ARCHIVES
of
FOUNDRY ENGINEERING

10.24425/afe.2026.158004

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

ISSN (2299-2944)
Volume 2026
Issue 2/2026

174 – 180

21/2

Effect of Superheat Temperature on Hardness and Impact Energy of AlMg1SiCu Cast-alloy

Akhyar Akhyar [a, *], Zulfadhli Zulfadhli [a], Muhammad R. Pahlevi [a], Lilik D. Setyana [b], Iskandar Hasanuddin [a], Ahmad Farhan [c]

[a] Department of Mechanical Engineering, Universitas Syiah Kuala, Jln. Syech Abdurrauf No.7 Darussalam, Banda Aceh 23111, Indonesia

[b] Vocational College, Universitas Gadjah Mada, Yogyakarta, Indonesia

[c] Department of Physics Education, Faculty of Teacher Training and Education, Universitas Syiah Kuala, Darussalam, Banda Aceh 23111, Indonesia

* Corresponding author: E-mail address: akhyar@usk.ac.id

Received 04.01.2025; accepted in revised form 24.03.2026; available online 14.07.2026

Abstract

This study aimed to evaluate the effect of superheat temperature variation on Vickers hardness and Charpy impact energy of AlMg1SiCu cast-alloy. The material used was Al 6061 metal alloy (re-melt) in the form of rectangular bars. This alloy was melted in an electric furnace and cast in a metal mold. The five superheat of liquidus temperatures applied were +50°C, +100°C, +150°C, +200°C, and +250°C. To reduce thermal shock due to the temperature difference between molten metal and the mold, the mold was heated before the casting process. Subsequently, samples for hardness and impact tests were prepared using machine cutting and tested according to ASTM standards. The results showed an increase in hardness and impact energy along with high superheat temperature. This showed that superheat temperature had a significant effect on the mechanical properties of AlMg1SiCu cast-alloy, with higher values contributing to increased hardness and toughness of the material.

Keywords: Superheat of liquidus, Vickers hardness, Charpy impact, AlMg1SiCu cast-alloy

1. Introduction

Aluminum (Al) alloy is often used as a preferred material across several industrial applications due to unique combination of superior mechanical properties. These include high strength, corrosion resistance, and the ability to be formed through a variety of manufacturing methods. Among the various types of Al alloy, AlMg1SiCu cast-alloy is the most widely used due to good casting and fabrication capabilities. This alloy is particularly preferred in the automotive, aerospace, construction, and marine engineering industries, where the need for material with superior mechanical performance and environmental resistance is critical.

The superior properties of AlMg1SiCu cast-alloy alloy can be determined by chemical composition and casting process, particularly based on temperature. This is because superheat temperature plays a significant role in determining the final microstructure of the material, which affects the mechanical properties, such as hardness, toughness, and ductility [1]. Variations in casting temperature can cause significant changes in the microstructure, including grain size, shape, and phase distribution, as well as the presence of micro-defects. In the fields of materials science and metallurgy, several investigations are being carried out on the variations of casting temperature on the mechanical properties of Al alloy [2]. This is due to the need to optimize casting parameters to produce materials with desired properties. Improving the efficiency and quality of products from Al 6061 alloy, mechanical properties such as hardness and toughness, are essential to ensure consistent and reliable performance [3].

Previous studies showed that variations in pouring temperature during metal casting played a significant role in hardness and other mechanical properties of metal alloy [4]. Pouring temperature affects the cooling rate, which also influences the microstructure. Generally, higher pouring temperature leads to slower cooling rate to obtain finer grain structure that is capable of increasing the hardness of the material. Based on previous reports, pouring temperature closer to the liquidus temperature produces a finer dendritic arrangement. This improvement is associated with increased hardness due to a reduction in the arm spacing of tertiary dendrites [5-6]. A study on Al-Zn (Zinc) alloy in aircraft structures has shown that increasing pouring temperature can improve hardness and mechanical properties. This is due to the formation of finer grain structures at higher temperature [7].

Pouring temperature affects microsegregation profile of alloy. Lower pouring temperature tend to increase microsegregation, which can affect the uniformity and hardness of casting material [8]. Experiments have shown that the hardness of alloy such as Al5.9Cu1.9Mg increases with higher temperature. For example, at 788°C, the hardness and impact energy are significantly higher compared to lower temperature [9]. This result underscores the importance of proper control of pouring temperature in metal casting to optimize hardness and overall mechanical properties of the final product [10-11].

