Materials Research Express

**PAPER**

Grain refinement and eutectic modification of A356 casting alloy by adding Al-B-Sr master alloys and its effect on tensile properties

K Eidhed and P Muangnoy

Department of Materials and Production Technology Engineering, Faculty of Engineering, King Mongkut’s University of Technology North Bangkok, Bangsue, Bangkok 10800, Thailand

* Author to whom any correspondence should be addressed.

E-mail: kittee.e@eng.kmutnb.ac.th

Keywords: modifications, grain refinements, master alloys, A356 alloy

Abstract

The effects of the grain refinement and eutectic Si modification on tensile properties by using Al-B-Sr master alloys in A356 cast alloy were investigated. Two different master alloys, Al-4%B-1%Sr (4B1Sr) and Al-3%B-3%Sr (3B3Sr), were developed. In microstructure observation, the master alloys were consisted of AlB2, SrB6, AlSrF, KAlF4 and Al4Sr compounds. It should be noted that the α-Al phase also exists in two master alloy. The result showed that the AlB2 area fraction in the 4B1Sr alloy was higher than the 3B3Sr alloy. The 4B1Sr alloy has better efficiencies of α-Al grain refinement and eutectic Si modification than the 3B3Sr alloy, and α-Al grains are refined from 3035 to 312 μm and the eutectic Si is modified from the acicular to fibrous morphology. The tensile properties of 4 wt% treated with 4B1Sr alloy has higher UTS and elongation compared to the treated with 3B3Sr alloy.

1. Introduction

Al–Si cast alloys are widely used in automotive parts and construction applications because of their high castability, high-quality surface finish and low density. In addition, the addition of Mg (Al-Si-Mg) and Cu (Al-Si-Cu) can improve mechanical properties through Mg2Si and Al12Cu nanoparticle precipitation during the aging process [1]. Several refinement methods have been developed, such as direct-current pulsed magnetic field, severe plastic deformation (SPD), rapid solidification and master alloy addition [2–4]. Currently, the addition of master alloys is widely used because of its ease of use and low cost compared with other methods of grain refinement.

The grain refinement with Al-Ti, Al-Fe, Al-Ti-B, Al-B, Al-Ti-B-Y and new Al-V-B master alloys occurs through their addition into the molten metal to form intermetallic compounds which act as nucleation sites such as Al4Ti3, Al12Fe2, TiB2, AlB2, TiC and VB2 particles [5–11]. The smaller α-Al grain size provides increased tensile and impact properties [12, 13] and improves casting quality, such as feeding, fluidity, surface finish, and machinability. Al-Fe and Al-Ti alloys have been widely used to refine pure aluminum [6, 14]. Researchers have found that (AlSi)3Ti intermetallic compounds are present in the microstructure [15]. Therefore, Al-5%Ti-1%B and Al-3%Ti-1%B master alloys have been used for grain refinement [16, 17]. The mechanism of grain refinement can be explained through AlTi3 and TiB2 promotion of α-Al grain refinement. However, prolonging the holding time reduces the efficiency owing to the agglomeration and sedimentation of AlTi3 and TiB2 on the surface silicon [18]. Many researchers have studied the effect of grain refining with an Al-B master alloy on Al-Si alloys. An Al-Si cast alloys (0%–10%Mg) revealed that Al-B master alloys showed excellent grain refinement to smaller grains, which caused AlB2 formation in the melt over the liquidus line and acted as nucleation sites, whereas pure aluminum did not affect grain refinement [19–22]. When comparing the efficiency of grain refinement in Al-5%Ti, Al-5%Ti-1%B, and Al-4%B master alloys, it was found that Al-4%B had a higher grain refinement efficiency [23]. Many research works, development the Al-B master alloy by using the KBF4 powder. The melting temperatures of pure Al melt are in the range of 750 °C to 1000 °C [19, 21, 24, 25], after that adding the KBF4 powder. They found that the microstructure of lower temperature melting has higher amount of AlB2.
and KAlF₄ compounds compared to high temperature melting because of lower free energy change of reaction of AlB₂ phase [24]. Thus, AlB₂ compound is stable phase at lower temperatures 975 °C in melting process. Recently, Al-Ti-C was developed and used for grain refinement [14, 26–28]. When added to pure aluminum, Al-Ti-C resulted in excellent refinement of α-Al. However, the grain size increased with prolonged holding time. Similarly, the grain refinement efficiency test in Al-Si cast alloys found that grain size decreased with short holding time but increased with prolonged holding time. A similar efficiency was also observed for Al-Ti-B. In some cases, refinement can be improved by stirring the liquid metal with a casting tool over a holding time of 120 min [18, 28]. The mechanism for grain refinement in Al-Ti-C master alloys involves TiC particles, which act as nucleation sites during solidification. The grain refinement efficiency depended on the TiC particle content [29]. Caution in producing Al-Ti-C master alloys is the participation of TiC particles, which can agglomerate both during production and after addition into the melt, leading to a reduced efficiency [26].

The Si element is important in Al casting, providing increased hardness and strength, increased fluidity of the melt, increased hot tear resistance, improved feeding characteristics, reduced specific gravity and coefficient of thermal expansion [30]. One important factor for the mechanical properties is the size and morphology of the eutectic Si phase [31–33]. The advantages of changing eutectic Si include improved wear resistance, improved bendability, [34, 35] and reduced solution heat treatment time. Naturally, the silicon had an acicular morphology and a large size because of the crystal growth direction. The silicon morphology was improved by the disguised atom, which inhibited the growth of silicon in the <112> direction and many directions of growth. Currently, Na and Sr are the major elements used for the modification of silicon [36–38]. When comparing the efficiency of silicon modification, it was found that Na was better than Sr. However, Na was more difficult to use and store. Therefore, Sr is widely used in casting. Recently, several researchers have modified eutectic Si using other rare elements such as Cr, Er, Bi, Gd, Zr, Sm and Y [39–45]. These elements can modify acicular Si into both fibrous and laminar morphologies. Moreover, Sato reported that K in the form of 60% KCl–40% KF modifies the coarser eutectic Si into a fibrous morphology [46].

