Optimization of cooling slope casting parameters and reheating process for semi-solid ADC12 aluminum alloy feedstock

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ABSTRACT

This study investigates the optimization of cooling slope (CS) casting parameters and reheating conditions for semi-solid ADC12 aluminum alloy feedstock to achieve refined microstructures and improved formability. ADC12, a hypoeutectic Al–Si–Cu alloy widely used in automotive applications, was cast using a water-cooled SS400 steel CS at angles of 30°, 45°, and 60°, with pouring temperatures of 585 °C, 595 °C, 605 °C, and 615 °C. The as-cast billets were reheated at 580 °C for holding times between 40 and 80 min to promote spheroidization of primary α-Al grains. Microstructural characterization was conducted using optical microscopy, and grain size and sphericity were quantified via ImageJ and statistically analyzed using the Weibull distribution in OriginPro. Results showed that a slope angle of 45° with a pouring temperature of 595 °C, followed by reheating at 580 °C for 80 min, produced fine, highly spherical α-Al grains with uniform distribution and minimal porosity. Compared with other tested conditions, this combination demonstrated superior microstructural stability, which is expected to enhance rheological behavior and mechanical integrity during subsequent semi-solid forming. The optimized parameters have direct applicability in producing high-quality ADC12 components for the automotive industry, reducing defects, and improving dimensional precision.

Keywords: Semi-solid processing; Cooling slope casting; ADC12; Thixocasting; Reheating; Grain spheroidization.

1. INTRODUCTION

Semi-solid processing (SSP) has emerged as a promising near-net-shape manufacturing technology for metallic alloys, offering advantages such as reduced porosity, minimized segregation, improved dimensional accuracy, and enhanced mechanical properties compared with conventional liquid-state casting methods [1, 2]. By processing alloys within the solid–liquid coexistence region, SSP promotes the formation of fine, non-dendritic microstructures, which improve rheological flow behavior and feeding during mold filling [3]. The improved microstructure arises from controlled solid fractions, which reduce turbulence, enhance surface finish, and allow for complex, high-quality components [4, 5].

Several techniques have been developed for generating semi-solid slurry, including rheocasting, thixocasting, thixomolding, magnetohydrodynamic stirring, ultrasonic stirring, gas-induced semi-solid, strain-induced melt activation, and spray casting [1, 2]. Among these, the CS casting method has attracted particular attention due to its simplicity, low equipment cost, and ability to produce high-quality feedstock without complex stirring devices [6-8].

In the CS process, molten alloy flows along an inclined, water-cooled surface before entering the mold. Rapid heat extraction and shear-induced dendrite fragmentation result in fine, near-spherical primary α-Al particles suspended in a partially solidified slurry. Previous studies have successfully applied CS processing to various aluminum alloys, producing refined microstructures and improved properties [6, 9-12]. For hypoeutectic Al-Si-Cu alloys such as ADC12, which is widely used in the automotive industry, CS casting can overcome microstructural limitations associated with high-pressure die casting, such as coarse dendrites, porosity, and shrinkage defects [13-15]. ADC12 is a hypoeutectic aluminum die-casting alloy noted for high castability, good fluidity, and low shrinkage; typical automotive applications include transmission cases, converter housings, and engine blocks [16]. Research on CS processing of ADC12 has primarily focused on either microstructural refinement or mechanical property improvement [16-19]. However, systematic optimization of CS parameters-specifically pouring temperature, slope angle, and slope length-and their interaction with subsequent reheating conditions remains limited. Reheating is a critical step in semi-solid forming, as it governs the final grain morphology, sphericity, and liquid fraction before forming [20]. The relationship between the initial microstructure generated during CS casting and its evolution during reheating is still not fully understood for ADC12 alloys.

Therefore, this study aims to optimize CS casting parameters and reheating conditions for ADC12 aluminum alloy feedstock. The research focuses on: (i) evaluating the effects of pouring temperature and slope angle on as-cast microstructure; (ii) analyzing microstructural evolution during reheating at 580 °C; and (iii) identifying the parameter combination that produces fine, spherical α-Al grains with uniform distribution and minimal porosity. The outcomes of this work are expected to contribute to improved process control and quality assurance in the industrial-scale semi-solid processing of ADC12 components.

