloy produced by mechanical stirring. Journal of Materials Processing Technology, 169(3), 382–387. https://doi.org/10.1016/j.jmatprotec.2005.04.071

Hayes, M. D., Edwards, D. B., & Shah, A. R. (2015). 1 - Introduction. In M. D. Hayes, D. B. Edwards, & A. R. Shah (Eds.), Fractography in Failure Analysis of Polymers (pp. 1–5). https://doi.org/https://doi.org/10.1016/B978-0-323-24272-1.00001-5

Hirai, M., Takebayashi, K., & Yoshikawa, Y. (1994). Effect of Chemical Composition on Apparent Viscosity of Semisolid Alloys. Isij International, 33(11), 1182–1189. https://doi.org/10.2355/isijinternational.33.1182

Hirt, G., & Kopp, R. (2009). Thixoforming: Semi-solid Metal Processing. In Thixoforming: Semi-solid Metal Processing. https://doi.org/10.1002/9783527623969

Jiang, J., Atkinson, H. V., & Wang, Y. (2017). Microstructure and Mechanical Properties of 7005 Aluminum Alloy Components Formed by Thixoforming. Journal of Materials Science and Technology, 33(4), 379–388. https://doi.org/10.1016/j.jmst.2016.07.014

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. Materials and Design, 193, 108859. https://doi.org/10.1016/j.matdes.2020.108859

Kang, C. G., Yoon, J. H., & Seo, Y. H. (1997). The Upsetting Behavior of Semi-Solid Aluminum Material Fabricated by Mechanical Stirring Process. Journal of Materials Processing Technology, 66, 30–38. https://doi.org/10.1016/S0924-0136(96)02493-4

Kapranos, P. U., Ward, P. J., Atkinson, H. V, & Kirkwood, D. H. (2000). Near net shaping by semi-solid metal processing. 387–394.

Kapranos, P, Kirkwood, D., & Sellars, C. (1993). Semi-Solid Processing of Aluminium and High Melting Point Alloys. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 207, 1–8.

Kapranos, Plato. (2019). Current state of semi-solid net-shape die casting. Metals, 9(12). https://doi.org/10.3390/met9121301

Kenney, M. P., Courtois, J. A., Evans, R. D., Farrior, G. M., Kyonka, C., & Koch, A. A. (1992). Semisolid metal casting and forging. ASM Handbook, 9ed, 15, 719–736.

Kirkwood, D. H. (1994). Semisolid metal processing. International Materials Reviews, 39, 173–189. https://doi.org/10.1179/imr.1994.39.5.173

Kirkwood, D. H., & Kapranos, P. (2016). Semisolid Processing. Reference Module in Materials Science and Materials Engineering, (March 2015), 1–8. https://doi.org/10.1016/b978-0-12-803581-8.03585-2

Kurz, W., Bezençon, C., & Gäumann, M. (2001). Columnar to equiaxed transition in solidification processing. Science and Technology of Advanced Materials, 2(1), 185–191. https://doi.org/10.1016/S1468-6996(01)00047-X

Kurz, W., & Fisher, D. J. (1989). Fundamentals of Solidification. Retrieved from https://books.google.com.my/books?id=gxJurgEACAAJ

Lashkari, O., & Ghomashchi, R. (2006). "The implication of rheological principles for characterization of semi-solid Al–Si cast billets." Journal of Materials Science, 41(18), 5958–5965. https://doi.org/10.1007/s10853-006-0280-8

Lashkari, O., & Ghomashchi, R. (2007). The implication of rheology in semi-solid metal processes : An overview. 182, 229–240. https://doi.org/10.1016/j.jmatprotec.2006.08.003

Lee, P. D., Chirazi, A., & See, D. (2001). Modeling microporosity in aluminum-silicon alloys: A review. Journal of Light Metals, 1(1), 15–30. https://doi.org/10.1016/S1471-5317(00)00003-1

Lee, S., & Oh, S. (2002). Thixoforming characteristics of thermo-mechanically treated AA 6061 alloy for suspension parts of electric vehicles. 131, 587–593.

Liu, D., Atkinson, H., Kapranos, P., Jirattiticharoean, W., & Jones, H. (2003). Microstructural evolution and tensile mechanical properties of thixoformed high performance aluminium alloys. Materials Science and Engineering: A, 361, 213–224. https://doi.org/10.1016/S0921-5093(03)00528-8

Liu, T., Ward, P., Atkinson, H., & Kirkwood, D. H. (2003). Response of semi-solid Sn-15 Pct Pb to rapid shear-rate changes. Metallurgical and Materials Transactions A, 34, 409–417. https://doi.org/10.1007/s11661-003-0342-3

Liu, Z. Y., Mao, W. M., Wang, W. P., & Zheng, Z. K. (2015). Preparation of semi-solid A380 aluminum alloy slurry by serpentine channel. Transactions of Nonferrous Metals Society of China (English Edition), 25(5), 1419–1426. https://doi.org/10.1016/S1003-6326(15)63741-4

