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Effects of Be additions on microstructure, hardness and tensile properties of A380 aluminum alloy

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Abstract: The effects of beryllium (Be) on the microstructure, hardness and tensile properties of A380 aluminum alloy were investigated. The base and Be-containing A380 alloys were conventionally cast in a ductile iron mold. The microstructure evolution was investigated using SEM and optical microscope. The mechanical properties were assessed using tensile and hardness tests, finally the rapture surfaces of the used samples were studied to reveal the fracture mechanism in the presence of Be. The results revealed that the platelet β intermetallic phases were transformed into relatively harmless Chinese script Be−Fe phase and eutectic Si phases changed from flake-like particles into fine ones. The corresponding ultimate tensile strength (UTS) and elongation values increased from 270 MPa to 295 MPa and 3.7% to 4.7%, respectively. Additionally, the hardness of A380 alloy decreased continuously with increasing Be content. While the fracture surfaces of the unmodified A380 alloy tensile samples showed a clear brittle fracture nature, while finer dimple and fewer brittle cleavage surfaces were seen in the alloys with Be addition. Moreover, in the presence of Be, due to the refined phases, there has been a decrease in the values of hardness.

Key words: Be addition; A380 aluminum alloy; hardness; tensile properties; fractography

1 Introduction

Al−Si alloys which are characterized by outstanding properties such as high specific strength, high corrosion resistance and low coefficient of thermal expansion are widely used in automobile and aerospace industries [1−3]. Furthermore, containing considerable Si content, these groups of alloys are considered to have excellent casting properties including higher fluidity, lower tendency to hot tearing and better air tightness. Thus, low-weight but high strength structures can be manufactured by these alloys. The refinement of eutectic silicon may lead to the substantial improvement in mechanical properties. Among the commercial Al–Si casting alloys, A380 aluminum alloy is the most commonly used for both cylinder heads and engine blocks due to the balance of properties that can be achieved using suitable heat treatments [4−6].

Iron is a common impurity element in Al−Si foundry alloys and can easily form intermetallic compounds (α-Fe and β-Fe) that can significantly affect the subsequent behavior of material properties [7]. However, the increase of Fe addition reduces the elongation capability of the samples to a marked extent, due to the presence of the needle β-Fe phase, which provides brittle behavior to the alloy [8].

Generally, in normal casting condition, Fe-containing phases grow coarse dendrites, and eutectic silicon particles exhibit coarse acicular needles. As a result, the tensile properties of the Al−Si cast alloys are remarkably weakened. Even though there is no known way to economically remove iron from aluminum, the chemical modification is regarded as an economical and effective modification method [9]. The addition of chemical elements in order to promote the formation of the α-phase instead of more detrimental β-phase (Al_5FeSi) is called iron neutralizing [10]. Co, Mo, Cr, Ni and Be are identified as popular iron neutralizing elements which reduce β-phase and promote α-phase ($Al_{15}Fe_3Si_2$) formation. WANG and XIONG [11] investigated the effects of Be addition on Al−7Si−

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0.4Mg−0.2Ti−*x*Fe−*x*Be cast alloy. The results show that Be addition changes the shape of iron-rich compound from needle or plate shapes to Chinese scripts or polygons and the iron-rich compound (named Be−Fe) is aggregated when the composition of Fe is high. Some studies have reported that in base alloy (Al−Si), the β-phase is mostly seen in the interdendritic regions as needles and plates, whereas with trace Be addition, a new Be−Fe phase with an altered morphology (Chinese scripts, polygons and hexagons) is observed inside the α-phase dendrites [12−14]. Recently, FARAHANY et al [15] and SUN et al [16] have observed that strontium (Sr) in very small amounts modifies the eutectic silicon morphology from a coarser, flake-like form to a fine fibrous one. The change in the morphology of Si, in turn, enhances the tensile properties, particularly ductility. According to HAN et al [17], at solution temperature of 520 °C, incipient melting of $Al_5Mg_8Cu_2Si_6$ phase and undissolved block-like Al_2Cu takes place. At the same time, Si particles become rounder. Therefore, the tensile properties of Mg-containing alloys can be controlled by combined effects of dissolution of Al_2Cu, incipient melting of $Al_5Mg_8Cu_2Si_6$ phase and Al_2Cu phase, as well as the Si particle characteristics.

