# CHARACTERIZATION OF WROUGHT ALUMINIUM FEEDSTOCK BILLET PRODUCED BY SEMISOLID METAL PROCESSING ROUTE

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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 institution.

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## ABSTRAK

Tesis ini mempersembahkan dapatan kerja-kerja kajian ke atas perincian bilet aluminium 6061 yang dihasilkan menggunakan kaedah Pemprosesan Logam Separa Pepejal (PLSP). Tesis ini juga bertujuan untuk menambah, memperbaiki dan menerangkan ilmu pengetahuan berkenaan sifat bilet aluminium 6061 yang telah melalui Pembentukan Tikso. Kerja-kerja kajian bermula dengan kajian Analisis Haba (AH) yang dilakukan demi untuk memahami hubungan di antara pecahan pepejal dan suhu. Kajian AH dilakukan pada tiga kadar pengejukan yang berbeza terdiri daripada penyejukan perlahan (0.03 °C/s), penyejukan sederhana (0.2 °C/s) dan penyejukan pantas (0.3 °C/s). Data yang diperolehi daripada kajian AH kemudiannya digunakan untuk menghasilkan bilet tiksotropik melalui Kaedah Haba Langsung (KHL). Suhu tuangan dan masa pegangan untuk kajian KHL masing-masing terdiri daripada 660 °C dan 20 s, 660 °C dan 60 s, 700 °C dan 20 s, 700 °C dan 60 s, dengan tiga sampel dihasilkan bagi setiap kombinasi. Sampel bilet-bilet ini kemudiannya disediakan untuk analisis mikrostruktur, ketumpatan dan ujian kekerasan. Sampel bilet-bilet ini seterusnya dipanaskan ke suhu 610 °C dan dilakukan pembentukan tikso. Konfigurasi mesin tekan hidrolik untuk operasi pembentukan tikso ditetapkan pada 155 bar untuk tekanan hidrolik dan 15 s untuk masa pegangan. Akhirnya, kebolehbentukan sampel diperhatikan. Hasil dapatan bagi AH mendapati penurunan julat suhu yang ketara muncul bagi pecahan pepejal diantara 20 % dan 40 % bagi kadar penyejukan 0.03 °C/s, berbanding kadar penyejukan 0.2 °C/s dan 0.3 °C/s. Pecahan pepejal bagi kadar penyejukan 0.2 °C/s dan 0.3 °C/s juga menunjukkan pembentukan pecahan pepejal yang ketara pada 20 % dengan suhu yang lebih tinggi pada masa yang singkat. Walau bagaimana pun, adalah kurang berkesan untuk mengekalkan pecahan pepejal pada 20 % dengan kadar penurunan haba yang singkat menggunakan 0.3 °C/s. Bilet yang dihasilkan dengan gabungan suhu tuangan 660 °C dan suhu pegangan 20 s mempunyai mikrostruktur yang paling sesuai untuk PLSP dengan mikrostruktur yang paling kecil bernilai purata 2797 µm². Suhu tuangan ini didapati berada hanya sedikit diatas suhu cecair menyebabkan kurangnya haba pendam yang perlu diekstrak, dimana ianya menghasilkan kadar penyejukan yang perlahan semasa penyejukan. Hasilnya, ia menggalakkan pembentukan lebih banyak bijian struktur dan menghasilkan butir struktur yang lebih kecil. Nilai kekerasan juga didapati meningkat dengan suhu tuangan dan masa pegangan yang rendah. Hasil kajian Pembentukan Tikso menunjukkan sampel dengan gabungan suhu tuangan 660 °C dan suhu pegangan 20 s mempunyai kemampuan memenuhi ruang kosong acuan yang paling ketara, dengan nilai perbezaan yang tidak terlalu ketara berbanding sampel-sampel lain. Hasil dapatan ini mengesahkan kehadiran butir struktur yang kecil dan bulat didalam sampel. Ia juga membuktikan bahawa walaupun gabungan konfigurasi sampel mempunyai nilai kekerasan dan ketumpatan yang lebih baik, faktor utama bagi memastikan kejayaan PLSP (kebolehbentukan) adalah saiz dan kebulatan butir struktur bilet. Kesimpulan bagi kajian ini telah mendokumentasikan bahawa perbezaan kadar penyejukan telah mengubah fasa suhu dengan peningkatan pecahan pepejal, mengambil masa yang lebih lama dan pada suhu yang lebih rendah bagi keadaan kadar penyejukan yang perlahan. Suhu tuangan 660 °C dengan masa pegangan 20 s telah menghasilkan mikrostruktur yang lebih baik dan seragam. Penemuan ini akan memberi lebih kefahaman mengenai sifat bahan dimana akan menerajui operasi pembuatan yang lebih baik, rekabentuk peralatan dan konfigurasi yang tepat diperlukan untuk memastikan kejayaan PLSP.

