EFFECT OF HEAT TREATMENT ON CONTROLLING THE MORPHOLOGY OF AlFeSi PHASE IN A380 ALLOY

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Abstract

In most aluminum–silicon-based die casting alloys, iron is considered one of the most harmful elements. The presence of iron in Al–Si-based alloys leads to the precipitation of a series of iron-containing intermetallic phases. Of these, the β-AlFeSi phase is the most detrimental to the toughness of Al–Si-based alloys. Reducing the formation of the β-AlFeSi phase has the potential of significantly improving the ductility of die casting alloys. The purpose of this work is to show how combined use of high-temperature and short-time heat treatment can be an effective way of controlling the morphology and fraction of β-AlFeSi phase in A380 alloy. Experimental results indicate that if heat treatment temperature goes up to 500 °C (932 °F), the higher temperature can reduce formation of β-AlFeSi with shorter heat treatment time. Evidence of this reduction is proved in optical and scanning electron microscopy images showing both the decomposition of β-AlFeSi and the transformation of β to α-AlFeSi.

Keywords: *A380 alloys, heat treatment, Al–Fe–Si phase*

Introduction

Aluminum–Silicon (Al–Si) alloys are the most widely used aluminum casting alloys. Iron is considered the most detrimental element in an Al–Si die casting alloy because its introduction can form many AlFeSi platelet intermetallic phases and lead to unacceptable mechanical properties, especially deterioration in ductility. Thus, controlling the fraction and morphology of the AlFeSi phase is an important way to ensure that the ductility of Al–Si die casting alloys is conserved.

Among all the Fe-rich phases, β-AlFeSi is thought to be the most deleterious. β-AlFeSi has irregular platelet or needle-like morphology, is hard and brittle, and generally leads to stress concentration at the needle point; thus, the β-AlFeSi phase severely decreases the toughness of Al–Si die casting alloys. Comparably, the α-phase has compact morphologies such as Chinese script, starlike, or polygon, which are less harmful than the β-AlFeSi phase. As a result, much effort has been conducted to reduce the amount of β-AlFeSi, to modify the morphology of β-AlFeSi, or to change β-AlFeSi to α-AlFeSi.[1–3]

Several methods have been developed to reduce the harmful effect of β-AlFeSi on the ductility of alloys. These methods include (1) composition control,[4,5] (2) fast cooling during solidification,[3] and (3) heat treatment.[6,7] It has been found that the amount of the β-AlFeSi phase can be reduced by reducing the iron content in the alloy. Low-iron alloys, such as Silafont-36 and Mercalloys, have been developed and applied for large-scale structural castings.[4] The addition of alloying elements, such as Mn, Cr, Ca, Be, Sr, Mg, and Co, has also been proven to be effective in reducing the amount or changing the morphology of the β-AlFeSi phase, while the introduction of some intermetallics and sludge can impair mechanical properties and castability of the alloy.[3] While increasing the cooling rate during solidification changes the morphology of the β phase, industrial application of this practice is limited due to the process production conditions and equipment.

Solution heat treatment tends to break up β phase needles and does not further introduce any additional sludge and intermetallics. However, this method has limited application as it causes surface blistering or dimensional instability of die casting parts.[6,7] The only way to solve the problem is to use a high temperature and a short heat treatment time. Lumley[8] claimed that 495 °C (923 °F)–505 °C (941 °F) short-time (<1 h) heat treatment can avoid blistering while increasing ultimate tensile strength (UTS) by 20 % for A380 alloy. The optimum solution treatment temperature for A1–6Si–3.5Cu–0.3Mg–1Fe alloys is found to be between 515 °C (959 °F) and 520 °C (968 °F).[9] While there is no systematical study on the AlFeSi phase evolution in A380 alloy with heat treatment, this paper examines the effect of solution time and temperature on the morphology and fraction change in the AlFeSi phase in the A380 alloy.

Experiment

The material used in this research was a commercial Alcoa aluminum alloy A380. It is a hypoeutectic alloy, having a relative low liquidus (593 °C) [1099 °F] and solidus (527 °C) [981 °F] temperature. The composition of the alloy is presented in Table 1.

The experiment details are shown in Table 2.