The combination of grain refinement and modification processes have been explored to improve various properties such as mechanical properties, wear resistance, toughness, and elimination of hot tears [47–51]. The combination of grain refiners mixed with modifier elements can be added during the molten stage, as with master alloys such as Al-B-Sr and Al-Ti-C-Sr [52–54]. These two methods have similar efficiency to refine α-Al and acicular silicon for grain refinement and modification, but the master alloy method is very easy to use and control the level of addition compared to the combined method between grain refiners mixed with modifier elements. The important caution with B and Sr addition comes in the form of SrB₆, which decreases the concentration of the grain refiner and modified element in the melt and decreases both the grain refinement and eutectic modification efficiency, especially over a prolonged time [55–58]. The density of the SrB₆ compound was 3.422 g cm⁻³ which decreased the concentration of solute Sr and silt in the melt [55].

However, the influence of prolonged exposure to AlB₂, SrB₆, KAlF₄, AlSrF and Al₅Sr containing compound in Al-B-Sr master alloys on solidification behavior and mechanical properties have not been extensively investigated. Therefore, in this study the effects of the grain refinement and eutectic Si modification on tensile properties by using Al-B-Sr master alloys in A356 cast alloy were investigated.

2. Experimental procedures

2.1. Development of Al-B-Sr master alloy

Firstly, potassium tetrafluoroborurate (KBF₄) was used by addition into pure Al melt at 800 °C in order to produce the Al-6%B (atomic percentage) alloy as a primary master alloy. When the KBF₄ powders were added into Al melt and held for 30 min, the chemical reaction between KBF₄ and Al melt occurred. The melting process was carried out in a SiC crucible by using the low-frequency induction furnace. Then, the Al-10%Sr alloy was added to the melt with a holding time of 30 min. Before pouring a melt into the mold, it was stirred in order to uniform chemical composition. The melt was poured into a stainless-steel mold and the control cooling rate was measured by a thermal data logger. The Al-4%B-1%Sr and Al-3%B-3%Sr (atomic percentage) master alloy specimens were prepared from the bottom of ingot cast specimen. The specimens were ground and polished using alumina powder and silicon suspension. Finally, the samples were etched using Ticker’s solution for 5–10 s. It should be noted that the microstructures were observed with an optical microscope (OM) and a scanning electron microscopy (SEM). Compositions of each compound were analyzed using the SEM with the energy dispersive spectroscopy (EDS).

2.2. Grain refinement and eutectic modification efficiency tests

The Al-7%Si-0.3%Mg alloy (A356) was used to study the grain refinement and eutectic modification efficiency tests. Its chemical composition is showed in table 1. The A356 was heated and melted at 800 °C. In melt...
Table 1. Chemical compositions of A356 alloy (wt%).

| Alloy | Si  | Fe  | Mg  | Cu  | Zn  | Al  |
|-------|-----|-----|-----|-----|-----|-----|
| A356  | 6.95| 0.14| 0.34| 0.04| 0.01| Bal |

Table 2. Marked specimens of the modified A356 treated with 4 wt% master alloys.

| Specimens | Marked |
|-----------|--------|
| Unmodified A356 alloy | A0     |
| Modified A356 with 4B1Sr alloy | A1     |
| Modified A356 with 3B3Sr alloy | A2     |
| Modified A356 with 4B1Sr alloy for 10 min with cooling rate 0.2 °C s⁻¹ | A1−10−0.2 |
| Modified A356 with 4B1Sr alloy for 30 min with cooling rate 0.2 °C s⁻¹ | A1−30−0.2 |
| Modified A356 with 4B1Sr alloy for 60 min with cooling rate 0.2 °C s⁻¹ | A1−60−0.2 |
| Modified A356 with 4B1Sr alloy for 120 min with cooling rate 0.2 °C s⁻¹ | A1−120−0.2 |
| Modified A356 with 4B1Sr alloy for 120 min with rapid cooling rate 10 °C s⁻¹ | A1−RC-120−10 |
| Modified A356 with 3B3Sr alloy for 10 min with cooling rate 0.2 °C s⁻¹ | A2−10−0.2 |
| Modified A356 with 3B3Sr alloy for 30 min with cooling rate 0.2 °C s⁻¹ | A2−30−0.2 |
| Modified A356 with 3B3Sr alloy for 60 min with cooling rate 0.2 °C s⁻¹ | A2−60−0.2 |
| Modified A356 with 3B3Sr alloy for 120 min with cooling rate 0.2 °C s⁻¹ | A2−120−0.2 |
| Modified A356 with 3B3Sr alloy for 120 min with rapid cooling rate 10 °C s⁻¹ | A2−RC-120−10 |

3. Results and discussion

3.1. Microstructure of developed Al-B-Sr master alloys

In development of master alloys, it is found that the microstructure of the 4B1Sr alloy consisted of SrB₆, AlB₂, AlSrF, KAlF₄, and Al₄Sr compounds, as shown in figure 1. The AlB₂ compound forms as a cluster and surrounding with the KAlF₄ compound. The AlSrF compound has a nodular morphology. The SrB₆ compound has a blocky morphology, whereas Al₄Sr has a lamina morphology. Thus, when addition KBF₄ into the melt, a chemical reaction between KBF₄ and molten aluminum leads to the formation of AlB₂ and KAlF₄ compounds [60].

Figure 2 shows the SEM image and EDS spectra positions. The identified elemental compositions of each compound in the 4B1Sr alloy are summarized in table 3. From position of spectrum 1, it is the AlB₂ (black) compound. Spectrum 2 position is identified as the KAlF₄ compound. Spectrum 3 position is the SrB₆ compound (white) showing a cubic morphology. Spectrum 4 position is the Al₄Sr compound showing a laminar morphology. Spectrum 5 position is the AlSrF compound (white) showing a cluster nodular morphology.

Figure 3 shows the microstructure of the 3B3Sr alloy which consisted of SrB₆, AlB₂, and Al₄Sr compounds. The small AlB₂ particles are surrounded by SrB₆ compound. The SrB₆ has a cluster cubic morphology. Al₄Sr has a lamina morphology. Its microstructure is identified using SEM–EDS, as shown in figure 4 and summarized in table 4. From the EDS results, spectrum 1 position is identified as the AlB₂ (black) compound surrounded by a SrB₆ (white) compound. Spectrum 2 position is identified as the KAlF₄, Spectrum 3 position is the SrB₆ compound. Spectrum 4 position is identified as the Al₄Sr compound. Spectrum 5 position is the AlSrF compound (white).

Area fraction of compound was measured by the image analyzer, as shown in table 5. In is clearly seen that the AlB₂ and KAlF₄ of the 4B1Sr alloy has higher amount than those of the 3B3Sr alloy. The SrB₆ and AlSrF
compounds are found higher area fraction in the 3B3Sr alloy. This is because of different ratio of chemical composition of the master alloys.

