Microstructure evolution of Al-Si hypoeutectic alloys prepared by controlled diffusion solidification

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Abstract
The possibility of changing the dendritic microstructure associated with the conventional casting processes of hypoeutectic Al-Si alloys to non-dendritic microstructure by using the controlled diffusion solidification process (CDS) has been investigated. The successful CDS process depends on mixing two precursor alloys heated at a superheat condition near their respective liquidus temperature. Experimental work and simulation work using Ansys software were carried out in the present study by employing Al-Si and Al-Cu systems. This study investigates the effect of the content of the two precursor alloys, the mass ratio changing from 2.6 to 8.3, and the superheat of the first precursor alloy on changing the microstructure. The experimental results show that the pure aluminum used as the first precursor alloy needs more undercooling and agitation during the mixing to form the non-dendritic microstructure compared with hypoeutectic Al-Si alloys. Furthermore, mixing pure aluminum with hypereutectic alloy can change the microstructure of hypoeutectic alloys leading to extending the possibility to choose the second precursor alloy. The results also show that a higher mass ratio is preferred when mixing pure aluminum with hypoeutectic alloy. Furthermore, the microstructure of the alloy Al- 6.45Si- 4Cu- 0.5 Mg- 0.66Fe- 0.66 wt%Zn was successfully changed via the CDS process by mixing Al- 7.75Si- 0.79Fe- 0.78Zn- 0.6 wt%Mg at 2 °C superheat into Al-24 wt%Cu at around 5 °C superheat. The simulation results show that lower air bubbles and better distribution of the two precursor alloys happen during the mixing step when using the Al-Cu system.

Keywords Controlled diffusion solidification · Al-Si alloys · Microstructure · Optical metallography

Nomenclature

- **Alloy1**: First precursor alloy
- **Alloy2**: Second precursor alloy
- **Alloy3**: Resultant alloy
- **A_L and B_L**: Variables of density
- **C_1**: Composition of **Alloy1** (wt%)
- **C_2**: Composition of **Alloy2** (wt%)
- **C_{Al}**: Aluminum concentration (wt%)
- **C_{Cu}**: Copper concentration (wt%)
- **C_o**: Composition of **Alloy3** (wt%)
- **C_P**: Specific heat (Jkg⁻¹ K⁻¹)
- **C_{Si}**: Silicon concentration (wt%)
- **C_{Solute}**: Solute concentration (wt%)
- **H_{sol}**: Heat of solution (J)
- **m1**: Mass of **Alloy1** (kg)
- **m2**: Mass of **Alloy2** (kg)
- **m_r**: Mass ratio (m_1/m_2)
- **N**: Number of species
- **T**: Temperature (K)
- **T_1**: **Alloy1** temperature (K)
- **T_2**: **Alloy2** temperature (K)
- **T_L**: Liquidus temperature (K)
- **T_S**: Solidus temperature (K)
- **T_{L1}**: Liquidus temperature of **Alloy1** (K)
- **T_{L2}**: Liquidus temperature of **Alloy2** (K)
- **T_{∞}**: Bulk temperature (K)
- **U**: Velocity (ms⁻¹)
- **β_T**: Temperature dependence variable
- **β_C**: Concentration dependence variable
- **η**: Viscosity (mPa)
- **Ω**: Regular solution
- **K**: Thermal conductivity (WK⁻¹m⁻²)
- **σ**: Surface tension (Nm⁻¹)
- **ρ**: Density (kgm⁻³)
- **η_{Alloy}**: Multicomponent viscosity (mPa)

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1 Introduction

The hypoeutectic aluminum–silicon alloys are abundant among the other alloys used in the casting process. The Al–Si alloys have wide application in domestic, automotive, and aerospace applications due to their low cost, good castability, favorable mechanical properties, and high strength to weight ratio [1–4].

The controlled diffusion solidification (CDS) process depends on mixing two precursor alloys in a liquid state to make the resultant alloy. The process was innovated to enable casting aluminum wrought alloys to near-net-shape resulting to form a non-dendritic microstructure similar to that forming in the semi-solid processes [5–10]. Khalaf [11] mixed pure aluminum into Al-Si eutectic alloy to make Al-1.8 wt%Si as a resultant alloy. The results show that the non-dendritic morphologies form the microstructure of the final solidified alloy. Khalaf et al. [6, 10–16] used the CDS process to mix pure aluminum with Al-Cu binary alloys that have different solute contents; the results show that the microstructure forms from globular morphologies, globular mixed with rosette morphologies, and rosette mixed with dendritic morphologies, where the change in the microstructure strongly depends on the mass ratio and the undercooling of the first precursor alloy. The undercooling strongly depends on the difference between the initial temperatures of the two precursor alloys prior to the mixing step [12, 17].