Based on the description, this study aimed to examine the effects of five variations of pouring temperature on Vickers hardness and Charpy impact energy of AlMg1SiCu cast-alloy. The experiment was carried out to obtain a more comprehensive understanding of the correlation between casting process parameters and final mechanical properties of alloy. The results were expected to contribute to the existing scientific literature and provide practical guidance for the industry in determining the optimal casting conditions for AlMg1SiCu cast-alloy, thereby improving the quality and performance of products in real applications.

2. Material and Method

Rectangular Al rods with dimensions of 25 mm x 25 mm x 1500 mm were cut into small pieces randomly using a saw before being melted in a furnace. During the experiment, five superheat with liquidus temperatures were +50°C, +100°C, +150°C, +200°C, and +250°C. These temperature variations were selected based on melting points shown in the phase diagram of Al alloy. The preheating temperature of 220°C was applied to the metal mould to ensure optimal filling efficiency and to preclude gas porosity caused by surface-bound moisture.

Chemical analysis of the alloy was conducted via spark-optical emission spectroscopy, the results of which are summarised in Table 1. This method facilitated the precise quantification of alloying elements and trace impurities. After Al was molten in the crucible, molten metal was poured into a permanent mold at five variations of superheat temperatures. The metal mold was rectangular with a cavity size of 200 x 200 x 12 mm, as shown in Figure 1. Subsequently, molten metal was poured through the sprue into the runner and ingate, filling the cavity from the bottom to the top. A vent was placed at the top of the mold to remove air during casting. K-type thermocouples were inserted into molten mold to measure superheat temperature and record the solidification temperature of alloy during the experiment. After complete solidification, the product was prepared for Vickers hardness and Charpy impact tests by the gravity casting process.

Table 1.
Chemical composition

Element	Wt.%
Mg	0.90
Si	0.70
Fe	0.60
Cu	0.30
Cr	0.25
Zn	0.20
Ti	0.10
Mn	0.05
Al	Bal.

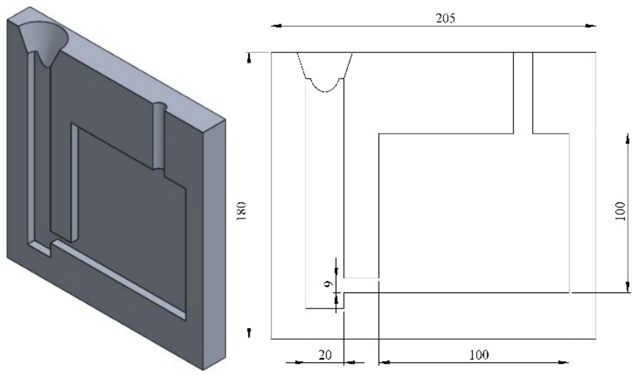


Fig. 1. The metal mold scheme

The test was conducted using Vickers hardness method, with a distribution scheme of 15 points for one variation of sample temperature, as shown in Figure 2. The Vickers hardness was determined using a diamond pyramid indenter with an apex angle (α) of 136°, in accordance with standard practice. Measurements were performed under a constant load of 9.80 N (1 kgf) for a dwell time of 15 seconds, denoted hereafter as HV1/15.

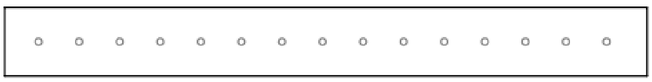


Fig. 2. Hardness testing point

Impact testing was carried out to determine the toughness of a material and ensure the fracture characteristics of material during loading. The toughness of the material properties was expressed as the ability to absorb the energy required to break the specimen from the impact force, significantly influenced by strength and ductility. Impact test samples were prepared from metal plates following American Society for Testing and Materials (ASTM) E23 standard, as shown in Figure 3. Charpy impact tests were performed using a Karl Frank GmbH pendulum impact testing machine (Type 53580). All tests were conducted at an ambient temperature of 25°C.