2. EXPERIMENTAL PROCEDURE

2.1. Material and chemical composition

The chemical composition of the ADC12 aluminum alloy, measured in weight percent, is 10.17 Si, 0.26 Mg, 0.19 Mn, 0.05 Cr, 0.73 Fe, 1.65 Cu, and 0.90 Zn, with the balance Al. The measured Si content confirms a hypoeutectic composition.

2.2. Determination of processing temperatures via DSC

Differential scanning calorimetry (DSC) analysis was performed using a Mettler Toledo TGA/DSC 3+ thermal analyzer to determine the solidus and liquidus temperatures of ADC12. Samples were heated from 30 °C to 700 °C and cooled back to 30 °C at a scanning rate of 10 K/min in an N_2 environment. The solidus and liquidus temperatures were 545 °C and 592 °C, respectively, yielding a 47 °C solidification range (figure 1a).

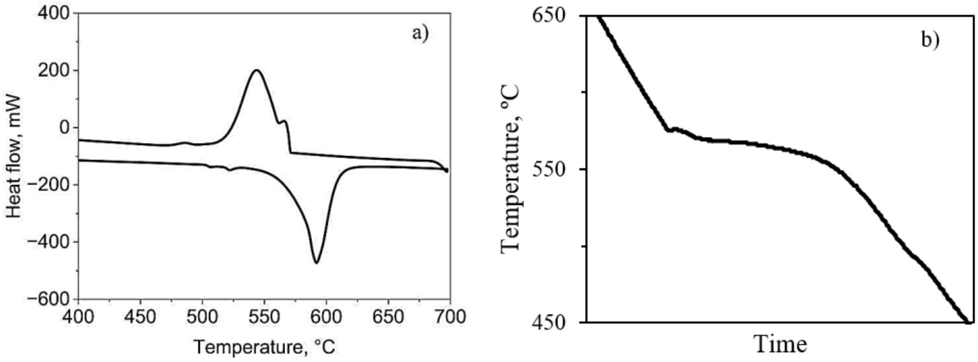


Figure 1. DSC (a) and cooling (b) curves of ADC12 alloy.

Following Birol's analysis [21], a scanning rate of 10 K/min produced a peak separation (ΔT) of 44 °C, corresponding to ΔT/2 = 22 °C. After applying a horizontal shift of 22 °C to the heating (or cooling) curve obtained from the DSC measurement, the liquid fraction-temperature curve was derived (figure 2).

In addition to this DSC-based curve, the liquid fraction of ADC12 alloy was also determined using ProCAST 3D simulation software. By inputting the measured chemical composition of the alloy into ProCAST, a simulated liquid fraction-temperature curve was generated. The close agreement between the shifted DSC curve and the ProCAST simulation confirms that the temperature-shifting method provides a reliable estimation of liquid fraction for subsequent semi-solid processing.

Based on the DSC and cooling curve (figure 1b) analyses, four pouring temperatures - 585, 595, 605, and 615 °C - were selected for the CS experiments. The slope angles were chosen as 30°, 45°, and 60°, following reported ranges from previous studies on semi-solid aluminum processing.