Ghiaasiaan et al. [9, 18–21] worked on the heat treatment of 7xxx (Al–Zn–Mg–Cu) wrought alloys that were made via the CDS process. Ghiaasiaan mixed two alloys instead of mixing pure aluminum into alloy using tilt pour gravity casting equipment that has a permanent steel mold heated to 375 °C [22]. The results show that the non-dendritic morphologies form the microstructure of the resultant alloy. Yang et al. [23] used the CDS process to make 7050 alloy by mixing pure aluminum into Al-Zn11.2-Mg5- Cu3 (wt%) alloy; the non-dendritic microstructure forms the resultant alloy. Khalaf [17] used Al-Zn binary alloys to study the microstructure of the CDS process, where pure aluminum was mixed into Al-Zn binary alloys at different mass ratios to make Al-4.5 wt%Zn as a resultant alloy. The final results were compared with Al-Cu alloys. Khalaf found that the non-dendritic microstructure has globular, rosettes, and dendritic morphologies coexisting in the entire samples of different experiments, where the ratio between the morphologies depends on the mass ratio, crucible temperature, and the difference between the initial temperatures of the mixed precursor alloys.

There are few studies published regarding changing the microstructure of the hypoeutectic Al-Si alloys by using the CDS process. This work was dedicated to changing the microstructure of the hypoeutectic Al-Si alloys formed via the CDS process. Experimental and simulation evidence coupled with optical microstructure images support the discussion in this study.

2 Experiments

The CDS process depends on mixing two precursor alloys generally named Alloy1 and Alloy2 in this work. The result of mixing is to make the resultant alloy (Alloy3). Two sets of CDS experiments were carried out in the present study. The first set represents mixing pure metal (Alloy1) into alloy (Alloy2), while the second set represents mixing alloy (Alloy1) into alloy (Alloy2). The first set and second set were involved in Tables 1 and 2, respectively.

Table 1 presents the list of the experiments carried out along with the independent parameters and constants. The experimental procedure, the crucible and funnel dimensions, and the schematic diagram of the setting up of the funnel and the crucible for the CDS process have been discussed in detail previously [11, 16, 17]. Figure 1a shows the Alloy1 and Alloy2 with their temperatures and concentrations placed on the Al-Si phase diagram, where Alloy1 is pure

| Designation | Alloy 1 | Alloy 2 | Alloy 3 |
|-------------|---------|---------|---------|
| m1 (g) | T1, C1 (°C) (wt%) | T1, C1 (°C) | m2 (g) | T2, C2 (°C) (wt%) | T12 (°C) | mr | Co (wt%) |
| Ex1         | 284     | 665     | 0       | 660     | 47 | 582 | 12.6 Si | 573 | 6 | 1.8 |
| Ex2         | 290     | 664     | 0       | 660     | 48 | 552 | 33 Cu  | 549 | 6 | 4.6 |
| Ex3         | 290     | 665     | 0       | 660     | 35 | 580 | 12.6 Si | 573 | 8.3 | 4.5 |
| Ex4         | Part of Ex3 sample re-melted at 665 °C and poured directly into a hot crucible re-heated at 570 °C | | | | | | |
| Ex5         | 252     | 665     | 0       | 660     | 78 | 580 | 12.6 Si | 573 | 3 | 3.1 |
| Ex6         | Part of Ex5 sample remelted at 665 °C and poured into a hot steel crucible heated at 580 °C | | | | | | |

Ex7         | 298     | 665     | 0       | 660     | 116 | 613 | 15 Si  | 609 | 2.6 | 4.5 |
aluminum with T1 fixed at 665 °C for the CDS experiments named Ex1 to Ex7 involved in Table 1. Figure 1b to e show the cooling curves of Alloy1 and Alloy2 used in the study, where the cooling curves were carried out by re-melting in a crucible of the alloys and allowed to solidify to evaluate the liquidus temperature; the temperature data was collected by inserting a thermocouple during the cooling. Figure 1b shows the cooling curve and the first derivative curve (dT/dt) for the pure aluminum that was used in the experiments. In Fig. 1b, the intercept point is 660.2 °C representing the melting point of the used pure aluminum.