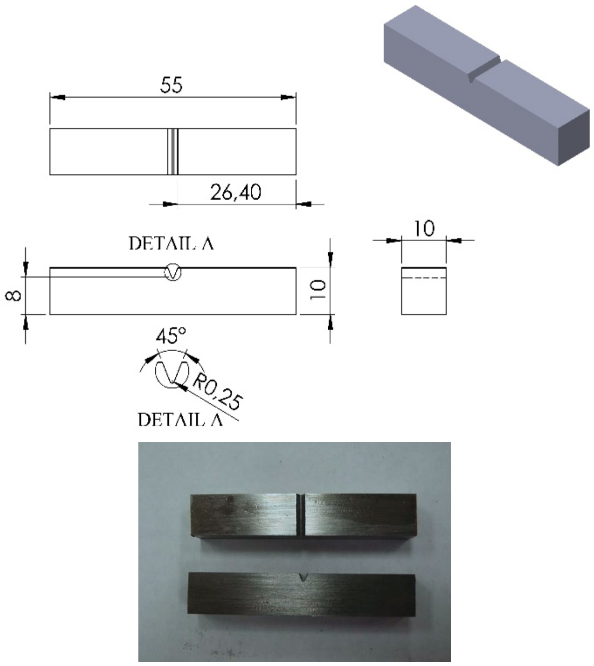


Fig. 3. Charpy impact test sample scheme [12]

3. Results and Discussion

Hardness test was carried out to determine the effect of variations in superheat temperature during casting of AlMg1SiCu cast-alloy, with hardness index shown in Figure 4.

Based on the results, hardness index at superheat temperature +50ºC showed the highest and lowest values of 75.00 HV and 62.90 HV, respectively, with an average of 70.88 HV (Figure 4a). Hardness index at 700ºC showed the highest and lowest values of 87.10 HV and 69.60 HV, respectively, with an average of 77.59 HV (Figure 4b). At +150ºC, the highest hardness index was 91.60 HV, the lowest was 66.10 HV, and the average was 82.67 HV (Figure 4c). When increased to +200ºC, the highest hardness index was 100.10 HV, and the lowest was 80.40 HV, with an average of 87.16 HV (Figure 4d). Meanwhile, the hardness index at +250ºC showed the highest and lowest values of 81.90 HV and 62.80 HV, respectively, with an average of 73.46 HV (Figure 4e). The average hardness index of cast sample AlMg1SiCu cast-alloy due to superheat temperature variation is shown in Figure 5.

The average hardness value showed an increasing trend with superheat temperature which was initially 71 HV at +50°C reaching a maximum of 87 HV at +200°C. Subsequently, the average hardness index value was observed to decrease to 73 HV at +250°C.

Figure 6 shows the average impact energy index measured on AlMg1SiCu cast-alloy due to the influence of variations in superheat temperature. By observing the trend line, the impact energy increased along with superheat temperature. The maximum impact energy index was 0.18 J at +50°C, and the minimum was 0.07 J at +100°C.

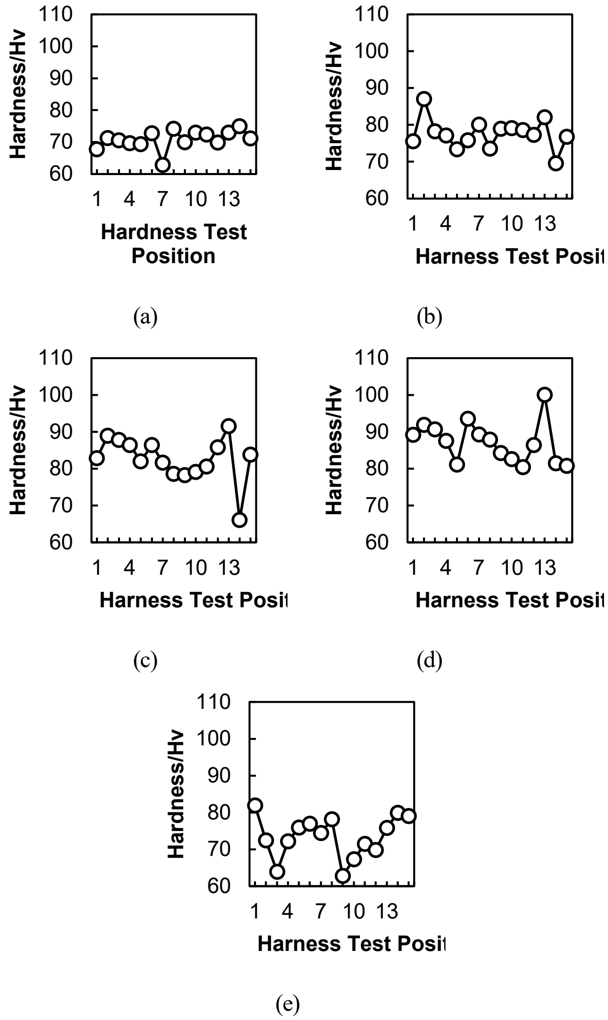


Fig. 4. Hardness index of AlMg1SiCu cast-alloy with different superheat temperatures: (a) +50°C, (b) +100°C, (c) +150°C, (d) +200°C, and (e) +250°C