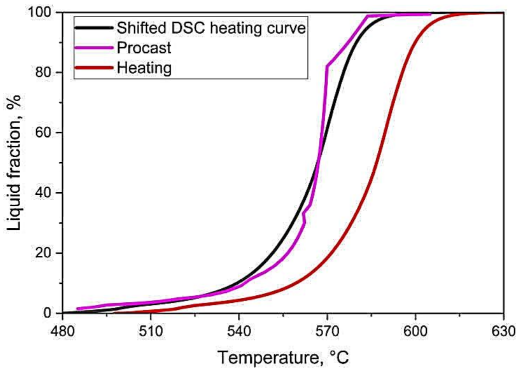


Figure 2. *Liquid fraction of ADC12 alloy.*

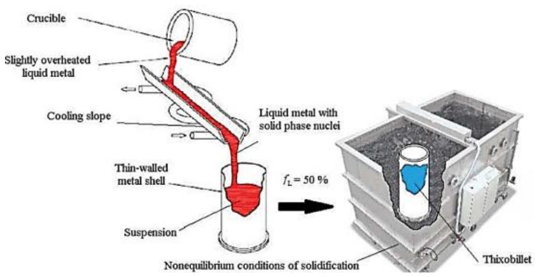


Figure 3. *Experimental equipment setup.*

Reheating billets to the semi-solid state and holding them isothermally is a critical step in feedstock preparation, as excessive reheating temperature can cause grain coarsening and instability. In contrast, insufficient temperature results in an inadequate liquid fraction and poor rheological behavior. Similarly, prolonged holding promotes grain coarsening, whereas insufficient holding time prevents complete spheroidization of α-Al grains. Previous studies indicate that a liquid fraction between 30% and 60% is optimal for stable semi-solid forming [1, 8]. Accordingly, reheating temperatures of 580 °C and 590 °C were initially considered. Based on the liquid-fraction analysis derived from the heating curve (figure 2), these temperatures correspond to ~ 34% and ~ 60% liquid fraction, respectively - i.e., mid-window versus the upper bound. However, billets reheated to 590 °C exhibited excessively rapid melting, indicating unsuitability for stable semi-solid processing. Therefore, 580 °C was selected as the reheating temperature for this study.

2.3. Cooling slope casting setup and procedure

The CS apparatus, previously employed for billet fabrication in [22], was 320 mm in length, made of SS400 steel, and coated with a mold release layer (Metalcote 1998/P) to prevent molten metal adhesion (figure 3). A water-cooling system was installed beneath the slope to ensure rapid heat extraction and promote heterogeneous nucleation during the slurry formation stage.

The molten ADC12 alloy was prepared in a Nabertherm L40/11 resistance furnace at 750 °C under PID temperature control. Pouring was carried out at the four selected temperatures (section 2.2) and slope angles of 30°, 45°, and 60°. At the end of the slope, the semi-solid slurry was collected into a cylindrical mold made of 304 stainless steel (60 mm diameter, 100 mm height) covered with an insulating cap to minimize heat loss and promote temperature homogenization. When the billet temperature decreased to 565 °C, quenching was performed in water to preserve the as-cast semi-solid microstructure.

2.4. Reheating procedure

The as-cast billets were reheated in a Nabertherm L40/11 furnace in air at the selected reheating temperature of 580 °C (section 2.2). The heating rate was 10 °C/min, and isothermal holding was conducted for 40, 60, 80, and 100 minutes to investigate microstructural evolution and identify the optimal spheroidization conditions without excessive grain coarsening. After holding, billets were quenched in oil to preserve the semi-solid microstructure for further characterization.

2.5. Characterization methods

Metallographic specimens were sectioned to dimensions of approximately 15 - 20 mm length and ~ 10 mm thickness. The samples were ground, polished, and etched using Keller's reagent Microstructural observations were conducted using a Leica DMi8M optical microscope. Grain size and sphericity of primary α-Al particles were then quantified from the obtained micrographs using ImageJ software. For each condition, more than 200 complete grains were measured based on their projected area and perimeter, excluding those intersecting image boundaries or lacking a clear definition. The calculated grain size and sphericity values were statistically analyzed in OriginPro 2024 SR1 using a Weibull distribution to evaluate characteristic grain size and average sphericity under different casting and reheating conditions.

3. RESULTS AND DISCUSSION

3.1. Effect of pouring temperature at a 30° slope angle

Figure 4 shows the microstructures of ADC12 cast at a slope angle of 30° with pouring temperatures of 585, 595, 605, and 615 °C.

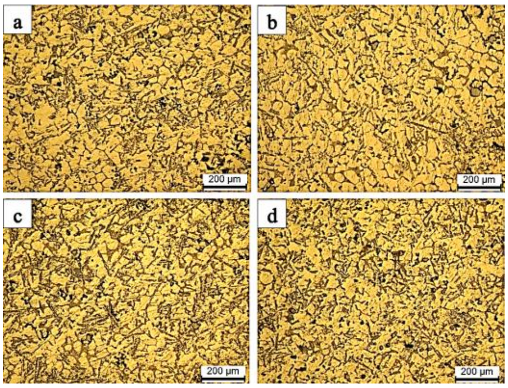


Figure 4. *As-cast at 30° slope:*
(a) 585; (b) 595; (c) 605; (d) 615 °C.