# ABSTRACT

This thesis presents the research works on the characterization of aluminium 6061 feedstock billet produced through semisolid metal processing (SSMP) route. This thesis also aims to add, improves and brighten the knowledge of wrought aluminium 6061 feedstock billet behaviour, which was then thixoformed. The experimental works started with a Thermal Analysis (TA) experiment which conducted purposely to understand the relationship between fraction solid and temperature. TA experiment was conducted at three different cooling rate conditions consist of slow cooling (0.03 °C/s), medium cooling (0.2 °C/s) and fast cooling (0.3 °C/s). The information gained from TA was used to produce thixotropic feedstock billet via Direct Thermal Method (DTM). The pouring temperature and holding time for the DTM experimental works consisted of 660 °C and 20 s, 660 °C and 60 s, 700 °C and 20 s, 700 °C and 60 s respectively, with three samples were produced for each combination. The feedstock billet samples were then prepared for microstructure analysis, density and hardness test. These feedstock billet samples were then heated to a temperature of 610 °C and thixoformed. The hydraulic press machine parameters for thixoforming operation were set at 155 bars for hydraulic pressure and 15 s for holding time. Finally, the samples formability was observed. The results for TA found that an extensive range of temperature dropped occurred for the fraction solid range between 20 % and 40 % for cooling rate of 0.03 °C/s, compare to a cooling rate of 0.2 °C/s and 0.3 °C/s. The fraction solid for the cooling rates of 0.2 °C/s and 0.3 °C/s also has shown rapid fraction solid formation at 20 % at a higher temperature with a shorter time. However, it was less effective to maintain the fraction solid at 20 % with a very short range of temperature drop compared with 0.03 °C/s. The feedstock billet with a combination of pouring temperature 660 °C and holding time 20 s produced the most suitable microstructure for SSMP which has the smallest microstructure with the sample average area value size of 2797 $\mu m^2$. This pouring temperature was slightly above liquidus temperature that caused less superheat to be extracted which provided a slow cooling rate action during the solidification stage. Consequently, it promoted the formation of more grain nuclei and resulted in a smaller grain size. Hardness value also was found increased with the lower pouring temperature and holding time. Thixoforming experimental results show that a sample with the combination of pouring temperature 660 °C with a holding time of 20 s showed the most significant length filled the mould cavity with a less significant difference with other samples. These results have confirmed the existence of smaller and globular grain structure within the sample. It also proved that although the other parameters combination sample has better hardness and density value, the main factor to ensure SSMP accomplishment (formability) was the grain structure size and circularity of the feedstock billet. The conclusions of this study have documented that different cooling rates conditions altered the phase changes temperature with the increment of fraction solid, took a long time and at a lower temperature for a slow cooling rate condition. Pouring temperature of 660 °C with a holding time of 20 s produced a better fine globular and uniform microstructure. These findings could give a better understanding of the material behaviour which could lead to a better manufacturing operation, equipment design and precise parameters needed to ensure the success of SSMP.

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## LIST OF SYMBOLS

| | |
|---|---|
| % | Percentage |
| °C | degree Celsius |
| T | Temperature |
| P | Density |
| K | Thermal conductivity |
| Bi | Biot number |
| H | convective heat transfer coefficient |
| V | Volume |
| $C_p$ | Specific heat |
| T | Time |
| H | Transfer coefficient |
| A | Surface area |
| $T_{\circ}$ | Ambient temperature |
| $Q_L$ | Latent heat of solidification |
| $F_s$ | Fraction solid |
| kN | kilo newton |
| Rpm | Revolutions per minute |
| α-Al | Aluminium primary phase |
| B-Al | Aluminium secondary phase |
| S | Second |
| A | Primary phase |
| B | Secondary phase |
| Al | Aluminium |
| Si | Silicon |
| Mn | Manganese |
| Mg | Magnesium |
| µ | Micron |