The morphology and size of β-phase and Al−Si eutectic have a significant effect on the tensile properties of the Al−Si cast alloys. The tensile properties of the Al−Si cast alloys, especially the ductility, are mainly controlled by the dendrites cell size of β-phase. Moreover, the eutectic silicon particles also play an important role in the fracture behavior and the tensile ductility of Al−Si cast alloys [18]. KARAMOUZ et al [19] investigated the influence of Li addition on the structure as well as the ultimate tensile strength of A380 castings. It was reported that with the addition of 0.6% Li (mass fraction), the ultimate tensile strength (UTS) and elongation values increased from 274 to 300 MPa and 3.8% to 6%, respectively. Also, they expressed that Li decreased the Brinell hardness of the alloys from BHN 87 to BHN 74.

This work was undertaken to investigate the effects of Be content on the microstructure characteristic, tensile and hardness properties and fracture behavior of A380 aluminum alloy.

2 Experimental

The chemical composition of base A380 aluminum alloy (Al−8.5%Si−3.5%Cu−1%Fe) studied in this work is given in Table 1. Melting procedure of the alloy was carried out in an electrical resistance furnace using a SiC crucible. Industrially pure elemental Al (99.87%), Si (99.99%), Cu (99.9%) and Al−8%Fe master alloy were used as starting materials to prepare the ingots. Then, the chopped ingots were remelted with and without addition of Be at 750 °C. Controlled amount of Be in the form of Al−5%Be master alloy was added to the melt in order to produce alloys with 0, 0.03%, 0.05% and 0.1% Be. The melt was degassed using C_2Cl_6-containing tablets submerged into the melt. A permanent ductile iron mold which was designed according to ASTM: B108−03a standard was used in this work (Fig. 1(a)). The sections of the samples were polished and etched with Keller's reagent. Quantitative data on the microstructure were determined using an optical microscope equipped with an image analysis system (Clemex Vision Pro. Ver 3.5.025). Also, the microstructural analysis was carried out using scanning electron microscopy (SEM). Phase identification was also performed by X-ray diffraction method (Philips).

Table 1 Chemical composition of A380 aluminum alloy (mass fraction, %)

Si	Cu	Fe	Al
8.5	3.5	1	Bal.

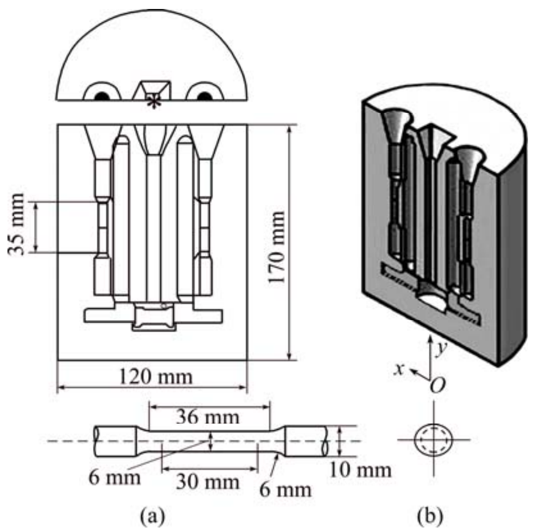

Fig. 1 Cast iron mould used for casting (a) and ASTM B557−10 sub-size specimens used for tensile tests (b)

Tensile test bars were machined according to ASTM: B557−10 sub-size specimens as shown in (Fig. 1(b)) and the test was carried out on a computer controlled Santam tension machine at a constant cross-head displacement rate of 1 mm/min at room temperature. At least four tensile specimens of each alloy were tested and the reported data were average values of these tests. The fracture surfaces of tensile test specimens were also examined with SEM. Hardness tests were carried out according to ASTM: E10 standard using an Eseway tester (Brinell hardness: 30 kg load and 2.5 mm indenter). The samples were firstly surface finished and at least five measurements were taken randomly in each sample and averaged to obtain the hardness value of the specimen.