The CDS experiments named Ex1 and Ex2 were carried out by mixing Alloy1 into Alloy2 through a 9-mm diameter funnel to make the resultant alloy (Alloy3). Ex1 was carried out by mixing Alloy1 (pure aluminum) into Alloy2 (Al-12.6 wt%Si) with mr 6 to make 1.8 wt%Si as a resultant alloy. Figure 1c shows the cooling curve and the first derivative curve (dT/dt) for the Al-12.6 wt%Si eutectic alloy that was used in the experiments. In Fig. 1c, the intercept point is 573 °C representing the liquidus temperature of the used eutectic alloy. Ex2 was carried out by mixing Alloy1 (pure aluminum) into Alloy2 (Al-33 wt%Cu) with mr 6 to make 4.6 wt%Cu as a resultant alloy. The temperature of the mixture of Ex1 and Ex2 was collected by two thermocouples named lower thermocouple and upper thermocouple inserted prior to the mixing step in the bottom and the middle of the crucible, respectively. Labatory discussion about mixing through a funnel was already reported [13].

The CDS experiments named Ex3, Ex5, and Ex7 were carried out by direct mixing of Alloy1 into Alloy2 to make

| Alloy1 | TL1 (°C) | T1 (°C) | Alloy2 | TL2 (°C) | T2 (°C) | mr | Alloy3 |
|--------|----------|---------|--------|----------|---------|----|--------|
| Ex8    | Al-5.36Cu-0.88Fe-0.67Mg-3.9Si-0.88Zn | 618 | 630 | Al-13.5wt%Si | 585 | 600 | 3 | Al-6.45Si-4Cu-0.5Mg-0.66Fe-0.66Zn |
| Ex9    | Al-7.75Si-0.79Fe-0.78Zn-0.6Mg | 602 | 604 | Al-24wt%Cu | 590 | 593 | 4.5 |

Fig. 1 a Al-Si phase diagram showing the location of Alloy1 and Alloy2 prior to mixing step; b, c, and d cooling curve and first derivative curve for pure aluminum, Al-12.6 wt%Si, and Al-15 wt%Si, respectively; e cooling curve and first derivative curve for the Alloy1 for Ex9 involved in Table 2; and f half of solidified sample of the experiments showing the locations of the middle and the edge specimens taken for the microstructure image.
the resultant alloy (Alloy3). Ex3 was carried out by mixing Alloy1 (pure aluminum) into Alloy2 (Al-12.6 wt% Si) with mr 8.3 to make 1.4 wt% Si as a resultant alloy. After the mixing step, the mixture was directly poured into an empty-backed clay crucible heated at 570 °C. Ex4 was carried out by re-melting a part of the solidified sample of Ex3 and directly pouring the melt into an empty-backed clay crucible that was heated at 570 °C. Ex4 represents a conventional solidification. Ex5 was carried out by mixing Alloy1 (pure aluminum) into Alloy2 (Al-12.6 wt% Si) with mr 3 to make 3.1 wt% Si as a resultant alloy. After the mixing step, the mixture was directly poured into an empty steel crucible heated at 580 °C. Ex6 was carried out by re-melting a part of the solidified sample of Ex5 and directly pouring the melt into an empty steel crucible that was heated at 580 °C. Ex6 represents a conventional solidification. Ex7 was carried out by mixing Alloy1 (pure aluminum) into Alloy2 (hypoeutectic alloy (Al-15 wt% Si)) with mr 2.6 to make 4.5 wt% Si as a resultant alloy. Figure 1d shows the cooling curve and the first derivative curve (dT/dt) for the Al-12 wt% Si and Al-30 wt% Cu alloy used in the study.

3 Phase diagram consideration

Figure 2a shows a comparison between the phase diagram of the hypoeutectic alloys for Al-Si and Al-Cu alloys. In Fig. 2a, TL and TS were the liquidus and the solidus lines, respectively. The Al-Cu system was chosen to compare with the Al-Si system because the microstructure of the Al-Cu alloys easily and successfully changes to non-dendritic by using the CDS process [6, 7, 10–17, 24–27]. Figure 2a can be employed to make two resultant
alloys that have the same content of 4.5 wt% taken as an example. Where points (C) and (E) represent the resultant alloys that have content of Al-4.5 wt%Cu and Al-4.5 wt%Si, respectively. Unlimited contents of Alloy1 and Alloy2 can be chosen to make the two alloys that could be mixed to make the resultant alloy by the CDS process. Pure aluminum with 5 °C superheat represented at point (A) can be mixed with eutectic alloys that have 5 °C superheat represented by points (B) and (C) for Al-Cu and Al-Si systems to make the resultant alloys, respectively. According to the phase diagram, the maximum difference in the initial temperature between the pure aluminum and the eutectic alloys was 110 and 83 °C employed by Al-Cu and Al-Si systems, respectively. Where, a higher difference between the temperatures of the two precursor alloys that are mixed at a temperature near to their respective liquidus temperature leads to a higher undercooling of the first precursor alloy happening during the mixing step resulting in a drastic increase in the nucleation rate [16, 17]. In addition, according to the level rule, the mass ratios (mr = m1/m2) required to make the resultant alloys are 6.3 and 1.82 for Al-Cu and Al-Si, respectively. One can suggest that the lower difference in the initial temperature for the Al-Si system decreases the undercooling of Alloy1 during the mixing step, this leads to a decrease in the nucleation rate. In addition, the lower mass ratio increases the amount of the dendritic morphologies forming among the globular and rosette morphologies creating in the microstructure of the hypoeutectic alloys formed by the CDS process [12, 15–17]. According to that, the microstructure of the Al-Si hypoeutectic alloys is expected to have more dendritic morphologies forming in the entire product made by the CDS process especially for the alloys that have a silicon content of more than 4.5 wt%Si when mixing pure aluminum into a hypo eutectic alloy.