The as-cast samples were sectioned, grinded, and polished carefully. The polished samples were etched using a solution of 0.5 % hydrofluoric acid in distilled water. Optical images were taken using a Leica DM LM/P 11888500 optical microscope. Scanning electron microscopy work was conducted by either a Hitachi S-4800 Field Emission SEM or a FEI Philips XL-40 SEM. The average size and fraction of α-AlFeSi and β-AlFeSi are calculated from 10 optical images taken from different positions of a sample with the ImageJ software.

Results and Discussion

Influence of Solution Temperature

From Figure 1, with an increase in solution temperatures, the fraction and morphology of AlFeSi phases change significantly. For the 450 °C (842 °F) and 500 °C (932 °F) heat treatment samples, there is no obvious AlFeSi phase change, and the β-AlFeSi phase predominates (Figure 1a, b). However, if the temperature rises to 515 °C (959 °F), β-AlFeSi phase is dissolved and the fraction and average length of β-AlFeSi are reduced (Figure 1c). Finally, if the temperature goes up to 525 °C, (977 °F) α-AlFeSi predominates as evidenced by the fraction and size of the α-AlFeSi phase increases (Figure 1d).

Table 1. Composition of A380 Alloy

Element	Si	Fe	Cu	Mn	Mg	Ni	Zn	Ti	Al
wt%	9.0	1.0	3.5	0.4	0.2	0.3	0.35	0.08	Bal.

Table 2. Experimental Conditions for Heat Treatment

No	Solution temperature (°C)	Solution time (h)
1	450	0.5
2	450	1
3	450	2
4	450	4
5	450	8
6	450	24
7	500	0.5
8	500	1
9	500	2
10	500	4
11	500	8
12	500	24
13	515	0.5
14	515	1
15	515	2
16	515	4
17	525	0.5
18	525	1
19	525	2
20	525	4

Table 3 shows that with increasing solution temperatures, the size and fraction of β-AlFeSi are decreased and the fraction of α-AlFeSi is increased. For the 450 °C (842 °F) sample, no β-AlFeSi morphology change is observed. However, once the temperature goes up to 500 °C (932 °F), decomposition of β-AlFeSi starts, suggesting that 500 °C (932 °F) is the lowest temperature at which decomposition of the β-AlFeSi phase can occur.

Influence of Solution Time

The heat treatment time at a given solution temperature has a great effect on the morphology of AlFeSi intermetallics. At 450 °C (842 °F) (Figure 2), even after 24 h of heat treatment, there is no obvious change in the AlFeSi phase (Figure 2a–c). The following parameters were selected in the study: β-length, β-width, aspect ratio, β-fraction, and α-fraction. The parameters of α and β-AlFeSi phase do not show any change (Table 4). It can therefore be said that no