## LIST OF ABBREVIATIONS

| | |
|---|---|
| SSMP | Semi-Solid Metal Processing |
| SSM | Semi-Solid Metal |
| MIT | Massachusetts Institute of Technology |
| MHD | Magnetohydrodynamic |
| NRC | New Rheocasting |
| SEED | Swirled Enthalpy Equilibration Device |
| SCR | Shearing-Cooling Roll |
| SIMA | Stress-Induced and Melt-Activated |
| RAP | Recrystallization and Partial Melting |
| DPRM | Direct Partial Remelting method |
| DTA | Differential Thermal Analysis |
| CA-CCA | Computer-Aided Cooling Curve Analysis |
| ZC | Zero-Curve |
| DTM | Direct Thermal Method |
| HV | Vickers Pyramid Number |
| DPH | Diamond Pyramid Hardness |
| ASTM | American society for testing and materials |
| CAD | Computer-aided design |
| CNC | Computer numerical control |
| CAM | Computer-aided manufacturing |
| DCP | Dendrite coherency Point |

# REFERENCES

AalcoMetals. (2018). *Aluminium Alloy 6061 - T6 Extrusions*. Retrieved from: http://www.aalco.co.uk/datasheets/Aluminium-Alloy-6061-T6-Extrusions_145.ashx

Abramov, V., Abramov, O., Bulgakov, V., & Sommer, F. (1998). Solidification of aluminium alloys under ultrasonic irradiation using water-cooled resonator. *Materials Letters, 37*(1-2), 27-34.

Adachi, M., Sasaki, H., Harada, Y., Sakamoto, T., Sato, S., & Yoshida, A. (1996). Method and apparatus of shaping Semi-solid metals. *European Patent, 0745694B1*.

Adachi, M., Sasaki, H., Harada, Y., Sakamoto, T., Sato, S., & Yoshida, A. (2004). Method of shaping semisolid metals: Google Patents.

Ahmad, A., Naher, S., & Brabazon, D. (2012). *In Effects of direct thermal method temperature and time on A35 microstructure.* Paper presented at the 15th International conference on advances materials and processing technology.

Ahmad, A., Naher, S., & Brabazon, D. (2014). Effects of cooling rates on thermal profiles and microstructure of aluminium 7075. *International Journal of Automotive and Mechanical Engineering, 9*, 1685.

Ahmad, A. H. (2015). *Effect of temporal thermal field on quality of semi-solid metal formed components.* Dublin City University.

Ahmad, A. H., Naher, S., & Brabazon, D. (2014). *Direct thermal method of aluminium 7075.* Paper presented at the Advanced Materials Research.

Apelian, D., Jorstad, J., & de Figueredo, A. (2001). Science and Technology of Semi-Solid Metal Processing. *NADCA, Rosemont, IL*, 7-1.

Arif, M., Omar, M. Z., Muhamad, N., Syarif, J., & Kapranos, P. (2013). Microstructural evolution of solid-solution-treated Zn–22Al in the semisolid state. *Journal of Materials Science & Technology, 29*(8), 765-774.

Atkinson, H. V. (2005). Modelling the semisolid processing of metallic alloys. *Progress in materials science, 50*(3), 341-412.

Atkinson, H. V. (2010). Semisolid processing of metallic materials. *Materials Science and Technology, 26*(12), 1401-1413.

Bäckerud, L., Chai, G., & Tamminen, J. (1990). Solidification Characteristics of Aluminum Alloys, Volume 2, Foundry Alloys. *AFS/SKANALUMINIUM*.

Barlow, J., & Stefanescu, D. (1998). Computer-aided cooling curve analysis revisited. *TRANSACTIONS-AMERICAN FOUNDRYMENS SOCIETY*, 349-354.

Birol, Y. (2009). Semi-solid processing of the primary aluminium die casting alloy A365. *Journal of Alloys and Compounds, 473*(1-2), 133-138.

Bol'shakova, N., & Il'in, A. (1987). Properties of graphite-containing crucibles. *Refractories*, *28*(5-6), 242-247.

Brabazon, D. (2014). 5.07 Routes to Spheroidal Starting Material for Semisolid Metal Processing.