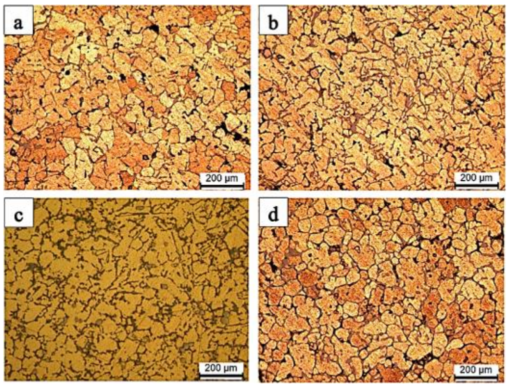


Figure 5. *Slope 30°, reheat 580 °C/40 min:*
(a) 585; (b) 595; (c) 605; (d) 615 °C.

Across all conditions, the typical dendritic α-Al morphology observed in conventional casting was effectively disrupted by the CS process, indicating that heterogeneous nucleation and dendrite fragmentation occurred during flow along the slope surface. However, α-Al grains remained irregular with indistinct boundaries, and eutectic Si persisted as long, acicular plates. This incomplete spheroidization suggested that further thermal treatment was necessary to achieve the rounded grain morphology and homogeneous microstructure required for semi-solid forming.

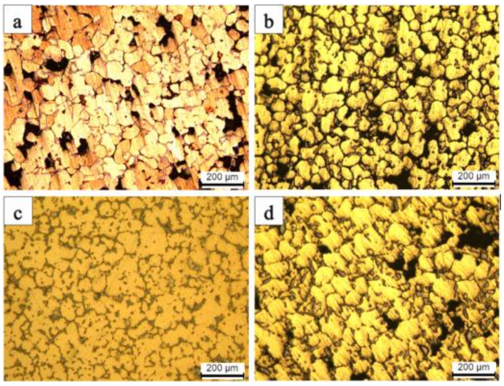


Figure 6. *Slope 30°, reheat 580 °C/60 min:*
(a) 585; (b) 595; (c) 605; (d) 615 °C.

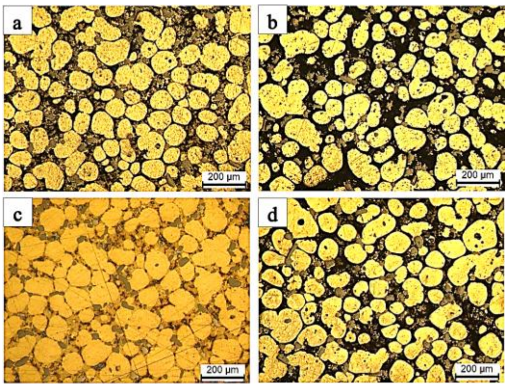


Figure 7. *Slope 30°, reheat 580 °C/80 min:*
(a) 585; (b) 595; (c) 605; (d) 615 °C.

To promote spheroidization, the 30° cast billets were reheated to 580 °C for different holding times. After 40 min (figure 5), α-Al grains began to round and eutectic Si became shorter and finer, particularly at the 615 °C pouring temperature. However, grains remained relatively coarse, and the transformation was incomplete.

Increasing the holding time to 60 min (figure 6) resulted in more distinct grain boundaries and a greater degree of spheroidization. However, porosity was observed in billets poured at 585, 595, and 615 °C, while the 605 °C sample still showed incomplete spheroidization.

At 80 min holding (figure 7), the α-Al grains became well-separated, uniformly distributed, and nearly spherical, while eutectic Si was finely broken and evenly dispersed.

At a 30° slope, dendritic features are largely suppressed after casting, yet extended reheating is still required to achieve stable spheroidization. Within the 585–595 °C pouring range, billets show better post-reheating grain size and sphericity than the other conditions.

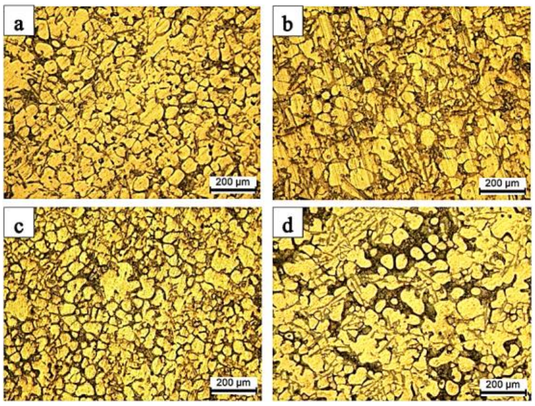
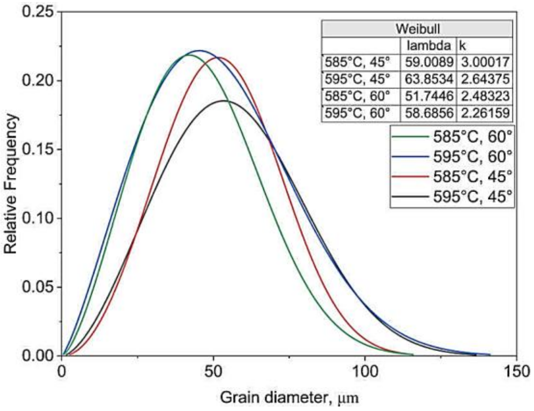