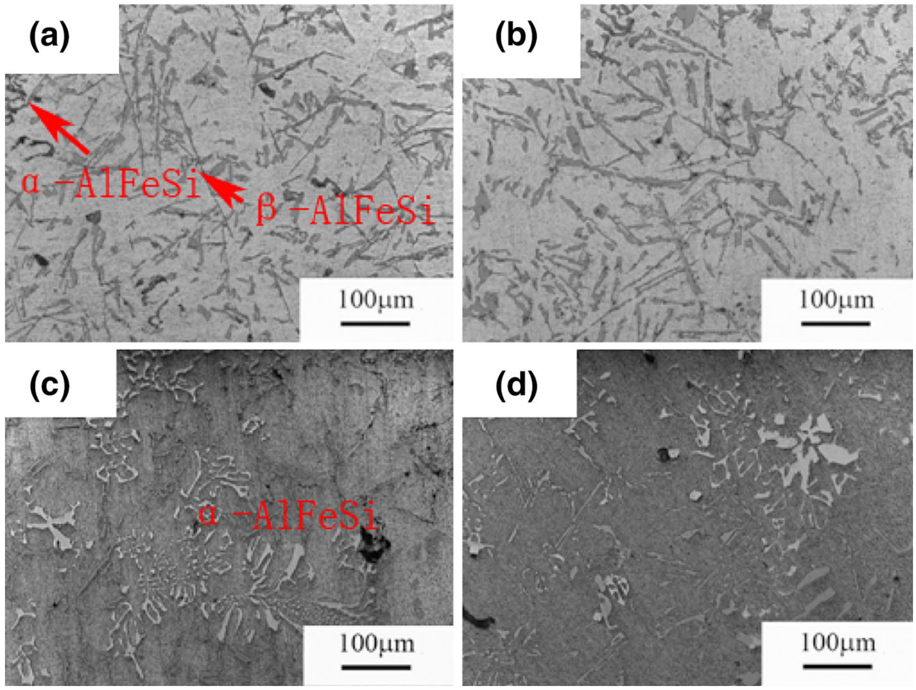

Figure 1. Optical sample of different heat treatment temperatures for 4 h. (a) 450 °C; (b)500 °C; (c)515 °C; (d)525 °C.

Table 3. Parameters of α-AlFeSi and β-AlFeSi Morphology of 4-h Heat Treatment Samples at Different Heat Treatment Temperatures

Heat treatment temperatures	β-length (μm)	β-width (μm)	Aspect ratio	β-fraction(%)	α-fraction(%)
450	315.03	10.32	30.58	1.35	2.30
500	300.15	9.11	32.96	0.98	2.43
515	65.13	3.21	20.31	0.31	3.56
525	–	–	–	–	4.13

β-AlFeSi phase transfers to α phase below 450 °C (842 °F) regardless of the duration of heat treatment.

If the treatment is at 500 °C (932 °F), there is no obvious morphology change for the 0.5-h and 2-h samples (Figure 3a, b). But once heat treatment duration reaches 8 h, the size of β-AlFeSi begins to decrease (Figure 3c). For the 24-h heat treatment, no β-AlFeSi is detected, suggesting that the entire β phase has changed to α-AlFeSi phase (Figure 3d). Table 4 shows that after an 8-h treatment, the size and fraction of β-AlFeSi begin to decrease (Table 5).

For the sample with a 515 °C (959 °F) 1-h heat treatment, the size of the β-AlFeSi is reduced significantly, (Figure 4b). After 4-h heat treatment, nearly all the β-AlFeSi was decomposed (Figure 4d), as can be seen by the β-fraction reduction in Table 6.

In the case of the 525 °C (977 °F) sample with only 0.5 h of heat treatment, β-AlFeSi is reduced to 1.19 % (Figure 5a). If the heat treatment time is longer, all β-AlFeSi transfers to α phase (Figure 5b–d; Table 7).

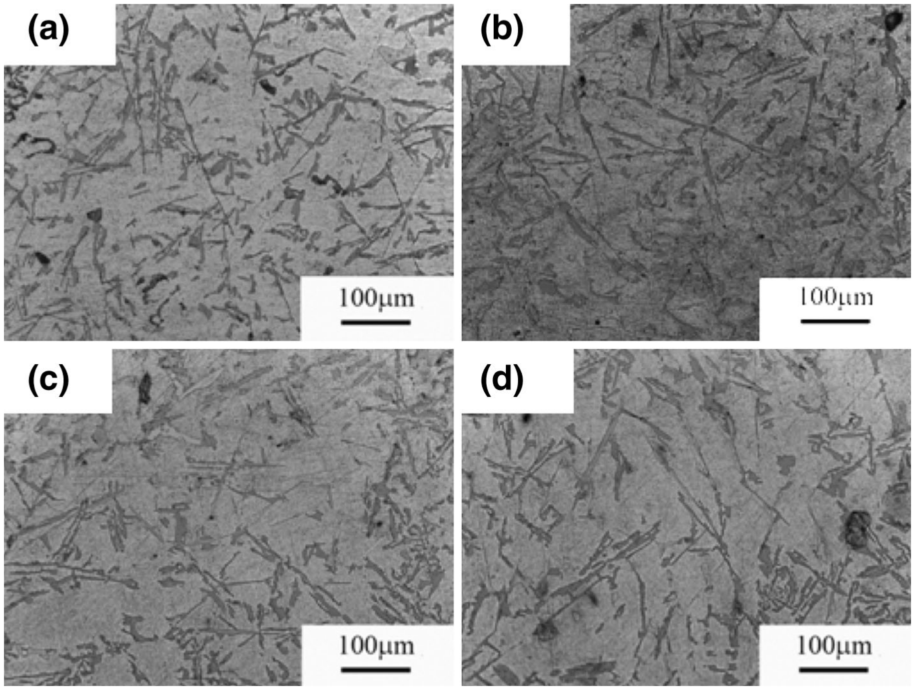

Figure 2. Optical sample of different heat treatment time at 450 °C. (a) 0.5 h; (b) 2 h; (c) 8 h; (d) 24 h.