Brown, M. E. (2001). *Introduction to thermal analysis: techniques and applications* (Vol. 1): Springer Science & Business Media.

Browne, D., Hussey, M., Carr, A., & Brabazon, D. (2003). Direct thermal method: new process for development of globular alloy microstructure. *International journal of cast metals research, 16*(4), 418-426.

Bünck, M., Warnken, N., & Bührig-Polaczek, A. (2010). Microstructure evolution of rheo-cast A356 aluminium alloy in consideration of different cooling conditions by means of the cooling channel process. *Journal of Materials Processing Technology, 210*(4), 624-630.

Camacho, A. M., Atkinson, H., Kapranos, P., & Argent, B. (2003). Thermodynamic predictions of wrought alloy compositions amenable to semi-solid processing. *Acta Materialia, 51*(8), 2319-2330.

Campo, K. N., Proni, C. T. W., & Zoqui, E. J. (2013). Influence of the processing route on the microstructure of aluminum alloy A356 for thixoforming. *Materials characterization, 85*, 26-37.

Cardoso, E., Atkinson, H. V., & Jones, H. (2004). Microstructural evolution of A356 during NRC processing.

Carr, A., Browne, D., Hussey, M., 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.

Charsley, E., Price, D., Hunter, N., Gabbott, P., Kett, V., Gaisford, S., . . . Scowen, I. (2019). *Principles of thermal analysis and calorimetry*: Royal society of chemistry.

Chavez, M., Amaro, A., Flores, C., Juarez, A., & González-Rivera, C. (2006). *Newton thermal analysis of gray and nodular eutectic cast iron.* Paper presented at the Materials science forum.

Chayong, S., Atkinson, H., & Kapranos, P. (2005). Thixoforming 7075 aluminium alloys. *Materials Science and Engineering: A, 390*(1-2), 3-12.

Choi, J. C., & Park, H. J. (1998). Microstructural characteristics of aluminum 2024 by cold working in the SIMA process. *Journal of Materials Processing Technology, 82*(1-3), 107-116.

Dahle, A., & StJohn, D. (1998). Rheological behaviour of the mushy zone and its effect on the formation of casting defects during solidification. *Acta Materialia, 47*(1), 31-41.

de Figueredo, A. (2001). *Science and technology of semi-solid metal processing*: North American Die Casting Assoc.

Dehnavi, M., Kuhestani, F., & Haddad-Sabzevar, M. (2015). Cooling curve analysis in binary Al-Cu alloys: Part I-Effect of cooling rate and copper content on the eutectic formation. *Metallurgical and Materials Engineering, 21*(3), 195-206.

Doutre, D., Hay, G., & Wales, P. (2002). Semi-solid concentration processing of metallic alloys: Google Patents.

Doutre, D., Langlais, J., & Roy, S. (2004). *The SEED process for semi-solid forming.* Paper presented at the 8th International Conference on Semi-Solid Processing of Alloys and Composites.

Evancho, J., & Staley, J. (1974). Kinetics of precipitation in aluminum alloys during continuous cooling. *Metallurgical transactions, 5*(1), 43.

Fan, Z. (2002). Semisolid metal processing. *International materials reviews, 47*(2), 49-85.

Ferrante, M., & De Freitas, E. (1999). Rheology and microstructural development of a Al–4wt% Cu alloy in the semi-solid state. *Materials Science and Engineering: A, 271*(1-2), 172-180.

Flemings, M., Riek, R., & Young, K. (1976). Rheocasting. *Materials Science and Engineering, 25*, 103-117.

Flemings, M. C. (1991). Behavior of metal alloys in the semisolid state. *Metallurgical Transactions A, 22*(5), 957-981.

Gibbs, J. W., & Mendez, P. F. (2008). Solid fraction measurement using equation-based cooling curve analysis. *Scripta Materialia, 58*(8), 699-702.

Grant, P. (1995). Spray forming. *Progress in materials science, 39*(4-5), 497-545.

Haga, T., & Kapranos, P. (2002). Billetless simple thixoforming process. *Journal of Materials Processing Technology, 130*, 581-586.

Haga, T., & Suzuki, S. (2004). A downward melt drag single roll caster for casting semisolid slurry. *Journal of Materials Processing Technology, 157*, 695-700.