Figure 8. *As-cast (a) 585 °C, 45°; (b) 595 °C, 45°; (c) 585 °C, 60°; (d) 595 °C, 60°.*

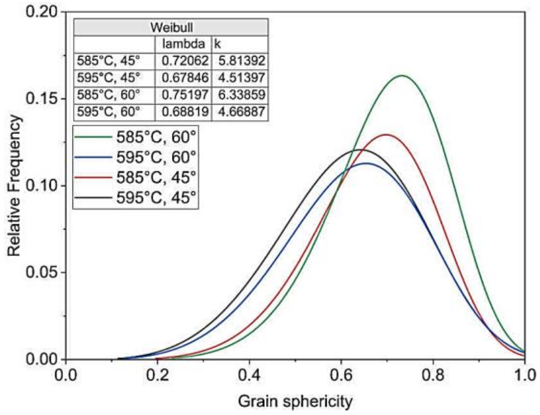


Weibull	lambda	k
585°C, 45°	59.0089	3.00017
595°C, 45°	63.8534	2.64375
585°C, 60°	51.7446	2.48323
595°C, 60°	58.6856	2.26159

Figure 9. *Grain diameter at 45° and 60° slopes.*

3.2. Effect of slope angle increase to 45° and 60°

Using the optimized pouring temperatures from the 30° trials (585 °C and 595 °C), the slope angle was increased to 45° and 60° (figure 8). Compared to the 30° condition, the α-Al grains were smaller, more spherical, and more uniformly distributed immediately after casting. The higher slope angle increased the shear rate and contact time with the cooled slope surface, leading to more effective dendrite fragmentation and rapid nucleation. However, acicular Si was still present, though less prominent than at 30°.



Weibull	lambda	k
585°C, 45°	0.72062	5.81392
595°C, 45°	0.67846	4.51397
585°C, 60°	0.75197	6.33859
595°C, 60°	0.68819	4.66887

Figure 10. *Grain sphericity at 45° and 60° slopes.*

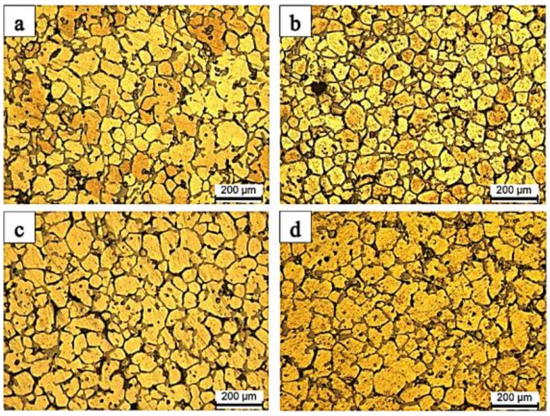


Figure 11. *Reheat 40 min: (a) 585 °C, 45°; (b) 595 °C, 45°; (c) 585 °C, 60°; (d) 595 °C, 60°.*

Grain size and sphericity were quantified using ImageJ (figures 9, 10), with data fitted to Weibull distributions in OriginPro. Billets poured at 585 °C and 595 °C exhibited the smallest average grain diameters and higher sphericity compared with 605 °C and 615 °C. This agrees with prior studies indicating that lower pouring temperatures enhance undercooling, promoting finer primary α-Al formation during CS processing. Grain size analysis (figure 9) showed that the 585 °C/60° condition produced the smallest grains, with the grain-size distribution curve shifted leftward, indicating a greater proportion of fine grains. Sphericity analysis (figure 10) revealed that the same condition achieved the highest proportion of grains with sphericity > 0.75, consistent with enhanced spheroidization during the CS process at steeper slope angles.

Increasing the slope angle to 45°/60° noticeably improves as-cast grain sphericity and reduces the burden on reheating. Within 585 - 595 °C, the 60° condition tends to yield smaller grains and higher sphericity than the 30° case.