3 Results and discussion

3.1 Microstructure characterization

Generally, two types of Al−Fe−Si intermetallic compounds were found in the alloy structure with (0.1% Be) and without Be element, which were identified to be Be−Fe (Al_8Fe_2SiBe) and β (Al_5FeSi) by X-ray diffraction, respectively, as shown in Fig. 2. Figure 3 demonstrates the microstructures of A380 aluminum alloy with and without Be element. From previous investigations [21], the microstructure of unmodified A380 alloy consists of primary aluminum phase, eutectic Si particles and β-phase platelets. In the as-cast condition (Fig. 3(a)) [19], the eutectic Si particles and the iron-rich intermetallic compounds are present in the form of coarse acicular plates and coarse β-phase platelets with an intersected and branched structure, respectively. It can be observed from Figs. 3(b)−(d) that the addition of Be changes the morphology of Si particles and β-phase from an acicular and coarse plates form to a fibrous and more harmless structure such as Chinese script, respectively. It is reported that the chemical formula of Be−Fe is near Al_8Fe_2SiBe [12]. It should be noted that the optimum content of Be by which the refinement is performed completely is about 0.05%. With further increase of the content of Be (more than 0.05%), coarser and rougher Be−Fe particles are undesirably formed (Fig. 3(d)). Microstructure modification in the presence of Be can also be noticed in the SEM images of the deep-etched samples (Fig. 4). Despite with more than 0.05% Be, the harmful β-phase is entirely replaced with Be−Fe phase, in the presence of 0.1% Be, this phase becomes coarser and rougher which is not desired.

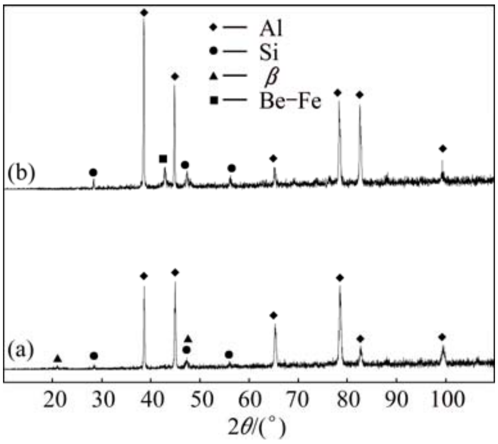

Fig. 2 XRD patterns of alloys without Be addition (a) and with 0.1% Be (b)

Figure 5 depicts the quantitative metallography results of microstructure features including the average length and the aspect ratio of β-phase and the eutectic silicon particles with different Be additions. It is observed that with addition of 0.03% Be, the average