3.2. Conventional cast of unmodified A356 alloy
The macrostructure and microstructure of unmodified A356 alloys are observed in order to use as a reference of this work. Coarse grain size of the unmodified A356 alloys can be observed and eutectic Si has an acicular
Figure 3. Microstructure of the 3B3Sr alloy showing Al₄Sr, AlB₂, SrB₆, AlSrF and KAlF₄ compounds.

Figure 4. SEM micrographs and identified EDS positions of the 3B3Sr alloy.

Table 4. Elemental concentration of compounds. (No. of spectrum correlates with figure 4).

| Spectrum positions | Compounds | Elemental concentration (wt%) |
|--------------------|-----------|------------------------------|
|                    |           | Al  | B  | Sr  | K  | F  |
| 1                  | AlB₂      | 56.03 | —  | 45.97 | —  | —  |
| 2                  | KAlF₄     | 25.23 | —  | —   | 41.21 | 33.56 |
| 3                  | SrB₆      | 5.88  | —  | 48.50 | 45.62 | —  |
| 4                  | Al₄Sr     | 58.60 | —  | —   | 41.40 | —  |
| 5                  | AlSrF     | 24.33 | —  | 51.45 | —   | 24.22 |

Table 5. Comparing area fraction of compound in the master alloys.

| Master alloys | Area fraction of compound (%) |
|---------------|-------------------------------|
|               | AlB₂  | SrB₆ | Al₄Sr | KAlF₄ | AlSrF |
| 4B1Sr alloy   | 3.40  | 0.91 | 0.19 | 2.23 | 0.15  |
| 3B3Sr alloy   | 1.28  | 3.48 | 0.21 | 0.56 | 0.21  |
morphology in the $\alpha$-Al matrix, as shown in figures 5(a) and (b). These typical macrostructure and microstructure exhibit poor tensile properties which are unsuitable for engineering applications.

3.3. Thermal analysis measurement of A356 with treated 4B1Sr alloy

In this experiment, thermal analysis was used to analyze the solidification behavior during casting of A356 treated with 4 wt% 4B1Sr alloy. It can be seen that the nucleation process of $\alpha$-Al formation strongly depends on the chemical composition of master alloys. In figure 6, the unmodified A356 shows higher undercooling because it has fewer heterogeneous nucleation sites. The undercooling is reduced after the addition of the 4B1Sr alloy with short holding times before pouring. The lower undercooling of cooling curve causes by the AlB$_2$ particle acted as heterogeneous nucleation sites. For longer holding time of 120 min, solidification behavior and undercooling are similar to the unmodified A356, which is well known as the fading effect [18].

The effect of the holding times on the $\alpha$-Al grain size of treated 4B1Sr alloy is observed by macrostructures as shown in figure 7. Refinement of $\alpha$-Al to smaller grain size is achieved in the ranges of 10–60 min compared to the unmodified A356 alloy. With a prolonged holding time in the furnace, the grain size is increased. The treated 4B1Sr alloy specimen consists of large amounts of AlB$_2$ compound which excellent promotes a heterogeneous nucleation site of $\alpha$-Al grain during solidification.

From the experimental results, the undercooling of eutectic Si of unmodified A356 occurs at 577.9 °C. When addition of the 4B1Sr alloy decreases the undercooling of eutectic Si to a range of 572.5 °C–576 °C after holding times of 10–60 min. A prolonged holding time of 120 min increases the undercooling of eutectic Si similar to the unmodified A356 alloy. Moreover, the solidification time is extended and shifted to the right-hand side, as shown in figure 8.
Figure 7. Macrostructures of A1 alloy, holding times for (a) 10 (b) 30 (c) 60 (d) 120 min, respectively.

Figure 8. Comparison cooling curves during eutectic Si formation of A1 alloy, showing undercooling with various holding times.

Figure 9. Microstructures of A1 alloy with holding time for (a) 10 (b) 30 (c) 60 (d) 120 min, respectively.
Figure 9 clearly shows effect of holding time on eutectic Si particle after addition 4 wt% of 4B1Sr alloy. The fibrous morphology of eutectic Si is found in the microstructure with the addition of the 4B1Sr alloy in the range of 10–60 min holding time, as shown in figures 9(a) and (c), whereas laminar and fibrous morphologies are observed with prolonged time, as shown in figure 9(d). Therefore, fully refined microstructure of the treated 4B1Sr alloy is maintained up to 120 min.

The formation of SrB₆ compound in the microstructure in the 4B1Sr alloy generally decreases the eutectic Si modification efficiency. But in this result indicated that eutectic Si is significantly modified throughout the holding time during melting. Because the AlKF₄ compound in the 4B1Sr master alloy is involved in modification process. From a previous work, they found that a present of K in the melt is effect to modify the eutectic Si morphology [46].

3.4. Thermal analysis measurement of A356 with treated 3B3Sr alloy
The unmodified A356 shows higher undercooling of cooling curve compared to the addition of 3B3Sr alloy with a short holding time (10–30 min). However, when prolonged time (60–120 min), undercooling is increased which caused by loss of modifying efficiency, as shown in figure 10.

A comparison of the macrostructure, which was treated with 4 wt% of 3B3Sr alloy. It can be seen that very fine grain sizes (figures 11(a) and (b)) are achieved form both specimens with holding times for 10–30 min. The grain size is coarser after a prolonged time from 60 to 120 min, as shown in figures 11(c) and (d). From this result, it can be concluded that the Al-B-Sr master alloy contains low AlB₂ and high SrB₆ area fractions have adverse effects to the grain refinement efficiency in during solidification [55, 56, 58].

In figure 12, the unmodified A356 is showing as acicular Si line. After addition of the 3B3Sr alloy can decreases the undercooling of eutectic Si to ~572 °C after holding times for 10 to 30 min. When the holding time is increased to 60 to 120 min, the cooling curve shows higher undercooling of eutectic Si compared to 10–30 min. In addition, when holding time of 120 min the undercooling was similar to that of the unmodified A356 alloy. Moreover, the solidification time increased with the addition of 3B3Sr alloy.
Figure 13 shows the fibrous morphology of eutectic Si which achieved from the treated 4 wt% of 3B3Sr alloy with holding time for 10 min. When holding times increase, mixture of acicular and fibrous morphologies can be observed in the range of 30 to 120 min, as shown in figures 13(b)–(d).