Lü, S. L., Wu, S. Sen, Zhu, Z. M., An, P., & Mao, Y. W. (2010). Effect of semi-solid processing on microstructure and mechanical properties of 5052 aluminum alloy. Transactions of Nonferrous Metals Society of China (English Edition), 20(SUPPL. 3), 758–762. https://doi.org/10.1016/S1003-6326(10)60577-8

Lü, S., Wu, S., Lin, C., Hu, Z., & An, P. (2011). Preparation and rheocasting of semisolid slurry of 5083 Al alloy with indirect ultrasonic vibration process. Materials Science and Engineering A, 528(29–30), 8635–8640. https://doi.org/10.1016/j.msea.2011.08.014

Luo, M., Li, D., Qu, W., Hu, X., Zhu, Q., & Fan, J. (2019). Mold-slug interfacial heat transfer characteristics of different coating thicknesses: Effects on slug temperature and microstructure in swirled enthalpy equilibration device process. Materials, 12(11). https://doi.org/10.3390/ma12111836

LUO, S., KEUNG, W. C., & KANG, Y. (2010). Theory and application research development of semi-solid forming in China. Transactions of Nonferrous Metals Society of China - TRANS NONFERROUS METAL SOC CH, 20, 1805–1814. https://doi.org/10.1016/S1003-6326(09)60378-2

Mao, W.-M., Zhen, Z. S., Yan, S. J., & Zhong, X. Y. (2004). Rheological behavior of semi-solid AZ91D alloy. Journal of Materials Science and Technology -Shenyang-, 20, 580–582.

Mehrabian, R., & Flemings, M. C. (1972). Rheological Behavior of Sn-15 Pct Pb in the Crystallization Range. 3(July).

Miller, W. S., Zhuang, L., Bottema, J., Wittebrood, A. J., & Smet, P. De. (2000). Recent development in aluminium alloys for the automotive industry. 280, 37–49.

Mohammed, M. N., Omar, M. Z., Salleh, M. S., Alhawari, K. S., & Kapranos, P. (2013). Semisolid Metal Processing Techniques for Nondendritic Feedstock Production. 2013.

Motegi, T. (2001). Continuous casting of semisolid Al-Si-Mg alloy. International Journal of Materials and Product Technology, 468–475.

Murayama, M., Hono, K., Saga, M., & Kikuchi, M. (1998). Atom probe studies on the early stages of precipitation in Al-Mg-Si alloys. Materials Science and Engineering A, 250(1), 127–132. https://doi.org/10.1016/S0921-5093(98)00548-6

Ning, Z. L., Wang, H., & Sun, J. F. (2010). Deformation behavior of semisolid a356 alloy prepared by low temperature pouring. Materials and Manufacturing Processes, 25(7), 648–653. https://doi.org/10.1080/10426910903447279

Nues, R., Adams, J. H., Ammons, M., Avery, H. S., Barnhurst, R. J., & Bean, J. C. (2002). ASM handbook-properties and selection: nonferrrous alloys and special-purpose materials. ASM Int, 2, 759–792.

Omar, M. Z., & Alhawari, K. (2014). An Overview of Semi-Solid Metal Processing. Australian Journal of Basic and Applied Sciences, (February 2015), 369–373.

Park, M. (2004). Tensile Testing.

Parshizfard, E., & Shabestari, S. G. (2011). An investigation on the microstructural evolution and mechanical properties of A380 aluminum alloy during SIMA process. Journal of Alloys and Compounds, 509(40), 9654–9658. https://doi.org/https://doi.org/10.1016/j.jallcom.2011.07.068

Qi, M., Kang, Y., Li, J., Wulabieke, Z., Xu, Y., Li, Y., … Chen, J. (2020). Microstructures refinement and mechanical properties enhancement of aluminum and magnesium alloys by combining distributary-confluence channel process for semisolid slurry preparation with high pressure die-casting. Journal of Materials Processing Technology, 285(March), 116800. https://doi.org/10.1016/j.jmatprotec.2020.116800

Razak, N. A., Ahmad, A. H., & Rashidi, M. M. (2017a). Investigation of pouring temperature and holding time for semisolid metal feedstock production. IOP Conference Series: Materials Science and Engineering, 257, 012085. https://doi.org/10.1088/1757-899X/257/1/012085

Razak, N. A., Ahmad, A. H., & Rashidi, M. M. (2017b). Investigation of pouring temperature and holding time for semisolid metal feedstock production. IOP Conference Series: Materials Science and Engineering, 257(1). https://doi.org/10.1088/1757-899X/257/1/012085

Razak, N. A., Ahmad, A. H., & Rashidi, M. M. (2020). Thermal profile and microstructure of wrought aluminium 7075 for semisolid metal processing. International Journal of Automotive and Mechanical Engineering, 17(2), 7842–7850. https://doi.org/10.15282/ijame.17.2.2020.03.0584