Table 4. Parameters of α-AlFeSi and β-AlFeSi Morphology of 450 °C Heat Treatment Samples with Different Heat Treatment Time

Heat treatment time	β-length (μm)	β-width (μm)	Aspect ratio	β-fraction(%)	α-fraction(%)
0.5 h	254.87	9.51	26.79	1.30	2.32
2 h	265.44	9.91	26.76	1.42	2.26
8 h	255.69	9.34	27.34	1.35	2.31
24 h	253.98	9.18	27.64	1.46	2.19

Lastly, heat treatment duration at the high temperatures used can affect the tensile properties of A380 alloy. These are shown in Table 8.

Discussion

Although the presence of the needle-shape β-AlFeSi phase in the Al–Si alloy has the potential to severely reduce the mechanical properties of alloys, the element alloying method has been introduced to ensure high-quality castings. However, with the benefit of the element alloying methods such as transferring β-AlFeSi to α-AlFeSi, some detrimental effects, especially introducing other intermetallics, will also adversely affect the properties of alloys.

Heat treatment of casting alloys is another effective method to minimize the detrimental effect of AlFeSi intermetallics. However, this method is not widely used in die casting Al–Si alloys for the following reasons: (1) During the die casting process, air will be absorbed and trapped in the solidified aluminum alloy. If heat treatment is needed, the entrapped gas will expand and blisters will form. (2) The diffusion rate of Fe in Al is very low. Because the diffusion coefficient of Fe in Al is only 4×10^{-11} cm^2/s, this means that the heat treatment temperature for solution of AlFeSi phase is comparatively higher than the normal solution temperature. (3) Heat treatment can affect the formation of other phases. For example, coarsening of the Si phase can result. In view of the above reasons, the high-temperature short-time heat treatment method was selected in this

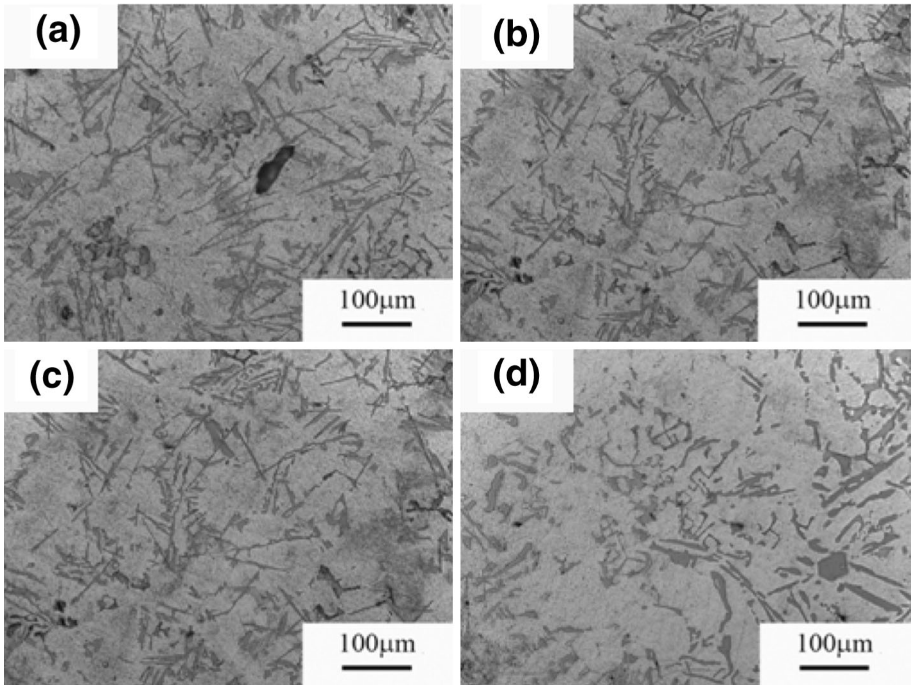

Figure 3. Optical sample of different heat treatment time at 500 °C. (a) 0.5 h; (b)2 h; (c)8 h; (d)24 h.