The increase in hardness and impact energy along with superheat temperature in Al alloy could be explained by several metallurgical mechanisms related to microstructural changes and solidification conditions [13]. At higher temperature, the molten metal showed more optimal fluidity, allowing better mold filling and more controlled cooling. This condition led to a more homogeneous microstructure with a finer grain size, increasing hardness [14-16]. Higher superheat temperatures also slowed down the initial cooling rate, allowing more time for dendritic growth. Therefore, it contributed to a reduction in compositional segregation in alloy and produced a more uniform component distribution. Higher superheat temperature could also reduce micro-defects, such as porosity and inclusions, which occurred due to incomplete mold filling at lower temperatures. The reduction in these defects led to a more homogeneous and stronger material, increasing hardness and impact energy [17]. Furthermore, the phase distribution in alloy was affected, and the precipitation of reinforcing particles. A more uniform and optimal precipitation distribution could increase hardness and impact energy by more efficiently inhibiting dislocation movement [18]. This showed that the combination of a more homogeneous microstructure, better dendritic control, reduced microdefects, and effective precipitation distribution at higher superheat temperature contributed to increased hardness and impact energy in Al alloy.

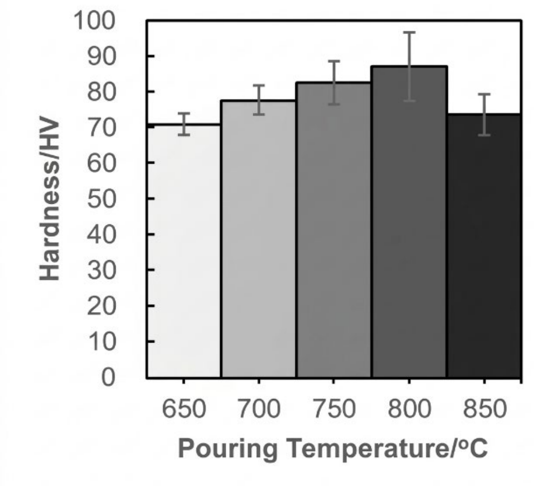


Fig. 5. Vickers hardness index due to variation in superheat temperature

Figure 7 presents the microstructure taken from the surface of a cast sample at a superheat temperature of +250°C. The bright areas indicate alpha Al, which is the dominant phase, while the dark regions represent theta phases consisting of Fe, Mg, and Si. The SEM images of the fracture surface at various magnifications are shown in Figure 8.

The fracture surface of the aluminum casting obtained from impact testing exhibited a dimpled morphology, indicating ductile fracture. The presence of dimples suggests that the material underwent significant plastic deformation prior to failure. Additionally, the size and distribution of the dimples were influenced by casting conditions such as cooling rate and temperature, which directly affect the microstructure and fracture behavior. The SEM examination of the aluminum cast alloy's fracture surface revealed key features indicative of the fracture mechanism. Prominent crack propagation patterns were observed on the primary fracture surface, further indicating ductile failure. Crack propagation with branching secondary cracks was clearly visible. Moreover, porosity-related casting defects were identified, which likely acted as stress concentrators, promoting crack initiation and propagation. These defects, along with the uneven distribution of voids, contributed to the overall weakening of the material's mechanical integrity.