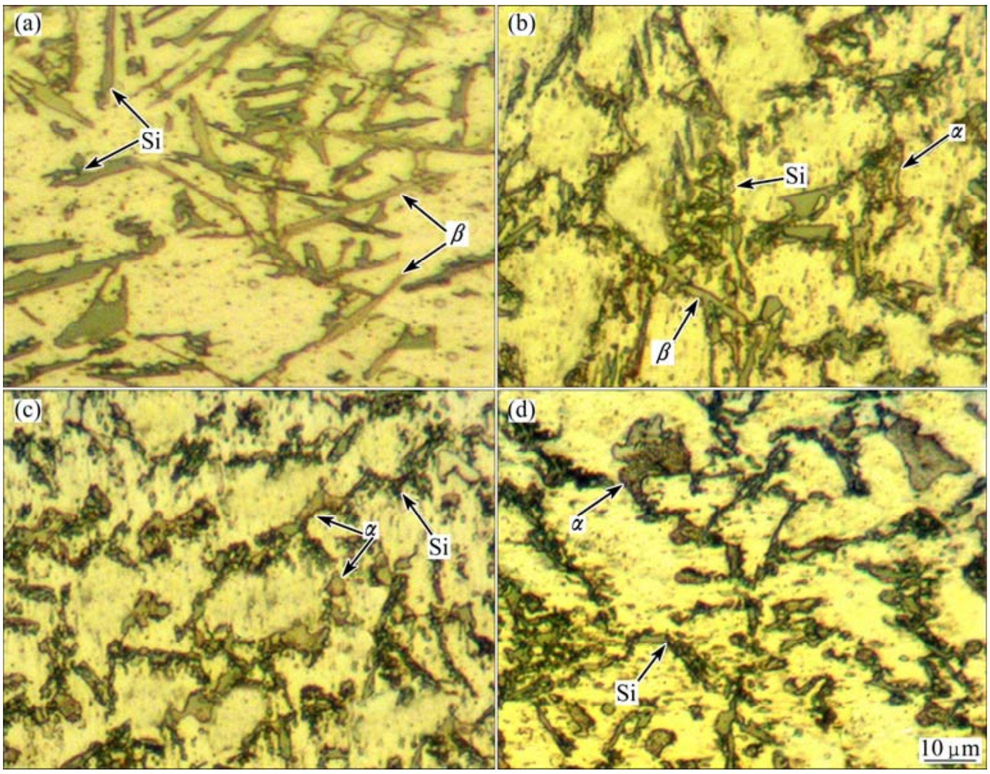

Fig. 3 Optical micrographs of A380 aluminum alloys showing effect of Be addition: (a) Be-free [20]; (b) 0.03% Be; (c) 0.05% Be; (d) 0.1% Be

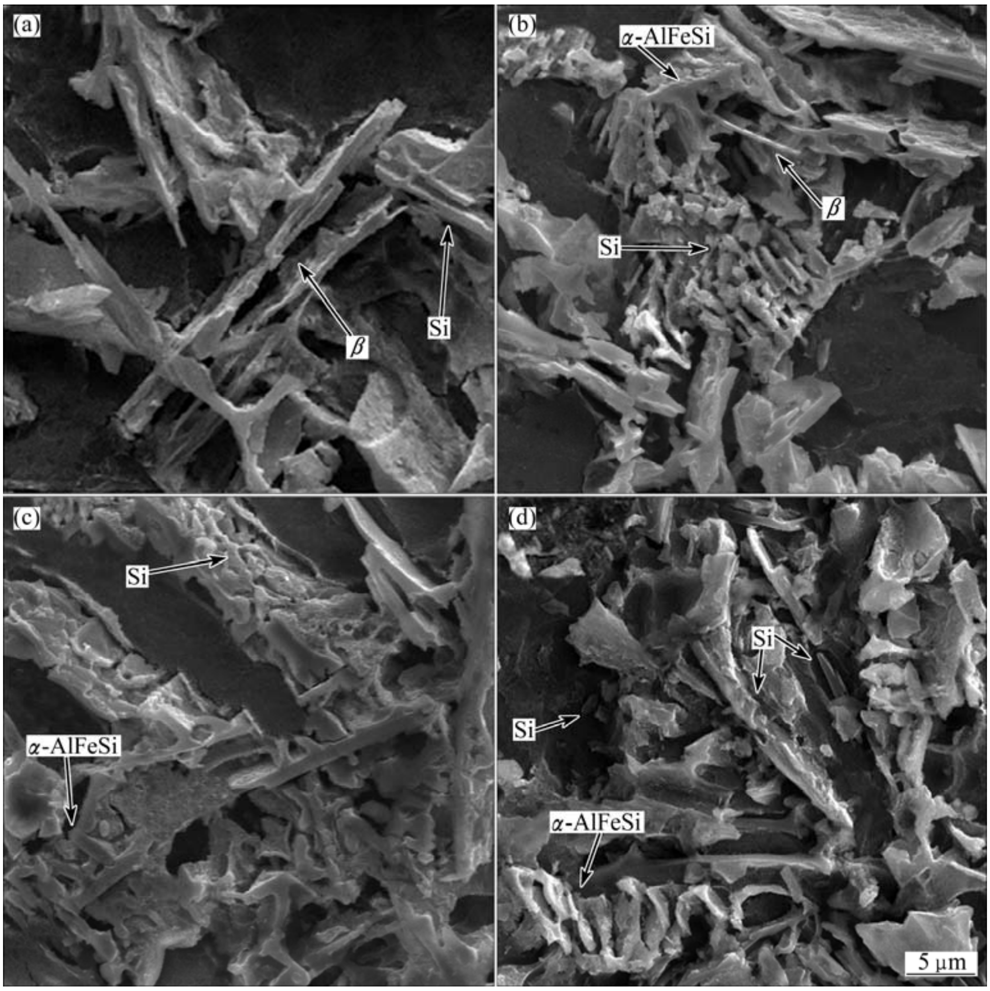

Fig. 4 SEM images showing effect of Be addition on microstructure of A380 aluminum alloys: (a) Be-free [20]; (b) 0.03% Be; (c) 0.05%Be; (d) 0.1%Be

lengths of the β-phase and eutectic Si particles decrease from 19.1 to 8.3 μm and 22.3 to 7.3 μm, respectively. Figure 5 also demonstrates that in the presence of 0.03% Be, the aspect ratio of the β-phase and the eutectic Si improves from 8.7 to 2.8 and 9.3 to 3.2, respectively. Additionally, with 0.05% of Be while phase β completely transforms to the less harmful Be−Fe phase, the average length and the aspect ratio of silicon particles reach 5 μm and 2, respectively .