Handbook, A. (1990). Properties of wrought aluminum and aluminum alloys. *ASM International Hand Book Committee, 2*, 62-122.

Hirt, G., Bleck, W., Bührig-Polaczek, A., Shimahara, H., Püttgen, W., & Afrath, C. (2006). *Semi solid casting and forging of steel.* Paper presented at the Solid State Phenomena.

Hogg, S., Atkinson, H., & Kapranos, P. (2004). Semi-solid rapid compression testing of spray-formed hypereutectic Al-Si alloys. *Metallurgical and Materials Transactions A, 35*(3), 899-910.

Hosseini, V., Shabestari, S., & Gholizadeh, R. (2013). Study on the effect of cooling rate on the solidification parameters, microstructure, and mechanical properties of LM13 alloy using cooling curve thermal analysis technique. *Materials & Design, 50*, 7-14.

Husain, N., Ahmad, A., & Rashidi, M. (2017). *An overview of thixoforming process.* Paper presented at the IOP Conference Series: Materials Science and Engineering.

Hussey, M., Browne, D., Brabazon, D., & Car, A. (2002). *A direct thermal method of attaining globular morphology in the primary phase of alloys.* Paper presented at the Proceedings of the 7th International Conference on Semi-Solid Processing of Alloys and Composites.

Ibáñez, G., Cuevas, S., & de Haro, M. L. (2003). Minimization of entropy generation by asymmetric convective cooling. *International Journal of Heat and Mass Transfer, 46*(8), 1321-1328.

Ihsan-ul-haq, Shin, J.-S., & Lee, Z.-H. (2004). Computer-Aided Cooling Curve Analysis of A356 Aluminum Alloy. *METALS AND MATERIALS International, 10*, 89~96.

Jones, P. D., Duncan, S. R., Rayment, T., & Grant, P. S. (2003). Control of temperature profile for a spray deposition process. *IEEE Transactions on Control Systems Technology, 11*(5), 656-667.

Kang, C., Seo, P., & Bae, J. (2007). *Computer Aided Simulation of the Rheology Forging Process for Aluminum Alloys and its Experimental Investigation.* Paper presented at the Key Engineering Materials.

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), 1-8.

Kapranos, P., Ward, P., Atkinson, H., & Kirkwood, D. (2000). Near net shaping by semi-solid metal processing. *Materials & Design, 21*(4), 387-394.

Kenney, M. P., Courtois, J. A., Evans, R., Farrior, G., Kyonka, C., Koch, A., & Young, K. (1988). Semisolid metal casting and forging. *Metals Handbook, 15*, 327-338.

Kirkwood, D. (1994). Semisolid metal processing. *International materials reviews, 39*(5), 173-189.

Kirkwood, D., & Kapranos, P. (1989). Semi-solid processing of alloys. *Metals and materials, 5*(1), 16-19.

Kirkwood, D. H., Sellars, C. M., & Boyed, L. G. (1992). Thixotropic materials: Google Patents.

Kissinger, H. E. (1957). Reaction kinetics in differential thermal analysis. *Analytical chemistry, 29*(11), 1702-1706.

Kiuchi, M., & Sugiyama, S. (1995). A new process to manufacture semi-solid alloys. *ISIJ international, 35*(6), 790-797.

Kopper, A. (2000). *Microstructure evolution during re-heating of 357 aluminium alloy and its effect on the flow properties in a semi-solid metal casting operation.* Paper presented at the 6th Int'1 Conf. on Semi-Solid Processing of Alloys and Composites.

Lee, S. H., Saito, Y., Sakai, T., & Utsunomiya, H. (2002). Microstructures and mechanical properties of 6061 aluminum alloy processed by accumulative roll-bonding. *Materials Science and Engineering: A, 325*(1–2), 228-235. doi:http://dx.doi.org/10.1016/S0921-5093(01)01416-2

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*(1-2), 213-224.

Liu, D., Atkinson, H. V., & Jones, H. (2005). Thermodynamic prediction of thixoformability in alloys based on the Al–Si–Cu and Al–Si–Cu–Mg systems. *Acta Materialia, 53*(14), 3807-3819.

Liu, F., Zhu, X., & Ji, S. (2020). Effects of Ni on the microstructure, hot tear and mechanical properties of Al–Zn–Mg–Cu alloys under as-cast condition. *Journal of Alloys and Compounds, 821*, 153458.