4 Simulation consideration

Ansys fluent software\(^1\) was used to simulate the mixing of Alloy1 into Alloy2 for the experiments Ex1 and Ex2 illustrated in Table 1. The 2D axisymmetric model was employed to simulate the mixing step using heat transfer, k–ε turbulence model, and the volume of fluid (VOF) with three species. Where dry air, pure aluminum (Alloy1), and Alloy2 (Al-12.6 wt%Si for Ex1 and Al-33 wt%Cu for Ex2) were the three phases coexisting in the simulation. Equations (1) to (3) represent the Navier stocks equation, continuity equation, and heat equation numerically solved in the simulation. Figure 2b shows the initial condition of the density distribution and the locations of the Alloy1, Alloy2, and the Air in the funnel and the crucible.

\[
\frac{\partial u}{\partial t} + \rho u \cdot \nabla u = \nabla \cdot \left( -p + \mu \left( \nabla u + (\nabla u)^T \right) \right) \tag{1}
\]

\[
\rho \frac{\partial p}{\partial t} + \rho \nabla u = 0 \tag{2}
\]

\[
\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T = \nabla \cdot \left( \kappa \nabla T \right) \tag{3}
\]

The parameters used in Eqs. (1) to (3) were \(\rho = 2375\) (kg/m\(^3\)) [13, 15] which is the density of the pure aluminum (Alloy1) at liquidus temperature; Eq. (4) represents the density of the liquid phase for hypoeutectic Al-Si alloys extrapolated from Thermo-Calc\(^2\) data as a function of the temperature and silicon content (wt%). In Eq. (4), \(\Delta L_{Al-Si} = 2528 + 3.374 CSi\), where \(BL = 0.23234 + (4E-5) CSi\). Equation (5) [15] represents the density of the Al-Cu hypoeutectic alloys extrapolated from data obtained from Factsage software to cover a range of copper concentrations and temperatures from (0 to 33) wt%Cu and (549.8 to 700) °C, respectively. In Eq. (5), \(\beta_C = -4.032 + (1.654E-2)T - (2.53E-5)T^2 + (1.23E-8)T^3\) and \(\beta_C = 22.19678 + (0.1629)C_{Cu} + (9.0973E-4)C_{Cu}^2 + (2.004E-5)C_{Cu}^3\) are variables that depend on the temperature and copper concentration, respectively. Figure 2c shows a comparison between the density of the Al-12.6 wt%Si and Al-33 wt%Cu, showing that the density of Al-Cu eutectic alloy is significantly bigger than that of Al-Si eutectic alloy. Further in Eqs. (1) to (4), CP is the specific heat, where CP-Al = 1179 [28], CP-Al-33Cu = 953.9 J kg\(^{-1}\) K\(^{-1}\) [12], CP-Al-12.6Si = 1106 J kg\(^{-1}\) K\(^{-1}\) was extrapolated in the same way for Al-Cu system [12]. KL = 70 [29] and KL = 95 W m\(^{-1}\) K\(^{-1}\) [30] for Al-Si and Al-Cu system respectively. \(\mu = 1.3\) mPa [28] is the viscosity of pure aluminum at the melting temperature (Tm), and Eq. (6) [31] evaluates the viscosity (\(n_{Alloy}\)) of a multi-component alloy that has (N) species. In Eq. (6), \(x_i\), \(n_{Alloy}^i\), and Ei were alloy content in mole fraction, pre-exponential parameter, and the activation energy for pure melts, where \(n_{Alloy}^i = 0.163mPa.s\) and \(n_{Cu}^i = 0.107mPa.s\), \(EAl = 16,114\) J mole\(^{-1}\), \(ESi = 23,488\) J mole\(^{-1}\), and \(ECu = 25,996\) J mole\(^{-1}\) [32]. Further in Eq. (6), \(AHsol\) is the heat of solution evaluated in Eq. (7). Where the solute content was in the mole fraction, \(\Omega\) is the regular solution parameter evaluated in Eq. (8) [33]. In Eq. (8), \(L0Al-Si = -11,340 - 1.234 T\), \(L1Al-Si = -3531 + 1.36 T\), and \(L2Al-Si = 2265\) are the parameters of silicon in aluminum alloy [34], and \(L0Al-Cu = -66,622 + 8.1 T\), \(L1Al-Cu = 64,800 - 90.8 T + 10 T(Ln(T))\), and \(L2Al-Cu = -2812\) [29].