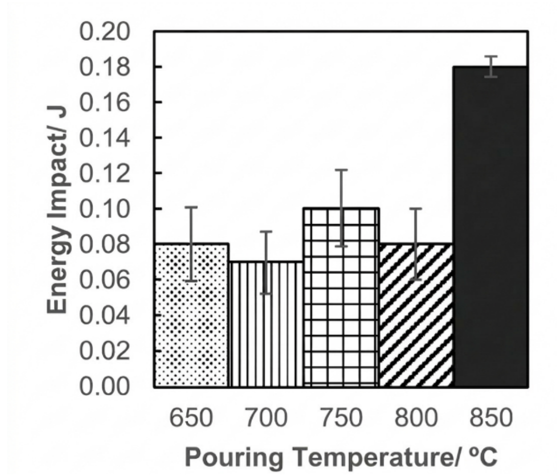


Fig. 6. Energy impact on AlMg1SiCu cast-alloy due to differences in poring temperature

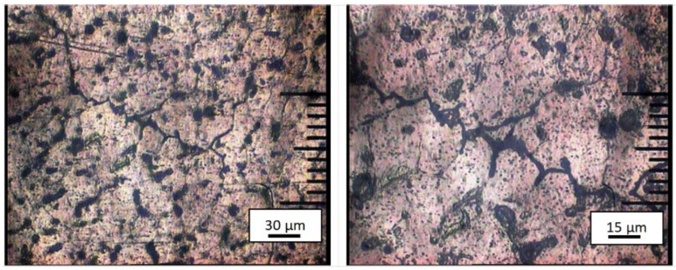
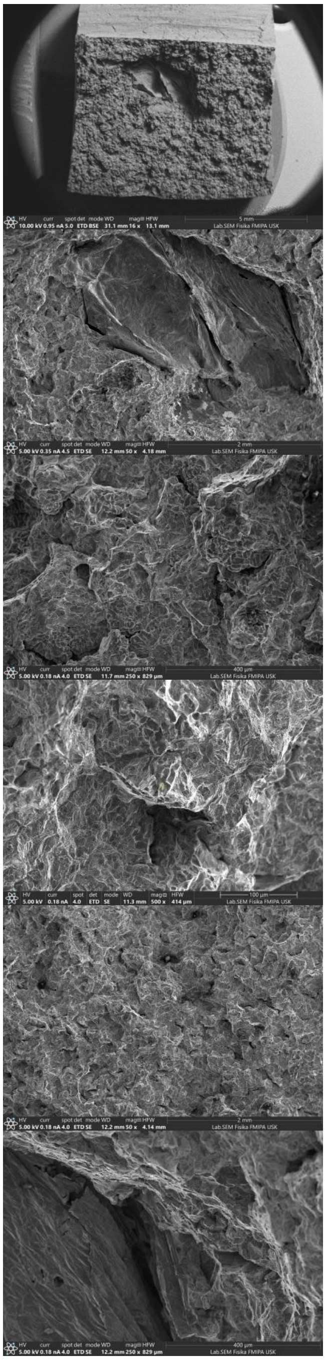


Fig. 7. Microstructure of AlMg1SiCu cast-alloy

Figure 9 presents the EDX spectrum and the SEM image of the mapping area, illustrating the elemental distribution within the analyzed region. The synergistic effects of Mg, Si, and Fe significantly dictate the mechanical performance of 6xxx series aluminium alloys. While an excess of Mg (Mg/Si > 1.73) is known to compromise ductility, resulting in reduced elongation at break, balanced Mg additions enhance grain boundary integrity and optimise precipitation behaviour [19]. Crucially, Mg improves the alloy's response to heat treatment, including artificial ageing, which facilitates a marked increase in strength following cold work. This is further enhanced when combined with elements such as Cu and Mn; for instance, Mn modifies recrystallisation behaviour to produce a fine subgrain structure, thereby increasing both strength and ductility [20].



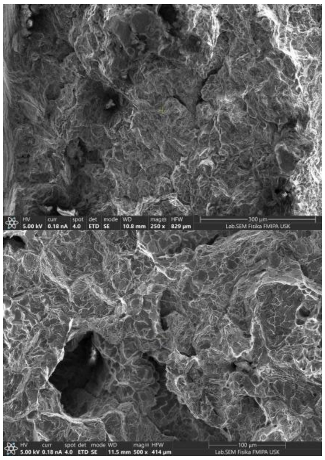
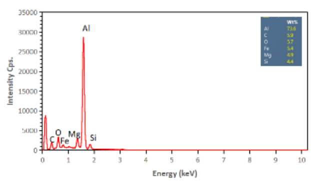


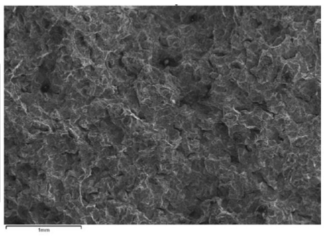
Fig. 8. SEM image of the impact fracture surface of the sample