Table 5. Parameters of α-AlFeSi and β-AlFeSi Morphology of 500 °C Heat Treatment Samples with Different Heat Treatment Time

Heat treatment time	β-length (μm)	β-width (μm)	Aspect ratio	β-fraction(%)	α-fraction(%)
0.5 h	260.24	10.10	26.02	1.29	2.32
2 h	258.04	10.65	24.23	1.20	2.31
8 h	165.21	7.65	21.56	0.71	2.91
24 h	–	–	–	–	3.56

study. In this way, it is possible to have both refined Fe-containing intermetallic phases and blistering can be avoided.

Narayanan et al.[10] adopted the nonequilibrium heat treatment method. The treatment temperature of this method is higher than the one of the regular solution. This results in a reduction in the length of the β phase because of the dissolution effect. Meanwhile, Yin[11] conducted heat treatment on A319 alloys and considered that the disintegrity in β-AlFeSi is the cause of dissolution. Both individuals mentioned that the α-AlFeSi phase is not influenced by heat treatment.

The platelet β-AlFeSi phase is relatively hazardous due to its role in the formation of stress concentrations and the separation of the matrix. If the needle-shape β-AlFeSi phase can be dissolved, the detrimental effect can be reduced. From that point on, the higher the heat treatment temperature, the shorter the iron phase, and the better are one's chances to improve the mechanical properties of the alloy. It was found that during heat treatment, and with the use of higher heat treatment temperatures, the size of silicon particles will increase. This is called coarsening. Compared to Figure 3a, d, the average length and width of silicon flakes increase from 15 and 5 μm to 40 and 10 μm, respectively, with the time of the heat treatment increasing

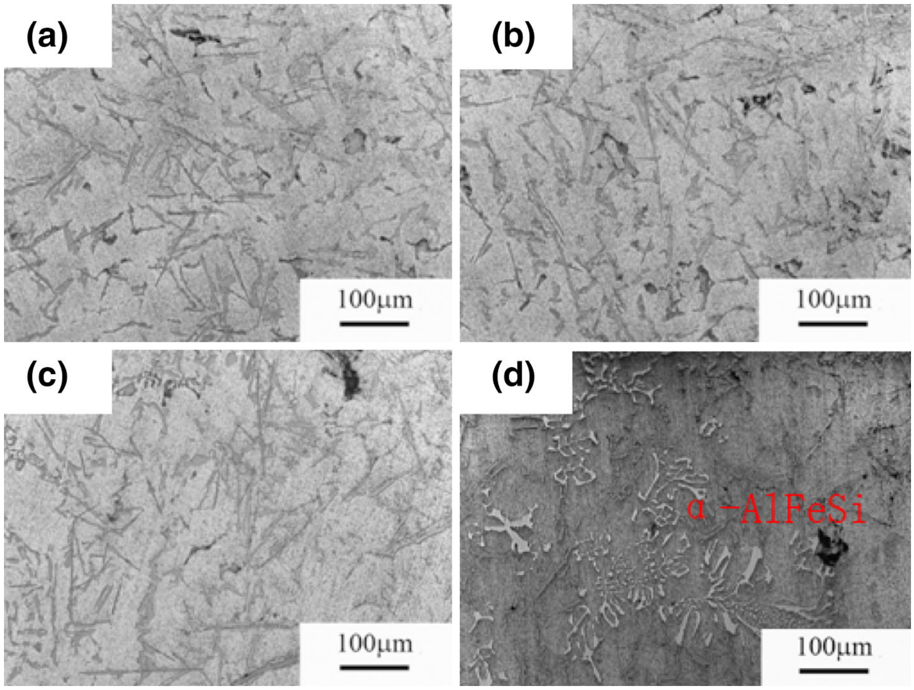

Figure 4. Optical sample of different heat treatment time at 515 °C. (a) 0.5 h; (b)1 h; (c)2 h; (d)4 h.