In order to clearly explain the effect of eutectic Si modification of A356 alloy by addition Al-B-Sr master alloy, we tried to compare the eutectic Si morphology at holding time for 60 min with high resolution (500x). In 4B1Sr alloys, it can be seen that eutectic Si has a fibrous morphology, as shown in figure 14(a). While the morphology of eutectic Si of treated 3B3Sr is an acicular morphology surrounded by a fibrous morphology. This phenomenon can be explain by the small amount of Al4Sr and KAlF4 compounds in the 3B3Sr alloys (Referred to table 5), which is not sufficient to fully modify acicular Si into a fibrous morphology. During solidification, when α-Al forms as a solid. Then, Sr is rejected into the melt and prohibits the growth of Si during eutectic reaction. However, in the specimen treated with 3B3Sr alloy most Sr atoms completely formed SrB6 compound during the master alloy production. Therefore, it has not sufficient amount Sr to modify the eutectic Si, as shown in figure 14(b).
3.5. Effect of holding time on grain size

In Figure 15, the average grain size of the unmodified A356 is 3120 \( \mu m \). This measured grain size value is applied from our previous work [58]. In this work, after addition the 4B1Sr alloy for the grain refinement, the average grain sizes are decreased to 309, 311, and 326 \( \mu m \) of holding times for 10, 30, and 60 min, respectively. In a case of treated with 3B3Sr alloy, short holding times for 10 and 30 min have smaller grain sizes compared to prolonged holding time for 60 and 120 min. The fading phenomenon strongly affects to the addition 3B3Sr alloy during holding the melt in a furnace for 30 to 120 min. For treated with 4B1Sr alloy, fading phenomenon occurs after holding longer than 60 min therefore, it can be concluded that addition of the 4B1Sr alloy has higher grain refinement efficiencies compared to the 3B3Sr alloy.

3.6. Solidification temperature formation with treated master alloys

Thermal analysis technique is widely used in order to predict the solidification behavior of casting process. A change of reaction temperature after treatment of the master alloys can be used to confirm the grain refinement and eutectic Si modification efficiencies. Figure 16(a) shows a schematic illustration of the effect of treated with master alloys on solidification in the Al-Si phase diagram. The \( \alpha \)-Al formation temperature of both addition master alloy shows high amount of AlB\(_2\) in the 4B1Sr alloy has lower undercooling compared to the combined AlB\(_2\) and SrB\(_6\) compounds in the 3B3Sr alloy, as shown in figures 16(b) and (c). Thus, high amount of AlB\(_2\) compound in the 4B1Sr alloy promotes higher nucleation sites in the melt. When addition 4B1Sr alloy into a furnace at 800 \(^\circ\)C, the AlB\(_2\) compound is completely dissolved into melt. While SrB\(_6\) compounds (\(T_m = 2500 \, ^\circ\)C) has higher melting point than AlB\(_2\) compound (\(T_m = 640 \, ^\circ\)C) [56, 57]. Therefore, the SrB\(_6\) compound still distributes as a solid particle in the melt [58]. Thus, SrB\(_6\) compound has lower effect on grain refinement efficiency compared to AlB\(_2\) compound.
The equilibrium eutectic Si temperature of Al-Si binary system is 577 °C. When addition the 4B1Sr or 3B3Sr alloys change the undercooling of eutectic Si to lower temperature as shown in figures 16(d) and (e). Form a data of table 5, area fraction of Al₄Sr compound is in a range 0.19%–0.21%. When addition master alloys into furnace the Al₄Sr compound is dissolved into the melt together with master alloy, simultaneously. Sr atom in the melt acts as nucleation sites of eutectic Si modification and reduction the undercooling of eutectic Si to lower temperature than equilibrium.

3.7. Effect of cooling rate on macrostructure and Si morphology

In all case of this work, both grain refinement and eutectic Si modification efficiencies are reduced after prolonged holding time because slow cooling during solidification in a mold. Therefore, in this section, the effect of the cooling rate is studied in order to improve the grain size and eutectic Si morphology [61, 62]. The melt was poured into the steel molds with very high cooling rate of 10 °Cs⁻¹ (Mold wall thickness 10 mm.) compared to previous results of 0.2 °Cs⁻¹ (Mold wall thickness 1 mm.) By increase the cooling rate, the grain size becomes smaller such as treated with 4B1Sr alloy and holding time for 120 min has 1072 μm and treated with 3B3Sr alloy has 1203 μm, as shown in figure 17. However, a reduction of grain size by increasing a cooling rate of this work can reduce about 49% compared to the slow cooling rate. Because, the α-Al grain size can be controlled by rapid cooling rate which increase the amount nucleation sites and reduce the radius of nuclei ($r^*_{Hetarogeneous}$) [63].

By increasing cooling rate, the modification of eutectic Si is affected for both treated 4B1Sr and 3B3Sr alloys, as shown in figure 18. A very fine fibrous Si morphology is observed in the treated with 4B1Sr alloy (figures 18(a) and (c)), while a coarser Si particle is observed in the treated with 3B3Sr alloy (figures 18(b) and (d)). It can be indicated that the rapid cooling rate significantly affects the eutectic Si modification.

3.8. Tensile properties of added master alloy specimens

In this experiment, 2 and 4 wt% additions of both master alloys were treated into the melt. Tensile test results reveal that the UTS of the unmodified A356 is 148 MPa, while the elongation is 4.7%, as shown in figure 19. With the addition of the 2 wt% 4B1Sr alloy, UTS increases to 164, 162 and 164 MPa while the elongation increases marginally to 14.4, 14.5 and 14.3% for holding times of 30, 60 and 120 min, respectively. When consideration of yield strength, unmodified A356 is 95 MPa and 2 wt% treated 4B1Sr alloy is 99 MPa. Thus, yield strength is increased by addition of 4B1Sr alloy because their smaller grain sizes.

Figure 16. Schematic illustrations (a) Al-Si phase diagram (b) α-Al formation temperature of A1 alloy (c) α-Al formation temperature of A2 alloy (d) undercooling of eutectic Si of A1 alloy (d) undercooling of eutectic Si of A2 alloy.