Silicon (Si) remains pivotal for precipitation hardening, provided there is sufficient 'effective Si', the fraction remain unbound from coarse AlFeSi intermetallics. A higher available Si content promotes the formation of strengthening precipitates during age hardening [21]. Although primary Si crystals in Al-Si alloys can inherently induce brittleness, intense plastic deformation can refine these crystals, promoting the formation of fracture dimples and increasing energy absorption during impact [22]. Conversely, elevated Fe content can sequester Si into intermetallic phases, thereby reducing the precipitation hardening potential in specific alloys like EN AW-6060, even if elongation in others, such as 6082-based alloys, remains unaffected or slightly improved [23,24]. Ultimately, the complex interplay between these elements and processing conditions, such as cold working and subsequent ageing, governs the final hardness and impact toughness of the matrix.

The average Brinell hardness of the as-cast Al-Zn alloy was determined to be 38.43 HB. To ensure analytical consistency throughout the study, hardness values were standardised using both the Brinell and Vickers scales. Within the specific hardness range investigated, these scales exhibit approximate numerical equivalence (HB ≈ HV), consistent with the empirical correlations established in ISO 18265. The impact toughness, evaluated via the Charpy impact method, was recorded at 7 J/cm^2, which characterises the material's capacity for energy absorption prior to catastrophic failure. Both hardness and impact toughness remain susceptible to further optimisation through grain refinement or designated heat treatments, such as the T4 or T6 temper cycles [25].



(a)



(b)

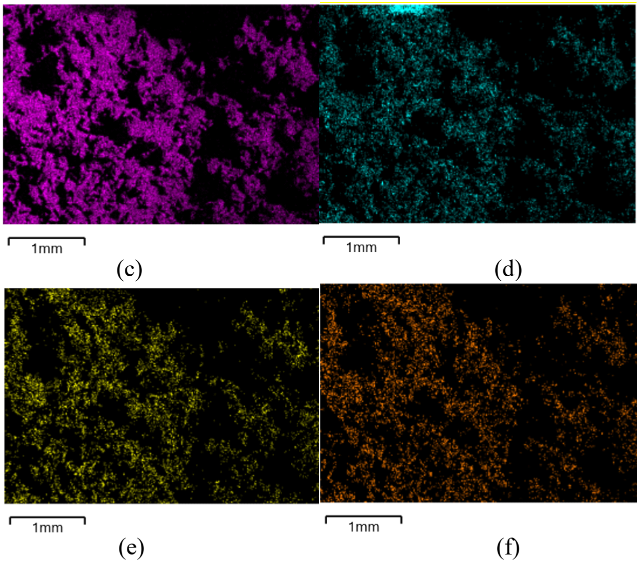


Fig. 9. (a) EDX spectrum and (b) SEM micrograph of the as-cast AlMg1SiCu alloy, with corresponding EDX elemental maps for (c) Al, (d) Mg, (e) Si, and (f) Fe

Furthermore, existing literature on Al-5.9Cu-1.9Mg alloys suggests that an increase in superheat temperature significantly enhances the hardness response. Specifically, a peak hardness of 103.67 HB was achieved at a pouring temperature of 788°C, whereas the minimum value of 95.67 HB was observed at 688°C. These variations indicate that elevated pouring temperatures profoundly influence microstructural evolution, which subsequently governs the resultant mechanical properties during the solidification process [26].

4. Conclusions

In conclusion, this study successfully investigated the effect of superheat temperature variation on the hardness and impact energy of AlMg1SiCu cast-alloy. The results showed that the impact energy increased along with superheat temperature, with a maximum value of 0.18 J at +50°C and a minimum of 0.07 J at +100°C. The average hardness value also increased along with superheat temperature, from 71 HV at +50°C to a peak of 87 HV at +200°C, before decreasing to 73 HV at +250°C. This showed that increasing superheat temperature led to a more homogeneous microstructure with finer grain size, which reduced micro-defects such as porosity and inclusions, as well as improved phase distribution and precipitation of reinforcing particles. Therefore, the variation in superheat temperature contributed to the increase in hardness and impact energy, serving as an essential factor in optimizing the mechanical properties of Al alloy. The interaction of Mg, Si, and Fe in aluminum alloys complexly influences their ductility, strength, and impact toughness, with outcomes highly dependent on alloy composition and processing conditions.