Table 6. Parameters of α-AlFeSi and β-AlFeSi Morphology of 515 °C Heat Treatment Samples with Different Heat Treatment Time

Heat treatment time	β-length (μm)	β-width (μm)	Aspect ratio	β-fraction(%)	α-fraction(%)
0.5 h	267.12	8.92	26.79	1.32	2.24
1 h	261.34	9.13	28.62	1.09	2.46
2 h	156.72	5.35	27.34	0.52	2.94
4 h	65.13	3.21	20.31	0.31	3.26

from 0.5 to 24 h. During the heat treatment process, it is difficult to keep the temperature constant. The fluctuation of temperature can result in the melting of the grain boundary if the temperature is too high, leading to a reduction in the strength and ductility of the alloy. Therefore, in practical heat treatment applications, the temperature should not be too high. From the experimental results for the 525 °C (977 °F) heat treatment case, 1-h treatment time is enough to reduce all visible β-AlFeSi. However, to avoid the problems mentioned above, one should maintain the heat treatment temperature around 515 °C (959 °F).

Changes in tensile properties also support the findings described above. For the 450 °C (842 °F) sample, the elongation rate remains almost static for the 0.5-h and 24-h heat treatment. For the 500 °C (932 °F) sample, the elongation rate increases drastically to 3.16 % for the 24-h heat treatment sample. As for the 515 °C (959 °F) condition, only a 2-h heat treatment is needed to reach the highest UTS (259.86 MPa) and elongation (3.21 %). Heat treatment at 525 °C (977 °F) is too high as both UTS and elongation decrease.

Thus, it is proven that the β-AlFeSi phase can be dissolved during heat treatment. The higher the holding temperature, the greater the degree of iron phases shortened, which is due to the more favorable conditions of higher temperature dynamics. On the other hand, as the fraction of α-AlFeSi decreases, the fraction of β-AlFeSi is also decreased. This cannot be fully explained by the theory of dissolving. The only explanation that can be offered is that β-AlFeSi transfers to α-AlFeSi. Figure 6 shows that heat treatment

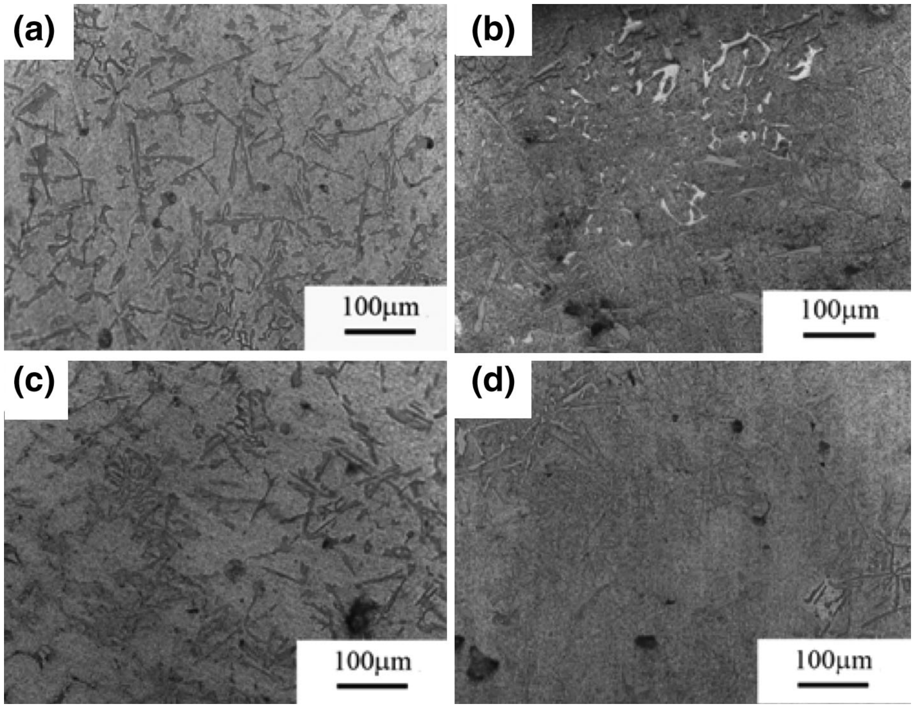

Figure 5. Optical sample of different heat treatment time at 525 °C. (a) 0.5 h; (b)1 h; (c)2 h; (d)4 h.