The equilibrium eutectic Si temperature of Al-Si binary system is 577 °C. When addition the 4B1Sr or 3B3Sr alloys change the undercooling of eutectic Si to lower temperature as shown in figures (d) and (e). Form a data of table 5, area fraction of Al₄Sr compound is in a range 0.19%–0.21%. When addition master alloys into furnace the Al₄Sr compound is dissolved into the melt together with master alloy, simultaneously. Sr atom in the melt acts as nucleation sites of eutectic Si modification and reduction the undercooling of eutectic Si to lower temperature than equilibrium.

3.7. Effect of cooling rate on macrostructure and Si morphology

In all case of this work, both grain refinement and eutectic Si modification efficiencies are reduced after prolonged holding time because slow cooling during solidification in a mold. Therefore, in this section, the effect of the cooling rate is studied in order to improve the grain size and eutectic Si morphology [61, 62]. The melt was poured into the steel molds with very high cooling rate of 10 °Cs⁻¹ (Mold wall thickness 10 mm.) compared to previous results of 0.2 °Cs⁻¹ (Mold wall thickness 1 mm.) By increase the cooling rate, the grain size becomes smaller such as treated with 4B1Sr alloy and holding time for 120 min has 1072 μm and treated with 3B3Sr alloy has 1203 μm, as shown in figure 17. However, a reduction of grain size by increasing a cooling rate of this work can reduce about 49% compared to the slow cooling rate. Because, the α-Al grain size can be controlled by rapid cooling rate which increase the amount nucleation sites and reduce the radius of nuclei ($r^*_{Hetarogeneous}$) [63].

By increasing cooling rate, the modification of eutectic Si is affected for both treated 4B1Sr and 3B3Sr alloys, as shown in figure 18. A very fine fibrous Si morphology is observed in the treated with 4B1Sr alloy (figures (a) and (c)), while a coarser Si particle is observed in the treated with 3B3Sr alloy (figures (b) and (d)). It can be indicated that the rapid cooling rate significantly affects the eutectic Si modification.

3.8. Tensile properties of added master alloy specimens

In this experiment, 2 and 4 wt% additions of both master alloys were treated into the melt. Tensile test results reveal that the UTS of the unmodified A356 is 148 MPa, while the elongation is 4.7%, as shown in figure 19. With the addition of the 2 wt% 4B1Sr alloy, UTS increases to 164, 162 and 164 MPa while the elongation increases marginally to 14.4, 14.5 and 14.3% for holding times of 30, 60 and 120 min, respectively. When consideration of yield strength, unmodified A356 is 95 MPa and 2 wt% treated 4B1Sr alloy is 99 MPa. Thus, yield strength is increased by addition of 4B1Sr alloy because their smaller grain sizes.
The addition of 4 wt% 4B1Sr alloy further increases both UTS to 165.5, 167.0 and 168.2 MPa and elongation to 18.4, 17.4 and 18.2% for holding times of 30, 60 and 120 min, respectively. In all the cases, the holding time has little effect on the UTS and elongation. Therefore, level of additional master alloy is important factor to the tensile properties. In case of 4 wt% treated 4B1Sr alloy has higher strength because of higher amount of B (grain refiner) and K (modifier) content compared with addition of 2 wt%.

For addition 2 wt% of 3B3Sr alloy increases the UTS to 163, 161 and 156 MPa while the elongation increased to 12.9, 12.9 and 11.9% after 30, 60 and 120 min, as shown in figure 20. High amount of SrB₆ compound in the addition 4 wt% increased the UTS to 163, 155 and 148 MPa while the elongation increased to 12.6, 12.5 and 13.2% for 30, 60 and 120 holding times, respectively. It can be seen that prolonged holding times of 60 to 120 min decrease the UTS to lower strength. This is because fading phenomenon of melt treatment due to high density of the SrB₆ compound. Therefore, it is agglomerated at the bottom of the furnace during casting. Thus, in the melt, it has low solute concentrations of B and Sr, which leads to decrease the mechanical properties.
3.9. Macrostructure and microstructure of tensile specimens

In order to clearly explain a relationship between tensile properties and structures of unmodified A356 compared to addition of Al-B-Sr master alloys. Thus, macro- and micro-tensile specimens were examined. The macrostructure and microstructure of the unmodified A356 show in figure 21. It has a large grain size and acicular morphology of eutectic Si, which is harmful to the UTS and elongation properties.

The macrostructure in figure 22 shows the grain size of the A356 alloy after 4 wt% addition of the master alloys. Because high amount of B element in the 4B1Sr alloy, after treatment of for 30 min holding time the melt has a high B solute concentration, which leads formed AlB2 during solidification and resulted of small equiaxed grains at the center of the casting specimen. With prolonged holding time, the equiaxed grain area is decreased, while the columnar zone region increased from the outer to the inner of the specimen, as shown in figure 22(b).

A coarser grain size is observed in the treated with 3B3Sr alloy both holding time for 30 and 120 min, as shown in figures 22(c) and (d), respectively. Coarser grain size is a reason of lower strength of treated with 3B3Sr alloy specimen compared to treated with 4B1Sr alloy specimen, as shown in figures 19 and 20.

In hypoeutectic Al-Si cast alloys, the eutectic Si area fraction depends on the Si content and addition level of modifier elements. The microstructure of the tensile specimens shows in figure 23. In the 4 wt% treated with 4B1Sr alloy results in a smaller fibrous Si morphology both short and long holding time specimens, as shown in figures 23(a) and (b). It can be observed that eutectic Si area fraction increases after treatment with the master alloy. Thus, modified Si morphology is effects to the elongation of the casting specimen.

In 4 wt% treated with 3B3Sr alloy, the Si morphology with high Sr content from the SrB6 compound. When holding time for 30 min, acicular eutectic Si is refined to fibrous Si morphology, as presented in figure 23(c). With prolonged holding time, the eutectic Si appears coarse acicular morphology, as shown in figure 23(d).

Table 6 shows comparison of mechanical properties of modified A356 treated with 4 wt% master alloys to clarify effect of the grain refinement and eutectic Si modification efficiencies. It can be seen that A1–30–0.2 and A1–60–0.2 specimens have smallest grain size and fibrous Si particle. They have higher yield strength and
elongation, when comparison to A2–30–0.2 and A2–60–0.2 specimens which have coarser grain size and mixture of fibrous and acicular Si particles.