Acknowledgements

This project is supported by a grant from the Research Fund of the Ministry of Research, Technology, and Education, Republic of Indonesia, and LPPM Universitas Syiah Kuala; the financial support is greatly appreciated (272/UN11.L1/PG.01.03/14205-PTNBH/2025 date 15 July 2025 - PP).

References

[1] Wang, H.Q., Sun, W.L. & Xing, Y.Q. (2013). Microstructure analysis on 6061 aluminum alloy after casting and diffuses annealing process. *Physics Procedia*. 50, 68-75. https://doi.org/10.1016/j.phpro.2013.11.013.

[2] Fan, C.H., Chen, Z.H., He, W.Q., Chen, J.H. & Chen, D. (2010). Effects of the casting temperature on microstructure and mechanical properties of the squeeze-cast Al–Zn–Mg–Cu alloy. *Journal of Alloys and Compounds*. 504(2), L42-L45. https://doi.org/10.1016/j.jallcom.2010.06.012.

[3] Akinwande, A.A., Adediran, A.A., Balogun, O.A., Yibowei, M.E., Barnabas, A.A., Talabi, H.K. & Olorunfemi, B.J. (2022). Optimization of selected casting parameters on the mechanical behaviour of Al 6061/glass powder composites. *Heliyon*. 8(5), e09350, 1-17. https://doi.org/10.1016/j.heliyon.2022.e09350.

[4] Akhyar, Iqbal, Nurdin, A. & Husin, H. (2023). Effect of variations in pouring temperature on tensile strength of CuZn cast alloys. *Materials Letters: X*. 17, 100182, 1-4. https://doi.org/10.1016/j.mlblux.2023.100182.

[5] Ferreira, A.F., Chrisóstimo, W.B., Sales, R.C., Garção, W.J.L. & de Paula Sousa, N (2019). Effect of pouring temperature on microstructure and microsegregation of as-cast aluminum alloy. *The International Journal of Advanced Manufacturing Technology*. 104(1), 957-965. https://doi.org/10.1007/s00170-019-03979-6.

[6] Ocaño, P,S., Manzoni, A., Lopez-Galilea, I., Ruttert, B., Laplanche, G. & Jácome, L.A. (2023). Influence of cooling rate on the microstructure and room temperature mechanical properties in the refractory AlMo0.5NbTa0.5TiZr superalloy. *Journal of Alloys and Compounds*. 949, 169871, 1-15. https://doi.org/10.1016/j.jallcom.2023.169871.

[7] 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. DOI:10.1080/10426914.2013.822980.

[8] Paradela, K.G., Baptista, L.A.D.S., Sales, R.C., Felipe, P. & Ferreira, A.F. (2019). Investigation of thermal parameters effects on the microstructure, microhardness and microsegregation of Cu-Sn alloy directionally solidified under transient heat flow conditions. *Materials Research*. 22(4), p.e20190259, 1-9. http://dx.doi.org/10.1590/1980-5373-MR-2019-0259.

[9] Iswanto, P.T. & Malau, V. (2022). Impact of pouring temperature on the mechanical properties of Al5. 9Cu1. 9Mg alloy. *Archives of Materials Science & Engineering*. 113(2), 49. DOI 10.5604/01.3001.0015.7016.

[10] Huang, H., Wang, Y.X., Fu, P.H., Peng, L.M., Jiang, H.Y. & Xu, W.Y. (2013). Fluidity of AZ91D and Mg–3Nd–0·2Zn–Zr