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\(^1\) Ansys 15, Ansys Inc.

\(^2\) Thermo-Calc academic 2020.
are the parameters of copper in aluminum alloy [35]. According to the calculation from Eqs. (6) to (8), \( \mu = 1.4 \) and 5.6 mPa are the viscosity of Al-12.6 wt%Si and Al-33 wt%Cu at their respective liquidus temperature. The other parameters were obtained from the default of the ANSYS software.

The surface tension (\( \sigma \)) was employed in the simulation. Equation (9) [36] evaluates the surface tension (\( \sigma \)) as a function of temperature that starts from the liquidus temperature. In Eq. (9), \( \sigma = 0.868 \) Nm\(^{-1}\) for pure aluminum at melting temperature [26], \( \sigma_L = 0.824 \) Nm\(^{-1}\) and \( (d\sigma/dT) = (−3.1 \times 10^{-4}) \) Nm\(^{-1}\) K\(^{-1}\) for Al-12 wt%Si [37], \( \sigma_L = 0.951 \) Nm\(^{-1}\) and \( (d\sigma/dT) = (−0.92 \times 10^{-4}) \) Nm\(^{-1}\) K\(^{-1}\) for Al-30 wt%Cu [36]. Figure 2d shows the comparison between the surface tension of Al-30 wt%Cu hypoeutectic alloy and Al-12 wt%Si hypoeutectic alloy, where both alloys lay near the eutectic alloy for Al-Cu and Al-Si systems.

\[
\Delta H_{\text{sol}} = \Omega C_{\text{Solute}} C_{\text{Al}} 
\]

\[
\Omega = \sum_{i=0}^{j} L_i (C_{\text{Al}} - C_{\text{Solute}})^i
\]

\[
\sigma(T) = \sigma_L + (d\sigma/dT)(T - T_L)
\]

\[\text{Results and discussion}\]

The experiments Ex1 and Ex2 involved in Table 1 were carried out by mixing Alloy1 (pure aluminum) with Alloy2 (eutectic alloy). The Alloy1 and Alloy2 were the precursor alloys placed in the phase diagram at points (A), (B), and (D) shown in Fig. 2a. The conditions of Ex2 are almost similar to that of Ex1 for Alloy1, m1, m2, T1, and mr. Figure 2a to d show a comparison between the microstructure of the experiments Ex1 and Ex2. Figure 2a shows a comparison between the microstructure of the experiments Ex1 and Ex2. Figure 2a to d show a comparison between the microstructure of the experiments Ex1 and Ex2. Figure 3a and b show optical microstructure images of the CDS sample for the experiment denoted as Ex1. Figure 3a shows an optical microstructure image for the specimen located in the middle of the sample. The specimen is pointed by (A) in Fig. 1f. In Fig. 3a, globular mixed with rosette morphologies would form the
non-dendritic microstructure. Figure 3b shows an optical microstructure image for the specimen located at the edge of the sample. The specimen is pointed by (B) in Fig. 1f. In Fig. 3b, dendritic morphologies mixed with rosette morphologies form the microstructure, where the dendrites dominate the microstructure. Figure 3c, d show optical microstructure images of the specimens located in the middle and the edge of the sample for the CDS experiment denoted as Ex2, respectively. In Fig. 3c, d, globular mixed with few rosette morphologies would form the non-dendritic microstructure. The microstructure results indicated in Fig. 3a to d show that the undercooling employed from Alloy2 for the Al-Cu system shown in Fig. 2a strongly affects the non-dendritic microstructure. The microstructure leading to the creation of the globular morphologies that dominate the entire microstructure of the sample compared with that for the Al-Si system.