3.3. Reheating effects at 45° and 60° slope angles

Reheating at 580 °C for 40 min (figures 11a, 11b) led to further grain rounding and a clear definition of grain boundaries, compared with the as-cast samples (figures 8a, 8b).

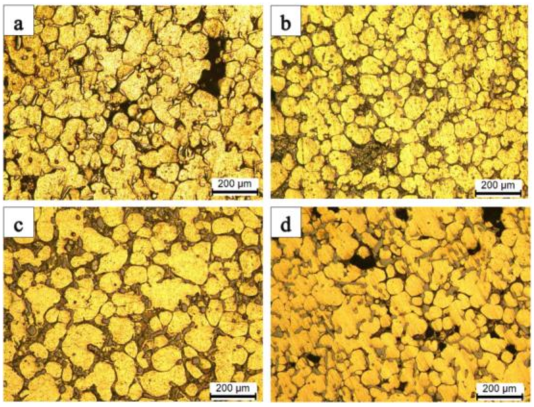


Figure 12. *Reheat 60 min: (a) 585 °C, 45°; (b) 595 °C, 45°; (c) 585 °C, 60°; (d) 595 °C, 60°.*

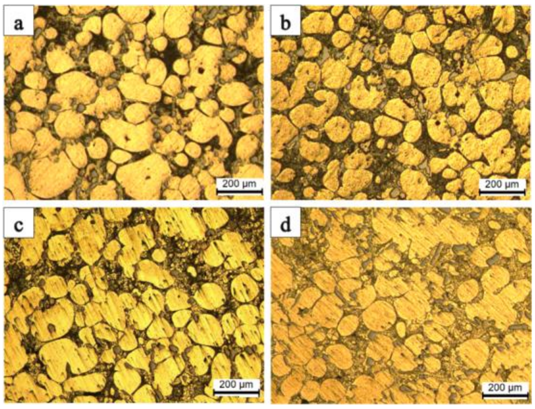


Figure 13. *Reheat 80 min: (a) 585 °C, 45°; (b) 595 °C, 45°; (c) 585 °C, 60°; (d) 595 °C, 60°.*

The eutectic Si became shorter, less angular, and more evenly distributed, especially in the 595 °C/45° sample. Grain size distributions (figure 14) indicated coarsening compared to as-cast conditions, but 585 °C/60° retained smaller grains than other conditions. Sphericity results (figure 15) showed modest improvement for all samples, with 595 °C/60° reaching the highest values.

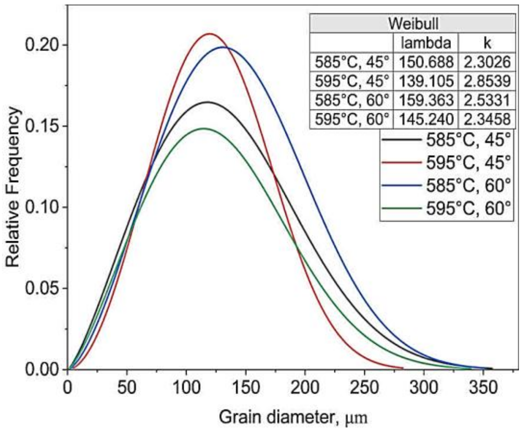


Figure 14. *Grain diameter at slope angles 45° and 60° after reheating (580 °C, 80 min).*

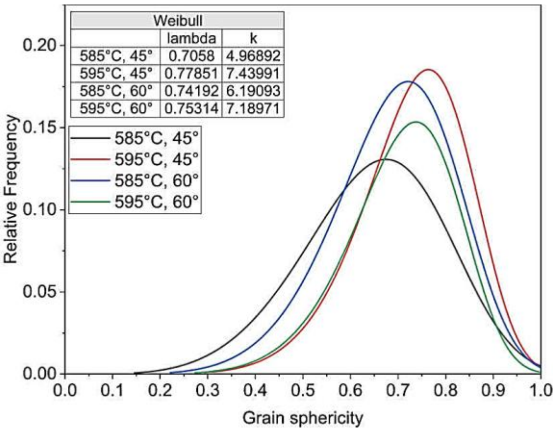


Figure 15. *Grain sphericity at slope angles 45° and 60° after reheating (580 °C, 80 min).*

After 60 min of reheating (figure 12), α-Al grains exhibited more advanced spheroidization, but eutectic Si reprecipitation was observed, notably in 595 °C/45° and 585 °C/60°. This is attributable to the holding temperature (580 °C) being close to the ADC12 eutectic temperature (577 °C). Grain size analysis (figure 14) showed that 595 °C/60° had the smallest grains, while sphericity analysis (figure 15) revealed that 585 °C/60° had the highest sphericity.