Table 7. Parameters of α-AlFeSi and β-AlFeSi Morphology of 525 °C Heat Treatment Samples with Different Heat Treatment Time

Heat treatment time	β-length (μm)	β-width (μm)	Aspect ratio	β-fraction(%)	α-fraction(%)
0.5 h	263.13	8.43	31.21	1.19	2.30
1 h	–	–	–	–	3.17
2 h	–	–	–	–	3.32
4 h	–	–	–	–	3.28

Table 8. Tensile Properties of A380 Alloy at Different Solution Treatment Conditions

Heat treatment	Average UTS (MPa)	Average elongation (%)
450 °C 0.5 h	251.33	1.14
450 °C 24 h	253.05	1.18
500 °C 0.5 h	256.21	1.23
500 °C 24 h	261.76	3.16
515 °C 0.5 h	253.23	1.18
515 °C 4 h	259.86	3.21
525 °C 0.5 h	249.13	1.19
525 °C 4 h	245.61	1.67

can facilitate the trend transformation of β-AlFeSi to α-AlFeSi. Also dissolution of β-AlFeSi (Figure 7), as noted by Narayanan et al.[10] and Yin[11] was observed.

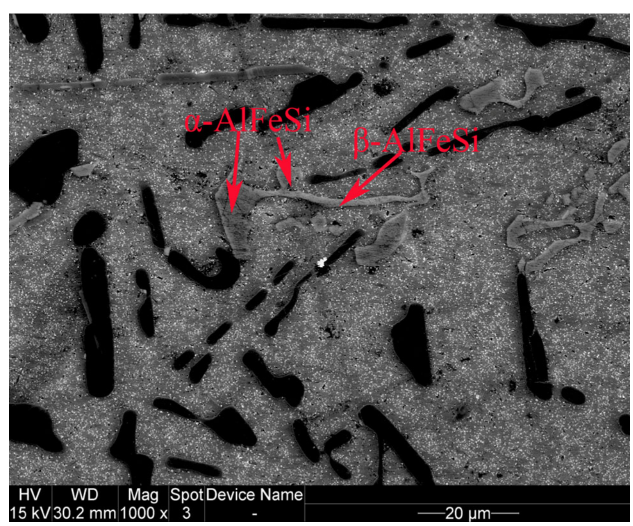

Figure 6. A380 sample heated at 515 °C for 2 h, β phase transferred to α phase.

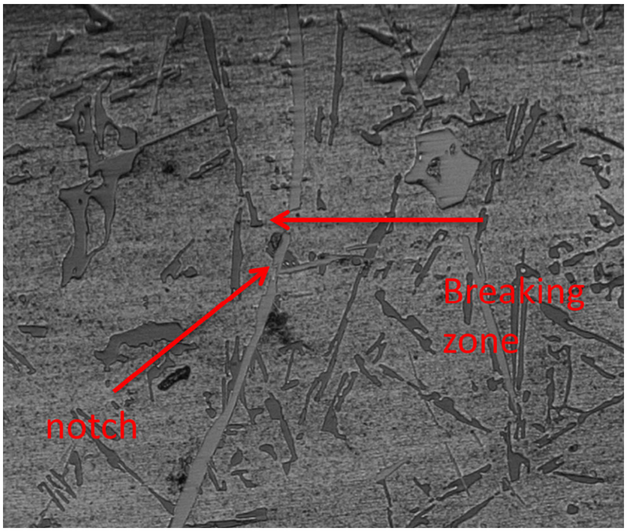

Figure 7. A380 sample heated at 515 °C for 2 h, β phase dissolved.

Conclusion

Based on the experimental findings in this study, heat treatment temperature and time affect the formation of β-AlFeSi phase in the A380 alloy. In summary, 450 °C (842 °F) is too low to diminish β-AlFeSi formation. If the heat treatment temperature is increased to 500 °C (932 °F), the higher temperature can reduce the β-AlFeSi with shorter heat treatment time. The reason is not only due to the decomposition of the β phase but also the transformation of β to α-AlFeSi. At 515 °C (959 °F), a 2-h heat treatment is sufficient to diminish β-AlFeSi formation for the A380 alloy.

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