Figure 3e shows the thermal curves of the experiments Ex1 and Ex2 drawn for the data collected by the lower thermocouple inserted in the crucible of Alloy2 prior to the mixing step. In Fig. 3e, the temperature data was superimposed to start at the same time to ease the comparison between the thermal curves, further, points (A) and (C) represent the starting of mixing of Alloy1 into Alloy2 and points (B) and (D) represent the maximum temperature of the mixture at the end of the mixing step for Ex1 and Ex2, respectively. Figure 3e also shows that thermal recalescence, some of them pointed by arrows, appear as an oscillation in the temperature happening between the starting and the end of mixing in the thermal curves for the experiments Ex1 and Ex2, where this kind of thermal recalescence indicates that the nucleation events occur during the mixing step of the CDS process [12]. In addition, the difference between the starting of mixing temperatures (points (A) and (C)) was around 582–552 = 30 °C, and the difference between the maximum temperatures (points (B) and (D)) was around 657–650 = 7 °C. According to that, the nucleation can occur in both the Al-Si and Al-Cu systems, and the heat issued from the nucleation events during the mixing of pure aluminum into Al-33 wt%Cu is significantly bigger than that when mixing pure aluminum into Al-12.6 wt%Si although the condition of Ex2 is almost similar to that of Ex1 for Alloy1, m1, m2, T1, and mr.

Figure 4a to d show the simulation results of density distribution at 0.4 s for Ex1 and Ex2 experiments illustrated in Table 1. Figure 4a to c show the simulation results of the density distribution for the Ex1 experiment. Figure 4b shows a magnified area at the funnel region shown in Fig. 4a, showing that the liquid surface that was pointed by arrows forms as a curved shape happening because of the effect of the surface tension employed in the calculation. This appears in all liquid surfaces for Al-Si and Al-Cu systems at all times in the present study when employing the surface tension in the simulation. Figure 4c, d show magnified areas of the mixture in the crucible region for Ex1 and Ex2 respectively. The crucible region is pointed by the square in Fig. 4a taken as an example. In Fig. 4c, d, the density distribution for Ex2 is significantly different compared with Ex1, wherein better distribution of Alloy2 in the mixture for the Al-Cu system. Furthermore, air bubbles that were pointed by arrows appear in both experiments forming at the contact area located between the stream of Alloy1 and Alloy2. The simulation results show that the air bubbles forming in the Al-Cu system are significantly less than that for the Al-Si system shown in Fig. 4d. One can suggest that the air bubbles forming during the mixing step strongly depend on the difference between the densities and the viscosities of the mixed alloys.

Figure 5a to f show the simulation results of density distribution for the mixture in the crucible taken during the mixing step at 0.8 s, 1.2 s, and at the end of the mixing step for the experiments named Ex1 and Ex2 illustrated in Table 1. Where Fig. 5a, b show the density distribution after 0.8 s, Fig. 5c, d show the density distribution after 1.2 s, and Fig. 5e, f show the density distribution at the end of mixing for Ex1 and Ex2, respectively. In Fig. 5a to f, the eutectic alloy for the Al-Cu system has a better probability to break into small masses, and this leads to making better distribution of Alloy2 in the entire mixture. One can suggest that the better distribution of the two precursor alloys during the mixing step could affect forming a non-dendritic microstructure in the CDS process. Furthermore, the simulation results show that the air bubbles distribute in the entire mixture by the agitation happening during the mixing, where some of them escape to the environment and the other exists in the mixture till the end of the mixing step.

Figure 6a, b show typical microstructure images of the specimens located in the middle and the edge of the CDS sample for the experiment denoted as Ex3 in Table 1, respectively. Figure 6a shows an optical microstructure image for the specimen located in the middle of the sample, showing that the non-dendritic microstructure forms the middle of the CDS process sample. In Fig. 6a, globular mixed with rosettes and a few dendritic morphologies would form the non-dendritic microstructure. Figure 6b shows an optical microstructure image for the specimen located at the edge of the sample. In Fig. 6b, the non-dendritic microstructure also has globular mixed with rosette and dendritic morphologies form in the edge of the sample. The microstructure of the experiment Ex3 differs from that forming in Ex1 especially at the edge of the sample. One can suggest that the experiment Ex3 is carried out by increasing the mass of Alloy1 (pure aluminum) and decreasing the mass of Alloy2 (eutectic alloy), and the nucleation starts from Alloy1 (pure aluminum with 665 °C) that is undercooled during the mixing because the mixing happens into the crucible of Alloy2 that has a lower temperature (580 °C) [16, 17]. Additionally,
the decrease of Alloy2 results in decreasing in the dendritic morphologies forming in the microstructure because the Alloy2 is prone to make the dendritic microstructure, especially when choosing pure aluminum as Alloy1 in the CDS process [17]. Furthermore, the mixture was poured directly after mixing step into an empty crucible heated at 555 °C. This leads to an increase in the nucleation rate in Alloy1 and makes an agitation applying to the mixture leading to a re-distribution of the morphologies forming in the mixture. According to that, more agitation during and after the mixing step is preferred for the hypoeutectic Al-Si system [13]. Figure 6c shows an optical microstructure image of a specimen taken from the sample for the experiment named Ex4 that was carried out by re-melting half the sample of the Ex3 at 700 °C and hence, the melt was directly poured into a hot empty backed-clay crucible heated at 555 °C. The experiment Ex4 represents the conventional solidification. In Fig. 6c, the dendritic microstructure forms the entire sample. The microstructure results shown in Figs. 5 and 6 would indicate that the Al-Si hypoeutectic alloys can form a non-dendritic microstructure via the CDS process when carefully choosing the mr, T1, T2, and the contents of the two precursor alloys.