Thus, it is clear that refinement of the flake-like eutectic Si particles and the platelet β intermetallic can be achieved by Be addition. SREEJA KUMARI et al [22] have reported that the nucleation temperature of Be–Fe phase is higher than that of β platelet phase. As a result, the Be−Fe phase consumes existing iron in the melt and the amount of the free iron available to precipitate in the form of β-phase either diminishes or entirely vanishes (with 0.05% Be, β-Fe phase was removed in the alloy). Also, the needle and plate shapes of β-phases are due to their monoclinic crystal structure, and more symmetry crystal structure (orthorhombic) of Be−Fe phase leads to the formation of the Chinese scripts and polygons shape [12]. These were supported from the microstructural observation of the replacement of platelet-phases by Chinese script phases.

In the unmodified alloy, after crystallization of the α(Al) phase, the β-phase along with the eutectic Si starts to crystallize by the ternary eutectic reaction (the α(Al), Si and β-phases are included in the eutectic phase) while in the modified alloy, Be−Fe intermetallic phase is formed at a temperature higher than that of eutectic reaction [22]. As a result, the Be−Fe particles may act as the nuclei for the eutectic Si during solidification. Increasing nucleation sites for Si changes the eutectic nucleation mode from acicular to fibrous structure.

3.2 Hardness

The results of hardness tests are shown in Fig. 6. It can be seen that the initial hardness of the unmodified alloy is BHN 87 and decreases to BHN 72 after adding 0.1% Be. The results show that the hardness of the alloys decreases with increasing Be content in the alloy. This

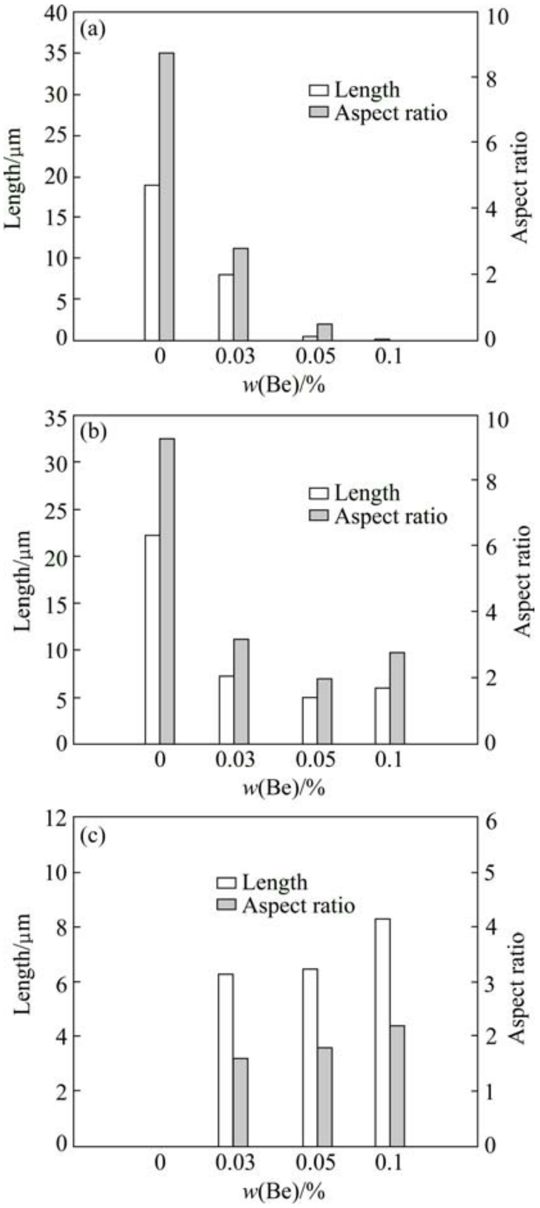

Fig. 5 Effects of Be addition on length and aspect ratio of eutectic Si, Be−Fe and β phases in A380 aluminum alloys: (a) β phase; (b) Eutectic; (c) Be−Fe phase