4. Discussion on grain refinement and modification mechanisms of the treated Al-B-Sr alloy

In this work, design and development of Al-B-Sr master alloys, the B:Sr ratios are 4:1 and 3:3 in order to produce different compounds in microstructure of the master alloys. From the grain refinement and modification efficiency tests, the specimen treated with 4B1Sr alloy results in the excellent refined α-Al and eutectic Si
compared to the treated with 3B3Sr alloy. According to compound area fractions in table 5, the 4B1Sr alloy consists of the AlB2, SrB6, Al4Sr, KAlF4 and AlSrF compounds for 3.40, 0.91, 0.19, 2.23 and 0.15%, respectively. While the 3B3Sr alloy consists of the AlB2, SrB6 and Al4Sr, KAlF and AlSrF compounds for 1.28, 3.48, 0.21, 0.56 and 0.21, respectively. Form experimental results, AlB2 and SrB6 compounds should be useful for grain refinement. However, in solidification, formed AlB2 in the melt has higher effect than SrB6. Figure 24 shows schematic illustrations of grain refinement mechanism of treated with 4B1Sr alloy and treated with 3B3Sr alloy.

It is clearly seen that the excellent grain size refinement is achieved in the modified A356 with treated by the 4B1Sr alloy.

The Al4Sr, KAlF and AlSrF compounds should be useful for the eutectic Si modification. In the casting process, these compounds are dissolved into melt after adding 4B1Sr alloy into the furnace. In solidification process, Sr and K can inhibit the Si transformation in the <112> direction and leads to change a shape form acicular to a fibrous eutectic Si morphology. Figure 25 shows schematic illustrations of eutectic Si modification mechanism during solidification of this work. After adding the master alloys at 800 °C, the Al4Sr, AlSrF and KAlF4 are dissolved in the melt. The melting points of the KAlF4 is 574 °C [60]. In the subsequent solidification process, the growth of α-Al phase leads to repelling the K, Sr, O and Si atom to the solid-liquid interface. When the solute concentration of Si in melt increases to 11.7%Si at ~577 °C. The eutectic reaction will be taken place. Then, Sr and K modifier adsorb on the silicon-liquid interface which decrease the undercooling and enhance the twinning of the eutectic Si growth according to the impurity induced twinning (IIT) model. The K modifying element has larger atom than Si

Table 6. Compared grain refinement, eutectic modification and mechanical properties of modified A356 treated with 4 wt% master alloys.

| Marked specimens | Grain size (μm) | Eutectic Si morphology | Yield strength (MPa) | Ultimate tensile strength (MPa) | Elongation (%) |
|------------------|-----------------|------------------------|---------------------|-------------------------------|---------------|
| A0               | 3120            | Acicular Si            | 95.2                | 147.8                         | 4.7           |
| A1–30–0.2        | 311             | Fibrous Si             | 98.1                | 165.5                         | 18.4          |
| A1–60–0.2        | 326             | Fibrous Si             | 98.7                | 167.0                         | 17.4          |
| A1–120–0.2       | 1089            | Fibrous Si             | 94.77               | 168.2                         | 18.2          |
| A2–30–0.2        | 337             | Fibrous Si             | 95.9                | 163.2                         | 12.6          |
| A2–60–0.2        | 860             | Fibrous and acicular Si| 95.0                | 154.8                         | 12.6          |
| A2–120–0.2       | 2458            | Fibrous and acicular Si| 93.6                | 147.9                         | 13.2          |
atom. It can promotes a change of acicular eutectic Si morphology to smaller particles \[64\]. Figure 26 and table 7 show the SEM-EDS analytical result of elemental concentrations of AlSiFeOKF and AlSrO compounds. The x-ray mapping examination in figure 27 clearly shows concentrated K and O elements contained in eutectic Si region. Therefore, the Sr and K in the 4B1Sr master alloy are highly effect to modify the eutectic Si.

5. Conclusions

1. In microstructural development of Al-B-Sr master alloys, their consist of AlB₂, SrB₆, AlSrF, Al₄Sr and KAlF₄ compounds. High amounts of AlB₂ and KAlF₄ compounds are found in the 4B1Sr alloy, while high amount of SrB₆ compound is found in the 3B3Sr alloy.

2. In the 4B1Sr alloy, high AlB₂ compound promotes the \(\alpha\)-Al grain refinement and KAlF₄ compound contributes eutectic Si modification. Their works as heterogenous nucleation sites during solidification.

3. In the 3B3Sr alloy, high SrB₆ compound reduces both grain refinement and modification efficiencies. Fading phenomenon is main predominant because high density of SrB₆ compound.
4. Completely dissolved Sr in the melt reduced the eutectic Si temperature to lower and shift eutectic Si composition to right-hand side. Thus, high amount of dissolved Sr in melt promotes high modification efficiency.

5. The mechanical properties of the tensile specimens depend on addition level and type of master alloys. Form tensile test result, addition of 4 wt% of 4B1Sr alloy has higher UTS and elongation compared to the addition of 3B3Sr alloy.

Table 7. Elemental concentration of compounds. (No. of spectrum correlates with figure 26).

| Spectrum positions | Compounds   | Al  | Si   | Sr  | Fe  | K  | O  | F  |
|--------------------|-------------|-----|------|-----|-----|----|----|----|
| 1                  | AlSiFeOKF   | 24.71 | 42.26 | 0   | 25.06 | 0.12 | 7.37 | 0.48 |
| 2                  | AlSrO       | 4.62  | 87.41 | 1.10 | 0   | 0  | 6.87 | 0  |

Figure 26. SEM micrograph and EDS positions of A1–60–0.2 alloy.
Acknowledgments

The authors would like to express sincere gratitude to Graduate College, King Mongkut’s University of Technology North Bangkok for the financial support.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