Figure 7a, b show typical microstructure images of the specimens located in the middle and the edge of the sample for the CDS experiment denoted as Ex5 in Table 1, respectively. In Fig. 7a, b, rosette mixed with equiaxed dendritic morphologies would form the microstructure. The microstructure of the experiment Ex5 differs from that forming in Ex1 and Ex3. The experiment Ex5 was carried out to make the mr = 3 by decreasing the mass of Alloy1 (pure aluminum) and increasing the Alloy2 (eutectic alloy). The nucleation starts from Alloy1 (pure aluminum with 665 °C) that is undercooled during the mixing because the mixing happens into the crucible of Alloy2 that has a lower temperature (580 °C) [16, 17]. Additionally, the Alloy2 was increased resulting in to increase in the dendritic microstructure because the Alloy2 is prone to make the dendritic
**Fig. 5** Simulation results of density distribution for Ex1 and Ex2 experiments. a and b taken at 0.8 s, c and d taken at 1.2 s, e and f taken at the end of mixing, respectively.

**Fig. 6** a Optical microstructure image taking from the middle of the sample for the experiment named Ex3 in Table 1, b optical microstructure image taking from the edge of the sample for the experiment named Ex3 in Table 1, and c optical microstructure image taking from the middle of the sample for the experiment named Ex4 in Table 1.

**Fig. 7** a Optical microstructure image taking from the middle of the sample for the experiment named Ex5 in Table 1, b optical microstructure image taking from the edge of the sample for the experiment named Ex5 in Table 1, and c typical microstructure image taking from the middle of the sample for the experiment named Ex6 in Table 1.
microstructure [17]. Furthermore, the mixture was poured directly after mixing step into an empty steel crucible heated at 580 °C. This leads to making an agitation to the mixture resulting in re-distributing of the morphologies forming in the entire mixture. Furthermore, the stable solid–liquid interface that exists with the growing nuclei would break to become unstable because of the high cooling rate established between the mixture and the steel crucible that has higher thermal diffusivity compared with that for the backed-clay crucible used for Ex1 to Ex4 [12, 15]. Figure 7c shows an optical microstructure image taken from the sample for Ex6 that was carried out by re-melting half of the sample for the Ex5 at 700 °C, and hence the melt was directly poured into the steel crucible heated at 580 °C. In Fig. 7c, the dendritic microstructure forms the entire sample. The columnar dendrites dominate the microstructure of the experiment Ex6 because of the high cooling rate established between the mixture and the steel crucible.

Figure 8 shows an optical microstructure image of the CDS experiment denoted as Ex7 in Table 1. In Fig. 8, a non-dendritic microstructure forms the entire sample for Ex7. The non-dendritic microstructure forms with lower dendrites compared with that for the CDS experiments Ex1 to Ex5, although the mixing takes place at a lower mass ratio (\(mr = 2.6\)) and lower difference in the initial temperature (665–613 = 42 °C). This happens because the solidification of the Alloy2 (Al-15wt%Si- hypereutectic alloy) differs from the solidification of hypoeutectic Al-Si alloys that are prone to form the dendritic microstructure. According to Ex7 results and the results reported by Khalaf [38], a new window can be opened of the CDS process at which the two precursor alloys can be chosen as hypoeutectic alloy mixing with hypereutectic alloy to make the resultant alloy.