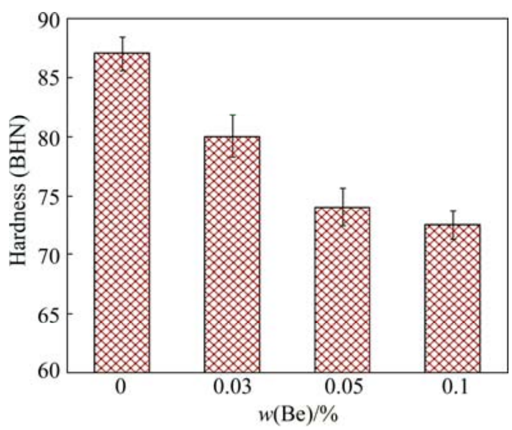

Fig. 6 Hardness of A380 type aluminum alloys as function of Be content

may be ascribed to the change of morphology and distribution of the iron-bearing phase in A380 alloy with the addition of Be. Hardnesses of materials corresponds to hardness and distribution of existing phases in the material structure. Be−Fe compound is softer than β phase and this point results in hardness decreasing of the modified alloy.

3.3 Tensile properties

The average ultimate tensile strength (UTS) and elongation (EL) values of the free-Be and Be-containing alloys are illustrated in Fig. 7. It has been observed that all added contents of Be increase the UTS and EL compared to those of the unmodified alloys. The highest improvement in UTS and EL has been observed in the addition of 0.05% Be to A380 alloy, which are 9% and 30% higher than those of the A380 aluminum alloy without Be, respectively. It can be attributed to the modifying and refining effects of Be on the flake-like eutectic Si and platelet β intermetallic phases which are the main crack nucleus in the alloy. The improvement of tensile properties of Be-containing alloy during the refinement process is contributed to the alternation of Fe-containing phases. Be addition changes the morphology of iron-rich compound from needle or plate shape to Chinese script or polygons. Further trace addition of Be results in the decrease of these two measurements. It should be noted that modified alloys with the highest Be content (0.1%) have lower UTS and EL in comparison with modified alloys with lower Be content (0.03% and 0.05%). The decline in the tensile properties due to the addition of 0.1% Be is attributed to the morphology of Be−Fe phase which has become rougher and coarser.

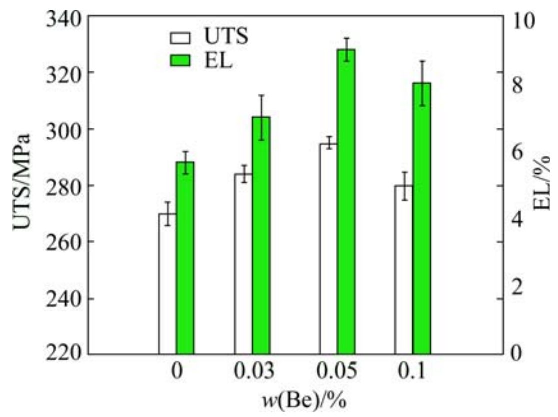

Fig. 7 Ultimate tensile strength and elongation as function of Be content

3.4 Fractography

Figure 8 demonstrates the SEM images of typical fractographs of the unmodified and Be-modified specimens. As it can be seen, the fracture surfaces of