Liu, T., Ward, P., Atkinson, H. V., & Kirkwood, D. (2003). Response of semi-solid Sn-15 pct Pb to rapid shear-rate changes. *Metallurgical and Materials Transactions A, 34*(2), 409-417.

Lozares, J., Plata, G., Hurtado, I., Sánchez, A., & Loizaga, I. (2020). Near solidus forming (NSF): Semi-solid steel forming at high solid content to obtain as-forged properties. *Metals, 10*(2), 198.

Luo, S.-J., Keung, W., & Kang, Y.-L. (2010). Theory and application research development of semi-solid forming in China. *Transactions of Nonferrous Metals Society of China, 20*(9), 1805-1814.

Luo, S., Chen, Q., & Zhao, Z. (2009). An investigation of microstructure evolution of RAP processed ZK60 magnesium alloy. *Materials Science and Engineering: A, 501*(1-2), 146-152.

Ma, Z., Zhang, H., Zhang, X., Wu, X., Fu, H., Jia, L., & Zhang, H. (2019). Rheological behaviour of partially solidified A356 alloy: Experimental study and constitutive modelling. *Journal of Alloys and Compounds, 803*, 1141-1154.

materia.com, t. (2013). Semi-Solid Thixoforming: Part One.

Miller, W., Zhuang, L., Bottema, J., Wittebrood, A. J., De Smet, P., Haszler, A., & Vieregge, A. (2000). Recent development in aluminium alloys for the automotive industry. *Materials Science and Engineering: A, 280*(1), 37-49.

Mohammed, M., Omar, M., Salleh, M., Zailani, M., & Alhawari, K. (2012). Joining two metals via partial remelting method. *Journal of Asian Scientific Research, 2*(11), 724.

Mohammed, M., Omar, M. Z., Salleh, M., Alhawari, K., & Kapranos, P. (2013). Semisolid metal processing techniques for nondendritic feedstock production. *The Scientific World Journal, 2013*.

Mohammed, M., Omar, M. Z., Salleh, M. S., & Alhawari, K. (2013). Study on thixojoining process using partial remelting method. *Advances in Materials Science and Engineering, 2013*.

Mohammed, M., Omar, M. Z., Syarif, J., & Salleh, M. (2014). Morphological evolution during partial re-melting of AISI D2 Cold-Work Tool Steel. *Sains Malaysiana, 43*(8), 1213-1219.

Motegi, T., & Tanabe, F. (2000). Continuous Casting of Semisolid AlSiMg Alloy. *Continuous Casting*, 82-86.

Omar, M. Z., Alfan, A., Syarif, J., & Atkinson, H. (2011). Microstructural investigations of XW-42 and M2 tool steels in semi-solid zones via direct partial remelting route. *Journal of Materials Science, 46*(24), 7696-7705.

Omar, M. Z., Atkinson, H., & Kapranos, P. (2011). Thixotropy in semisolid steel slurries under rapid compression. *Metallurgical and Materials Transactions A, 42*(9), 2807-2819.

Omar, M. Z., Atkinson, H. V., Palmiere, E. J., Howe, A. A., & Kapranos, P. (2004). Microstructural development of HP9/4/30 steel during partial remelting. *Steel research international, 75*(8-9), 552-560.

Ping, W., Jianzhong, C., & Guimin, L. (2009). Semi-solid Thixoforming Simulation of Al-Cu-Mn-Ti Alloy Parts via AnyCasting. *Journal of Materials Sciences and Technology*, *23*(03), 359-362.

Razak, N., Ahmad, A., & Rashidi, M. (2017). *Investigation of pouring temperature and holding time for semisolid metal feedstock production.* Paper presented at the IOP Conference Series: Materials Science and Engineering.

Salleh, M. S., Omar, M. Z., Syarif, J., & Mohammed, M. (2013). An overview of semisolid processing of aluminium alloys. *ISRN Materials Science, 2013*.

Satyanarayana, K., Ojha, S., Kumar, D. N. N., & Sastry, G. (2001). Studies on spray casting of Al-alloys and their composites. *Materials Science and Engineering: A, 304*, 627-631.

Shabestari, S., & Malekan, M. (2005). Thermal analysis study of the effect of the cooling rate on the microstructure and solidification parameters of 319 aluminum alloy. *Canadian metallurgical quarterly*, *44*(3), 305-312.