Reisi, M., & Niroumand, B. (2012). Initial stages of solidification during semisolid processing of a transparent model material. Materials Chemistry and Physics, 135(2–3), 738–748. https://doi.org/10.1016/j.matchemphys.2012.05.053

Rogal, Dutkiewicz, J., Atkinson, H. V., Lityńska-Dobrzyńska, L., Czeppe, T., & Modigell, M. (2013). Characterization of semi-solid processing of aluminium alloy 7075 with Sc and Zr additions. Materials Science and Engineering A, 580, 362–373. https://doi.org/10.1016/j.msea.2013.04.078

Rosso, M. (2012). Thixocasting and rheocasting technologies , improvements going on. 54(1), 110–119.

Rosso, M., Peter, I., & Torino, P. (2013). New frontiers for thixoforming. 8.

Rovira, M. M., Lancini, B. C., & Robert, M. H. (1999). Thixo-forming of Al ± Cu alloys. 93, 42–49.

Sakkaki, M., Sadegh Moghanlou, F., Parvizi, S., Baghbanijavid, H., Babapoor, A., & Shahedi Asl, M. (2020). Phase change materials as quenching media for heat treatment of 42CrMo4 steels. Journal of Central South University, 27(3), 752–761. https://doi.org/10.1007/s11771-020-4328-8

Sala, K., Mallik, M., Zhang, J. H., Xing, S. M., Morita, S., & Yasuda, H. (2017). Investigation of pouring temperature and holding time for semisolid metal feedstock

production Investigation of pouring temperature and holding time for semisolid metal feedstock production. https://doi.org/10.1088/1757-899X/257/1/012085

Salleh, M. S., Omar, M. Z., Syarif, J., & Mohammed, M. N. (2013). An Overview of Semisolid Processing of Aluminium Alloys. ISRN Materials Science, 2013, 679820. https://doi.org/10.1155/2013/679820

Stefanescu, D. M., & Ruxanda, R. (2004). Fundamentals of Solidification. 1–24.

Turng, L., & Wang, K. (1991). Rheological behaviour and modelling of semi-solid Sn-15% Pb alloy. Journal of Materials Science, 26, 2173–2183. https://doi.org/10.1007/BF00549185

Vaneetveld, G., Rassili, A., Pierret, J. C., & Lecomte-Beckers, J. (2008). Improvement in thixoforging of 7075 aluminium alloys at high solid fraction. Solid State Phenomena, 141–143(February 2015), 707–712. https://doi.org/10.4028/www.scientific.net/ssp.141-143.707

Verran, G. O., Mendes, R. P. K., & Rossi, M. A. (2006). Influence of injection parameters on defects formation in die casting Al12Si1,3Cu alloy: Experimental results and numeric simulation. Journal of Materials Processing Technology, 179(1–3), 190–195. https://doi.org/10.1016/j.jmatprotec.2006.03.089

Wan, G., Witulski, T., & Hirt, G. (1994). Thixoforming of Al alloys using modified chemical grain refinement for billet production. Metallurgia Italiana, 86, 29–36.

Wang, H., Li, B., Jie, J., & Wei, Z. (2011). Influence of thermal rate treatment and low temperature pouring on microstructure and tensile properties of AlSi7Mg alloy. Materials and Design, 32(5), 2992–2996. https://doi.org/10.1016/j.matdes.2011.01.002

Wang, Q. G., Apelian, D., & Lados, D. A. (2001). Fatigue behavior of A356-T6 aluminum cast alloys. Part I. Effect of casting defects. Journal of Light Metals, 1(1), 73–84. https://doi.org/10.1016/S1471-5317(00)00008-0

Yang, X., Huang, X., Dai, X., Campbell, J., & Tatler, J. (2004). Numerical modelling of entrainment of oxide film defects in filling of aluminium alloy castings. International Journal of Cast Metals Research, 17(6), 321–331. https://doi.org/10.1179/136404604225022748

Zhang, J., Song, B., Wei, Q., Bourell, D., & Shi, Y. (2019). A review of selective laser melting of aluminum alloys: Processing, microstructure, property and developing trends. Journal of Materials Science and Technology, 35(2), 270–284. https://doi.org/10.1016/j.jmst.2018.09.004

Zhen Xu, S. W., & , Hongbin Wang , Hua Song, S. L. and X. C. (2020). Effect of Cooling Rate on Microstructure and Properties of Twin-Roll Casting 6061 Aluminum Alloy Sheet. 3, 1–11.

Zoqui, E., Paes, M., & Es-Sadiqi, E. (2002). Macro- and microstructure analysis of SSM A356 produced by electromagnetic stirring. Journal of Materials Processing Technology, 120, 365–373. https://doi.org/10.1016/S0924-0136(01)01148-7