(wt-%) magnesium alloys: response to pouring and mould temperature. *International Journal of Cast Metals Research*. 26(4), 213-219. https://doi.org/10.1179/1743133613Y.0000000055.
[11] Das, P. (2023). Optimisation of melt pouring temperature and low superheat casting of Al-15Mg2Si-4.5Si composite. *International Journal of Cast Metals Research*. 36(1-3), 76-89. https://doi.org/10.1080/13640461.2023.2211895.
[12] Iqbal, Ali, N., Husin, H. Akhyar, Khairil, & Farhan, A. (2021). Effect of pouring temperature on impact toughness on brass (Cu-Zn) through metal casting. *Metalurgija*. 60(3-4), 223-226.
[13] Liu, Y., Liu, M., Luo, L., Wang, J. & Liu, C. (2014). The solidification behavior of AA2618 aluminum alloy and the influence of cooling rate. *Materials*. 7(12), 7875-7890. https://doi.org/10.3390/ma7127875.
[14] Li, M., Li, Y. & Zhou, H. (2020). Effects of pouring temperature on microstructure and mechanical properties of the A356 aluminum alloy diecastings. *Materials Research*. 23(1), p.e20190676, 1-11. https://doi.org/10.1590/1980-5373-MR-2019-0676.
[15] Jiao, X., Li, X., Zhan, L., Wang, G., Ding, J. & Yang, J. (2022). The microstructural evolution and grain growth kinetics of fine-grained extruded Mg-Nd-Zn-Zr alloy. *Materials.* 15(10), 3556, 1-15. https://doi.org/10.3390/ma15103556.
[16] Liu, Q., Wang, G., Sui, X., Liu, Y., Li, X. & Yang, J.(2019). Microstructure and mechanical properties of ultra-fine grained MoNbTaTiV refractory high-entropy alloy fabricated by spark plasma sintering. *Journal of Materials Science & Technology*. 35(11), 2600-2607. https://doi.org/10.1016/j.jmst.2019.07.013.
[17] Zhu, M.F., Kim, J.M. & Hong, C.P. (2001). Modeling of globular and dendritic structure evolution in solidification of an Al–7mass% Si alloy. *ISIJ international*. 41(9), 992-998. https://doi.org/10.2355/isijinternational.41.992.
[18] Tan, L., He, G., Liu, F., Li, Y. & Jiang, L. (2018). Effects of temperature and pressure of hot isostatic pressing on the grain structure of powder metallurgy superalloy. *Materials.* 11(2), 328, 1-10. https://doi.org/10.3390/ma11020328.
[19] Remøe, M.S., Marthinsen, K., Westermann, I., Pedersen, K., Røyset, J. & Marioara, C. (2017). The effect of alloying elements on the ductility of Al-Mg-Si alloys. *Materials Science and Engineering: A*. 693, 60-72. https://doi.org/10.1016/j.msea.2017.03.078.
[20] Vladimir, A., Grechnikov, F., Aryshenskii, E., Erisov, Y., Konovalov, S., Tepterev, M. & Kuzin, A. (2022). Alloying elements effect on the recrystallization process in magnesium-rich aluminum alloy. *Materials*. 15(20), 7062, 1-26. https://doi.org/10.3390/ma15207062.
[21] Österreicher, J.A., Arnoldt, A.R., Gneiger, S. & Kunschert, G. (2023). Tolerance of Al–Mg–Si wrought alloys for high fe contents: the role of effective Si. *Metallurgical and Materials Transactions A.* 54(11), 4472-4480. https://doi.org/10.1007/s11661-023-07180-z
[22] Ervina Efzan, M.N., Kong, H.J. & Kok, C.K. (2013). Review: effect of alloying element on Al-Si alloys. *Advanced Materials Research.* 845, 355-359. https://doi.org/10.4028/www.scientific.net/amr.845.355
[23] Wang, Y., Deng, Y., Dai, Q., Jiang, K., Chen, J. & Guo, X. (2021). Microstructures and strengthening mechanisms of high Fe containing Al–Mg–Si–Mn–Fe alloys with Mg, Si and Mn modified. *Materials Science and Engineering: A*. 803, 140477. https://doi.org/10.1016/j.msea.2020.140477.
[24] Kenyon, M., Robson, J., Fellowes, J. & Liang, Z. (2019). Effect of dispersoids on the microstructure evolution in Al–Mg–Si alloys. *Advanced Engineering Materials*. 21(4), p.1800494, 1-7. https://doi.org/10.1002/adem.201800494.
[25] Akhyar, H., Husaini (2016). Study on Cooling Curve Behavior During Solidification and Investigation of Impact Strength and Hardness of Recycled Al–Zn Aluminum Alloy. *International Journal Metalcasting*. 10, 452–456. https://doi.org/10.1007/s40962-016-0024-8.
[26] Akhyar, A., Iswanto, P.T. & Malau, V. (2022). Impact of pouring temperature on the mechanical properties of Al5.9Cu1.9Mg alloy. *Archives of Materials Science and Engineering*. 113(2), 49-55. https://doi.org/10.5604/01.3001.0015.7016.