Sigworth, G. (2018). Aluminum Casting Alloys and Casting Processes. In K. F. Anderson, J. Weritz, & J. G. F. Kaufman (Eds.), *Aluminum Science and Technology* (Vol. 2A, pp. 0): ASM International.

Spencer, D., Mehrabian, R., & Flemings, M. C. (1972). Rheological behavior of Sn-15 pct Pb in the crystallization range. *Metallurgical and Materials Transactions B, 3*(7), 1925-1932.

Tsai, Y.-L., & Hwang, W.-S. (2004). Pasty ranges and latent heat release modes for Sn-9Zn-xAg lead-free solder alloys. *Materials transactions, 45*(6), 1949-1957.

Turng, L., & Wang, K. (1991). Rheological behaviour and modelling of semi-solid Sn-15% Pb alloy. *Journal of Materials Science*, *26*(8), 2173-2183.

Upadhya, K. G., Stefanescu, D., Lieu, K., & Yeger, D. (1989). Computer-aided Cooling Curve Analysis, Principles and Applications in Metal Casting (Vol. 97, pp. 61-66).

Veldman, N. L., Dahle, A. K., StJohn, D. H., & Arnberg, L. (2001). Dendrite coherency of Al-Si-Cu alloys. *Metallurgical and Materials Transactions A, 32*(1), 147-155.

Vold, M. J. (1949). Differential thermal analysis. *Analytical chemistry*, *21*(6), 683-688.

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

Wang, J., Lin, H., Li, Y., & Jiang, Q. (2008). Effect of initial as-cast microstructure on semisolid microstructure of AZ91D alloy during the strain-induced melt activation process. *Journal of Alloys and Compounds*, *457*(1-2), 251-258.

Wang, S., Cao, F., Guan, R., & Wen, J. (2006). Formation and Evolution of Non-dendritic Microstructures of semisolid alloys prepared by shearing/cooling Roll process. *Cailiao Kexue Yu Jishu (Journal of Materials Science & Technology), 22*(2), 195-199.

Wannasin, J., Janudom, S., Rattanochaikul, T., Canyook, R., Burapa, R., Chucheep, T., & Thanabumrungkul, S. (2010). Research and development of gas induced semi-solid process for industrial applications. *Transactions of Nonferrous Metals Society of China, 20*, s1010-s1015.

Wannasin, J., Martinez, R., & Flemings, M. (2006). Grain refinement of an aluminum alloy by introducing gas bubbles during solidification. *Scripta Materialia, 55*(2), 115-118.

Wannasin, J., Martinez, R. A., & Flemings, M. C. (2006). *A novel technique to produce metal slurries for semi-solid metal processing.* Paper presented at the Solid State Phenomena.

Wannasin, J., & Thanabumrungkul, S. (2008). Development of a semi-solid metal processing technique for aluminium casting applications. *Songklanakarin Journal of Science & Technology, 30*(2).

Weimin, M., Zhen, Z., Shijian, Y., & Zhong, X. (2004). Rheological behavior of semi-solid AZ91D alloy. *材料科学技术 (英文版)*(2004 年 05), 580-582.

Xia, K., & Tausig, G. (1998). Liquidus casting of a wrought aluminum alloy 2618 for thixoforming. *Materials Science and Engineering: A, 246*(1-2), 1-10.

Young, K. P., Kyonka, C. P., & Courtois, J. A. (1983). Fine grained metal composition: Google Patents.

Zesheng, J., & Maoliang, H. (2009). Effect of Holding Time on Thixotropic Fluidity of Semi-solid AZ91D Magnesium Alloy. *Journal of Materials Sciences and Technology, 23*(02), 247-252.

Zhang, Z.-Q., Le, Q.-C., & Cui, J.-Z. (2008). Microstructures and mechanical properties of AZ80 alloy treated by pulsed ultrasonic vibration. *Transactions of Nonferrous Metals Society of China, 18,* s113-s116.

Zhao, Z., Chen, Q., Chao, H., & Huang, S. (2010). Microstructural evolution and tensile mechanical properties of thixoforged ZK60-Y magnesium alloys produced by two different routes. *Materials & Design, 31*(4), 1906-1916.

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*(1-3), 365-373.