ORCID iDs

P Muangnoy https://orcid.org/0000-0002-6787-2896

References

[1] Lumley R 2010 Fundamentals of Aluminium Metallurgy: Production, Processing and Applications (Cambridge: Woodhead Publishing Limited)
[2] Kotadia H R, Babu N H, Zhang H and Fan Z 2010 Microstructural refinement of Al–10.2%Si alloy by intensive shearing Mater. Lett. 64 671–3
[3] Zhou W, Yu J, Lin J and Dean T A 2019 Manufacturing a curved profile with fine grains and high strength by differential velocity sideways extrusion Int. J. Mach. Tools Manuf 140 77–88
[4] Liang G, Ali Y, You G and Zhang M X 2018 Effect of cooling rate on grain refinement of cast aluminium alloys Materiaha 3 113–21
[5] Kashyap K T and Chandrashekar T 2001 Effects and mechanisms of grain refinement in aluminium alloys Bull. Mater. Sci. 24 345–53
[6] Zhang Y, Ma N, Yi H, Li S and Wang H 2006 Effect of Fe on grain refinement of commercial purity aluminium Mater. Des. 27 794–8
[7] Li G, Huang M, Ma M, Ye W, Liu D Y, Song D M, Bai B Z and Fang H S 2006 Performance comparison of AlTiC and AlTiB master alloys in grain refinement of commercial and high purity aluminium Trans. Nonferrous Met. Soc. China 16 242–53
[8] Liu Y, Ding C and Li Y X 2011 Grain refining mechanism of Al-3B master alloy on hypoeutectic Al-Si alloys Trans. Nonferrous Met. Soc. China 21 1435–40
[9] Li P, Liu S, Zhang L and Liu X 2013 Grain refinement of A356 alloy by Al-Ti-B-C master alloy and its effect on mechanical properties Mater. Des. 47 522–8
[10] Jia P, Zhang J, Hu X, Teng X, Zuo M, Gao Z, Yang C and Zhao D 2018 Grain refining effects of the melt thermal-rate treatment and Al-Ti-B-Y refiner in as-cast Al-95Si-0.3Mg alloy Mater. Res. Express 5 66520
[11] Zhao C, Li Y, Xu J, Luo Q, Jiang Y, Xiao Q and Li Q 2021 Enhanced grain refinement of Al-Si alloys by novel Al-V-B refiners J. Mater. Sci. Technol. 94 104–12
[12] Samuel E, Golbahar B, Samuel A M, Dotty H W, Valtierra S and Samuel F H 2014 Effect of grain refiner on the tensile and impact properties of Al-Si-Mg cast alloys Mater. Des. 56 468–79
[13] Dong X, Zhang Y and Ji S 2017 Enhancement of mechanical properties in high silicon gravity cast AlSi9Mg alloy refined by Al3Ti3B master alloy Mater. Sci. Eng. A 700 291–300
[11] Ma X, Liu X and Ding H 2009 A united refinement technology for commercial pure Al by Al-10Ti and Al-Ti-C master alloys J. Alloys Compd. 471 56–9
[12] Samuel A M, Elgallad E M, Doty H W, Valtierra S and Samuel F H 2016 Effect of metallurgical parameters on the microstructure, hardness impact properties , and frae-structures Mater. Des. 107 426–39
[13] Li B, Wang H W, Zhao R F and Wei Z J 2009 Optimization of processing parameters for preparation of Al-3Ti-1B grain refiner Trans. Nonferrous Met. Soc. China 19 387–91
[14] Ghdirmi H, Hossein Nezhad S and Eghbali B 2013 Enhanced grain refinement of cast aluminum alloy by thermal and mechanical treatment of Al-5Ti-1B master alloy Trans. Nonferrous Met. Soc. China 23 63–8
[15] Limannevichitich C and Edshed W 2003 Fading mechanism of grain refinement of aluminum–silicon alloy with Al-Ti-B grain refiners Mater. Sci. Eng. A 349 197–206
[16] Wang T, Chen Z, Fu H, Xu J, Fu Y and Li T 2011 Grain refining potency of Al-B master alloy on pure aluminum Ser. Mat. 64 1121–4
[17] Birod Y 2012 AlB3 master alloy to grain refine AlSi10mg and AlSi2Cu aluminum foundry alloys J. Alloys Compd. 513 150–3
[18] Wang T, Chen Z, Fu H, Gao L and Li T 2012 Grain refinement mechanism of pure aluminum by inoculation with Al-B master alloys Mater. Sci. Eng. A 549 136–43
[19] Chen Z, Wang T, Gao L, Fu H and Li T 2012 Grain refinement and tensile properties improvement of aluminum foundry alloys by treatment with Al-B master alloy Mater. Sci. Eng. A 533 32–6
[20] Mohanty P S and Gruzleski J E 2006 Grain refinement mechanisms of hypoeutectic Al-Si alloys Acta Mater. 44 3749–60
[21] Wang X 2005 The formation of Al2B3 in an Al-B master alloy J. Alloys Compd. 403 283–7
[22] Wang Q, Zhao H, Li Z, Shen L and Zhao J 2013 Production of Al–B master alloys by mixing KBF 4 salt into molten aluminum Trans. Nonferrous Met. Soc. China 23 294–300
[23] Birod Y 2006 Grain refining efficiency of Al-Ti-C alloys J. Alloys Compd. 422 128–31
[24] Kumar G S V, Murty B S and Chakraborty M 2009 Grain refinement response of LM25 alloy towards Al-Ti-C and Al-Ti-B grain refiners J. Alloys Compd. 472 112–20
[25] Kumar G S V and Kumar G S, Murty B S and Chakraborty M 2005 Development of Al-Ti-C grain refiners and study of their grain refining efficiency on Al and Al-7Si alloy J. Alloys Compd. 396 143–50
[26] Wang H, Gao T, Wang H, Nie J and Liu X 2017 Influence of C/Ti stoichiometry in TiC coatings on the grain refinement efficiency of Al–Ti–C master alloy Mater. Sci. Technol. 33 616–22
[27] Kaufman J G and Rooy E L 2004 Aluminum Alloy Castings: Properties, Processes, and Applications (Ohio: ASM International)
[28] Wessén M, Andersson N E and Granath O 2010 Effect of sodium modification on microstructure and mechanical properties of thick-walled AlSi6Cu2.5 rheocast component Trans. Nonferrous Met. Soc. China 20 1643–8
[29] Shin S S, Kim E S, Yeom G Y and Lee J C 2012 Modification effect of Sr on the microstructures and mechanical properties of Al–10.5Si–2.0Cu recycled alloy for die casting Mater. Sci. Eng. A 533 151–7
[30] Samuel A M, Garza-Elizondo G H, Doty H W and Samuel F H 2015 Role of modification and melt thermal treatment processes on the microstructure and tensile properties of Al-SiAlloys Mater. Des. 80 99–108