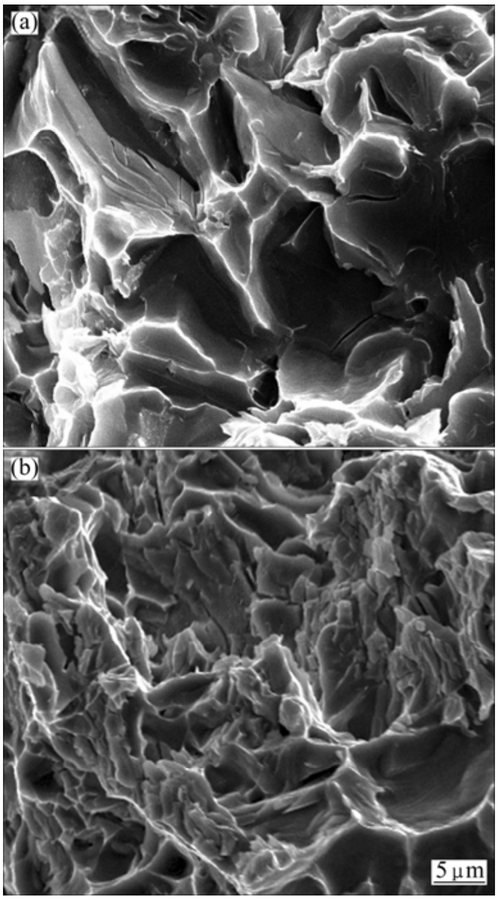

Fig. 8 Fracture surfaces of A380 type aluminum alloys: (a) Base alloy; (b) With 0.05% Be

the A380 base alloy show a clear brittle fracture nature and quasi-cleavage feature can be observed. It is pointed out that the addition of Be increases the number of dimples and the fracture surfaces of the modified A380 alloy with the addition of 0.05% Be display a mixed quasi-cleavage and dimple morphology. It can be evidently seen from this figure that many elongated eutectic Si particles and platelet β phase are present in the microstructure of the unmodified A380 alloy. The eutectic Si and β phase as brittle phases are prone to act as crack initiators and weaken the tensile properties [19]. For the base alloy, the elongated eutectic Si particles which are the main sources of stress concentration are prone to rupture compared to the modified alloy with near-spherical shaped eutectic Si particles [23]. In addition, it should be noted that the β-platelets tend to be much more prone to fracture and crack linkage than the Be−Fe Chinese script particles. From comparison of Fig. 8(b) with (a), the existence of fine and uniformly distributed equiaxed dimples in the modified alloy indicates that the ductility of the material is superior to that of the unmodified alloy. Moreover, in the Be-modified alloys, plastic deformation can be observed on the exterior surface of the tensile-failed specimens. This means that it undergoes a larger amount of plastic deformation prior to fracture.

4 Conclusions

1) In the presence of Be, harmful Fe-containing β-phases which start to crystallize during the solidification are replaced with less deteriorating Be−Fe phase and Be addition changes the morphology of iron-rich compounds to Chinese scripts and polygons.

2) Long eutectic Si particles which are prone to act as crack initiator are refined and transformed to finer particles with less detrimental effects by Be addition.

3) Adding 0.03%−0.1% Be to the A380 aluminum alloy decreases the hardness values of the alloys.

4) The elongation and UTS of Be-containing alloys are improved significantly. Among the Be-containing A380 aluminum alloys, specimens with addition of 0.05% Be exhibit the best tensile properties.

5) The fracture surfaces of unmodified alloys which consist of long eutectic Si particles show brittle and quasi-cleavage fracture. Addition of Be results in a dimple structure throughout the matrix. Increasing the Be content up to 0.05% results in the appearance of the fine and uniformly distributed equiaxed dimples, indicating the ductility of the material.

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References

[1] GRUZLESKI J E, CLOSSET B M. The treatment of liquid aluminum-silicon alloys [M]. Schaumberg: American Foundry Society, 1990.

[2] TSAI Y C, CHOU C Y, LEE S L, LIN C K, LIN J C, LIM S W. Effect of trace La addition on the microstructures and mechanical properties of A356 (Al−7Si−0.35Mg) aluminum alloys [J]. Journal of Alloys and Compounds, 2009, 487: 157−162.

[3] WANG Shou-ren, MA Ru, WANG Ying-zi, WANG Yong, YANG Li-ying. Growth mechanism of primary silicon in cast hypoeutectic Al−Si alloys [J]. Transactions of Nonferrous Metals Society of China, 2012, 22(6): 1264−1269.

[4] RODRÍGUEZ A, TORRES R, TALAMANTES-SILVA J, VELASCO E, VALTIERRA S, COLÁS R. Metallographic study of a cast Al–Si–Cu alloy by means of a novel etchant [J]. Materials Characterization, 2012, 68: 110−116.

[5] ROY N, SAMUEL A M, SAMUEL F H. Porosity formation in Al−9wt%Si−3%wtCu alloy systems: Metallographic observations [J]. Metallurgical and Materials Transactions A, 1996, 27: 415−429.