The CDS process was presented as a casting process depending on mixing two precursor alloys. Therefore, there are unlimited possibilities to choose the contents of the precursor alloys. The alloy Al-6.45Si-4Cu-0.5 Mg-0.66Fe-0.66Zn was made by the CDS process in two different ways by choosing the Alloy1 and Alloy2 as illustrated in Table 2. Figure 9a, b, and c show typical microstructure images of the specimens located in the middle and the edge of the sample for the CDS experiment denoted as Ex8 and Ex9 indicated in Table 2, respectively. Figure 9a shows a typical microstructure image of the specimen located in the middle of the CDS experiment denoted as Ex8. In Fig. 9a, the dendritic microstructure forms in the entire sample. Figure 9b, c show typical microstructure images of the specimens located in the middle and the edge of the sample for the CDS experiment denoted as Ex9. In Fig. 9b, c, the non-dendritic microstructure forms the entire sample, where, globular, rosette, and a few equiaxed dendritic morphologies would coexist in the microstructure. The significant result extracted from Ex9 is that the non-dendritic microstructure forms in the entire sample although the difference between the temperatures of the precursor alloys was 11 °C. The parameters illustrated in Table 2 of the experiment Ex9 indicate that the Alloy1 and Alloy2 have 2 and 3 °C superheat prior to the mixing step, respectively. Furthermore, Alloy2 has all the copper content and has the lower crucible temperature. One can suggest that lower superheat of Alloy1 with less than 5 °C and improving the spontaneous nucleation that may happen to make copious nucleation in the hypoeutectic Al-Si system [11, 16].

![Fig. 8 Typical microstructure image of the sample for the experiment named Ex7 involved in Table 1](image)

![Fig. 9 a Optical microstructure image taken from the middle of the sample for the experiment named Ex8 in Table 2, b optical microstructure image taken from the middle of the sample for the experiment named Ex9](image)

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6 Conclusion

This study dedicates to changing the microstructure of the hypoeutectic Al-Si alloys from dendritic to non-dendritic microstructure by the controlled diffusion solidification process (CDS). Nine experiments representing the CDS process and conventional casting were carried out in this study. Pure aluminum and hypoeutectic alloys would be employed as the first precursor alloy while eutectic alloy for Al-Si system and Al-Cu system (used for comparison), hypoeutectic Al-Si alloys, and hypereutectic Al-Si alloys would be employed as the second precursor alloy (Alloy2), where Alloy1 and Alloy2 would be mixed with a mass ratios of 8.3, 6, 4.5, 3, and 2.6. The mixing of Alloy1 into Alloy2 happens directly and through a 9-mm diameter funnel. The Al-Si and Al-Cu experiments that were mixed through the funnel were simulated by using Ansys software to present a better understanding of the distribution of Alloy2 in the mixture. The results of this study are summarized below:

1. The CDS process would change the microstructure of the hypoeutectic Al-Si alloys to a non-dendritic microstructure. The process presents many ways to choose the precursor alloys.

2. The non-dendritic microstructure forms the sample when pure aluminum with around 5 °C superheat would be used as a first precursor alloy. In this case, increasing the mass ratio by decreasing the mass of Alloy2 represents a solution to form the non-dendritic microstructure with lower dendrites forming in the CDS sample.

3. The simulation results carried out by Ansys software for the CDS process give a better explanation for the Alloy1 and Alloy2 distribution in the mixture during the mixing step.

4. The simulation results show that the air interrupted during the mixing step form between the Alloy1 stream and Alloy2 depending on the density and the viscosity of the mixed alloys.

5. The hypereutectic Al-Si alloys can be employed as Alloy2 to form a non-dendritic microstructure for hypoeutectic Al-Si alloys. Where using the hypereutectic Al-Si alloys increases the mass ratio and changes the solidification pathway of Alloy2 leading to reduce the dendrites forming during the solidification of the mixture.

6. The superheat of Alloy1 and Alloy2 less than 5 °C is preferred to change the microstructure of hypoeutectic alloys when using alloys as Alloy1. This gives a better solution when the difference in temperature between the two precursor’s alloys is less than 20 °C for the alloys under study.

7. Pure aluminum employed as Alloy1 needs more undercooling to form the non-dendritic microstructure compared with employing an alloy.

The variation in choosing the precursor alloys in this study explains the parameters preferred to form the non-dendritic microstructure in hypoeutectic Al-Si alloys.

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Author contribution AAK designed the study, performed the research, analyzed the data, wrote the paper, and conducted experiments and data processing.

Availability of data and materials The experimental and simulation data is transparent.

Declarations

Ethics approval This article does not contain any studies with human participants performed by any of the authors.

Consent to participate This work was conducted with no human test subjects.

Consent for publication This work has consent for publication.

Conflict of interest The authors declare no competing interests.

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