[31] Zhang X H, Su G C, Ju C W, Wang W C and Yan W S 2010 Effect of modification treatment on the microstructure and mechanical properties of Al-0.35%Mg-7.0%Si cast alloy Mater. Des. 31 4408–13
[32] Marzouk M, Jain M and Shankar S 2014 Effect of Sr modification on the bendability of cast aluminum alloy A356 using digital image correlation method Mater. Sci. Eng. A 598 277–87
[33] Li L, Nagita K and Dahle A K 2005 Combining Sr and Na additions in hypoeutectic Al-Si foundry alloys Mater. Sci. Eng. A 399 244–53
[34] Liao C, Chen J, Li Y, Tu R and Pan C 2012 Morphologies of AlSrIntermetallic Phases and Its Modification Property upon A356 Alloys J. Mater. Sci. Technol. 28 524–30
[35] Faccoli M, Dionis D, Cecchel S, Corranchia G and Panvini A 2017 Optimization of heat treatment of gravity cast Sr-modified B356 aluminum alloy Trans. Nonferrous Met. Soc. China 27 1698–706
[36] Edshed W 2008 Modification of β-Al5Fe5Si compound in recycled Al-Si–Fe cast alloy by using Sr, Mg and Cr additions J. Mater. Sci. Technol. 24 45–7
[37] Shi Z M, Wang Q, Zhao G and Zhang R Y 2015 Effects of erbium modification on the microstructure and mechanical properties of A356 aluminum alloys Mater. Sci. Eng. A 626 102–7
[38] Colombo M, Garbaldi E and Morri A 2017 Er addition to Al-Si-Mg–based casting alloy: Effects on microstructure, room and high temperature mechanical properties J. Alloys Compd. 708 1234–44
[39] Farahany S, Ourdijini A, Idris M H and Thai L T 2011 Effect of bismuth on microstructure of unmodified and Sr-modified Al-7Si–0.4Mg alloys Trans. Nonferrous Met. Soc. China 21 1455–64
[40] Liu W, Xiao W, Xu C, Liu M and Ma C 2017 Synergistic effects of Gd and Zr on grain refinement and eutectic Si modification of Al-Si cast alloy Mater. Sci. Eng. A 693 95–100
[41] Hu Z, Yan H and Rao Y S 2013 Effects of samarium addition on microstructure and mechanical properties of as-cast Al-Si-Cu alloy Trans. Nonferrous Met. Soc. China 23 3228–34
[42] Jia P, Hu X, Zhang J, Teng X, Gao G, Zhao D, Yang Z, Zuo M, Zhang S and Hu G 2018 Strengthening effects of Y and Sr on Al–9Si–0.5Mg alloy Mater. Res. Express 6 16358
[43] Ashhapi P, Tezuka H and Sato T 2005 Modification of Fe-containing intermetallic compounds by K addition to Fe-rich AA319 aluminum alloys Ser. Mat. 53 937–42
[44] Mallapur D R, Udupa K R and Kori S A 2011 Studies on the influence of grain refinement on microstructure and mechanical properties of forged A356 alloy Mater. Sci. Eng. A 528 4747–52
[45] Samuel A M, Doty H W, Valtierra S and Samuel F H 2014 Effect of grain refining and Sr-modification interactions on the impact toughness of Al-Si-Mg cast alloys Mater. Des. 56 264–73
[46] Liu G L, Si N C, Sun S C and Wu Q F 2017 Effects of grain refining and modification on mechanical properties and microstructures of Al-7.5Si–4Cu cast alloy Trans. Nonferrous Met. Soc. China 24 946–53
[47] Kumar S, Sharma A and Di M 2017 Effect of mould temperature , grain re nement and modification on hot tearing test in Al-7Si-3Cu alloy Eng. Fail. Anal. 79 592–605
[48] Riestra M, Ghassemali E, Boganoff T and Seifeddine S 2017 Interactive effects of grain refinement, eutectic modification and solidification rate on tensile properties of Al-10Si alloy Mater. Sci. Eng. A 703 270–9
[49] Cui X L, Wu Y Y, Gao T and Liu X F 2014 Preparation of a novel Al-3B-5Sr master alloy and its modification and refinement performance on A356 alloy J. Alloys Compd. 615 906–11
[50] Rao A K P, Das K, Murty B S and Chakraborty M 2009 Al-Ti-C-Sr master alloy–A melt inoculant for simultaneous grain refinement and modification of hypoeutectic Al-Si alloys J. Alloys Compd. 480 147–9
[54] Zhao H L, Wang J, Song Y and Guan S K 2010 Microstructure and synthesis mechanism of Al-Ti-C-Sr master alloy *Trans. Nonferrous Met. Soc. China (English Ed.)* 20 751–6
[55] Li J G, Zhang B Q, Wang L, Yang W Y, Ma H T, Lu L and Dahle A K 2006 Effects of combined additions of Sr and AlTiB grain refiners in hypoeutectic Al-Si foundry alloys *Mater. Sci. Eng. A* 328 169–76
[56] Li J G, Zhang B Q, Wang L, Yang W Y and Ma H T 2002 Combined effect and its mechanism of Al-3 wt%Ti-4 wt%B and Al-10 wt%Sr master alloy on microstructures of Al-Si-Cu alloy *Mater. Sci. Eng. A* 328 169–76
[57] Birol Y 2017 Melt treatment of Al-Si foundry alloys with B and Sr additions *J. Mater. Sci.* 52 6856–65
[58] Muangnoy P and Eidhed K 2022 Fading mechanism on grain refinement and modification with Al-B-Sr master alloys in an aluminium-silicon cast alloy *Arch. Metall. Mater.* 67 1137–44
[59] Tenevedjiev N and Thomas-Sadowski S 1995 *Microstructures and Thermal Analysis of Strontium-treated Aluminum-silicon Alloys* (Illinois: American Foundrymen’s Society)
[60] Wang X 2017 Boride phase formation in the production of Al-B master alloys *J. Alloys Compd.* 722 302–6
[61] Chen R, Shi Y F, Xu Q Y and Liu B C 2014 Effect of cooling rate on solidification parameters and microstructure of Al-7Si-0.3Mg-0.15Fe alloy *Trans. Nonferrous Met. Soc. China* 24 1645–52
[62] Dang B, Cong L C, Liu F, Zhuo L Y and Bing L Y 2016 Effect of as-solidified microstructure on subsequent solution-treatment process for A356 Al alloy *Trans. Nonferrous Met. Soc. China* 26 634–42
[63] Porter D A and Easterling K E 2009 *Phase Transformations in Metals and Alloys (Revised Reprint)* (Boca Raton, FL: CRC Press)
[64] Lu S Z and Hellawell A 1987 The mechanism of silicon modification in aluminum-silicon alloys: Impurity induced twinning *Metall. Trans. A* 18 1721–33