Prolonging the reheating time to 80 min (figure 13) resulted in significant coarsening of α-Al grains, with fewer grains per unit area due to Ostwald ripening. All conditions exhibited eutectic Si, but the 595 °C/45° billet showed the smallest grain size and highest sphericity (figures 14, 15). This combination of fine, spherical grains and reduced porosity indicates superior suitability for semi-solid forming.

Reheating at 580 °C promotes α-Al spheroidization and refines eutectic Si; however, holding times > 80 min induce grain coarsening, especially near the eutectic region. The combination 595 °C (pouring) – 45° (slope) – 580 °C/80 min (reheating) delivers fine, spherical α-Al with minimal defects and the best stability across stages.

4. CONCLUSIONS

This study investigated the influence of CS casting parameters and reheating conditions on the microstructure evolution of semi-solid ADC12 feedstock. The main conclusions are as follows:

- Effect of slope angle and pouring temperature: Increasing the slope from 30° to 45°/60° significantly enhances α-Al sphericity and reduces porosity in as-cast billets; 585–595 °C pouring leads to finer grains and better sphericity after reheating.

- Microstructural evolution during reheating: Reheating at 580 °C enhances α-Al spheroidization and refines eutectic Si; holding times >80 min trigger grain coarsening, particularly near the eutectic region.

- Optimal parameters: The condition 595 °C (pouring) – 45° (slope) – 580 °C/80 min (reheating) yields fine, spherical α-Al, minimal defects, and high structural stability across processing stages - suitable for subsequent semi-solid forming.

- Industrial implication: Proper optimization of CS casting and reheating can shorten the reheating stage, save energy, and improve feedstock quality for semi-solid forming of ADC12 at industrial scale.

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TÓM TẮT

Tối ưu hóa thông số đúc máng nghiêng và quá trình nung lại cho phôi hợp kim nhôm ADC12 ở trạng thái bán lỏng

Nghiên cứu này tập trung tối ưu hóa các thông số công nghệ đúc bằng máng nghiêng và chế độ nung nóng lại để chế tạo phôi hợp kim nhôm ADC12 ở trạng thái bán lỏng, nhằm đạt được tổ chức vi mô tinh mịn và cải thiện khả năng tạo hình. ADC12 là hợp kim Al–Si–Cu trước cùng tinh được sử dụng rộng rãi trong công nghiệp ô tô, được đúc qua máng nghiêng bằng thép SS400 làm mát bằng nước ở các góc 30°, 45° và 60°, với nhiệt độ rót 585, 595, 605 và 615 °C. Các phôi đúc được nung nóng lại ở 580 °C với thời gian giữ nhiệt từ 40 đến 80 phút nhằm thúc đẩy quá trình cầu hóa các hạt α-Al sơ cấp. Việc đặc trưng vi cấu trúc được thực hiện bằng kính hiển vi quang học; kích thước hạt và độ cầu tròn được định lượng bằng phần mềm ImageJ và phân tích thống kê theo phân bố Weibull trên phần mềm OriginPro. Kết quả cho thấy, góc nghiêng 45° kết hợp với nhiệt độ rót 595 °C, sau đó nung nóng lại ở 580 °C trong 80 phút, tạo ra tổ chức hạt α-Al tinh mịn, độ cầu cao, phân bố đồng đều và ít rỗ khí. So với các điều kiện khác, tổ hợp thông số này cho thấy độ ổn định vi cấu trúc vượt trội, dự kiến cải thiện đáng kể tính lưu biến và độ bền cơ học trong quá trình tạo hình bán lỏng tiếp theo. Kết quả của nghiên cứu này được kỳ vọng sẽ góp phần nâng cao khả năng kiểm soát quy trình và đảm bảo chất lượng trong gia công bán lỏng hợp kim ADC12 ở quy mô công nghiệp.

Từ khoá: Bán lỏng; Đúc máng nghiêng; ADC12; Đúc xúc biến; Nung lại; Cầu hóa hạt.