[6] BOILEAU J M, ALLISON J E. The effect of solidification time and heat treatment on the fatigue properties of a cast 319 aluminum alloy [J]. Metallurgical and Materials Transactions A, 2003, 34: 1807−1820.

[7] TAYLOR J A. The effect of iron in Al−Si casting alloys [C]//Proceedings of the 35th Australian Foundry Institute National

Conference. Adelaide: Australian Foundry Institute (AFI), 2004: 148−157.

[8] YILDIRIM M, ÖZYÜREK D. The effects of Mg amount on the microstructure and mechanical properties of Al−Si−Mg alloys [J]. Materials & Design, 2013, 51: 767−774.

[9] CHANG J Y, KIM G H, MOON I G, CHOI C S. Rare earth concentration in the primary Si crystal in rare earth added Al−21wt.%Si alloy [J]. Scripta Materialia, 1998, 39: 307−314.

[10] LIN Chong, WU Shu-sen, ZHONG Gu, WAN Li, AN Ping. Effect of ultrasonic vibration on Fe-containing intermetallic compounds of hypereutectic Al−Si alloys with high Fe content [J]. Transactions of Nonferrous Metals Society of China, 2013, 23(5): 1245−1252.

[11] WANG Y, XIONG Y. Effects of beryllium in Al−Si−Mg−Ti cast alloy [J]. Materials Science and Engineering A, 2000, 280: 124−127.

[12] MURALI S, RAMAN K S, MURTHY K S S. Morphological studies on β-$FeSiAl_5$ phase in Al−7Si−0.3Mg alloy with trace additions of Be, Mn, Cr, and Co [J]. Materials Characterization, 1994, 33: 99−112.

[13] LU L, NOGITA K, MCDONALD S D, DAHLE A K, LU L, DAHLE A K. Eutectic solidification and its role in casting porosity formation [J]. The Minerals, Metals & Materials Society, 2004, 56: 52−58.

[14] ALIPOUR M, EMAMY M, SEYED EBRAHIMI S H, AZARBARMAS M, KARAMOUZ M, RASSIZADEHGHANI J. Effects of pre-deformation and heat treatment conditions in the SIMA process on properties of an Al−Zn−Mg−Cu alloy modified by Al–8B grain refiner [J]. Materials Science and Engineering A, 2011, 528: 4482−4490.

[15] FARAHANY S, OURDJINI A, IDRIS M H, THAI L T. Effect of bismuth on microstructure of unmodified and Sr-modified Al−7Si−0.4 Mg alloys [J]. Transactions of Nonferrous Metals Society of China, 2011, 21(7): 1455−1464.

[16] SUN Shao-chun, YUAN Bo, LIU Man-ping. Effects of moulding sands and wall thickness on microstructure and mechanical properties of Sr-modified A356 aluminum casting alloy [J]. Transactions of Nonferrous Metals Society of China, 2012, 22(8): 1884−1890.

[17] HAN Y, SAMUEL A M, DOTY H W, VALTIERRA S, SAMUEL F H. Optimizing the tensile properties of Al−Si−Cu−Mg 319-type alloys: Role of solution heat treatment [J]. Materials & Design, 2014, 58: 426−438.

[18] CÁCERES C H, DAVIDSON C J, GRIFFITHS J R. The deformation and fracture behaviour of an Al−Si−Mg casting alloy [J]. Materials Science and Engineering A, 1995, 197: 171−179.

[19] KARAMOUZ M, AZARBARMAS M, EMAMY M, ALIPOUR M. Microstructure, hardness and tensile properties of A380 aluminum alloy with and without Li additions [J]. Materials Science and Engineering A, 2013, 582: 409−414.

[20] KARAMOUZ M, AZARBARMAS M, EMAMY M. On the conjoint influence of heat treatment and lithium content on microstructure and mechanical properties of A380 aluminum alloy [J]. Materials & Design, 2014, 59: 377−382.

[21] WANG J G, LU P, WANG H Y, LIU J F, JIANG Q C. Semisolid microstructure evolution of the predeformed AZ91D alloy during heat treatment [J]. Alloys and Compounds, 2005, 395: 108−112.

[22] SREEJA KUMARI S S, PILLAI R M, RAJAN T P D, PAI B C. Effects of individual and combined additions of Be, Mn, Ca and Sr on the solidification behaviour, structure and mechanical properties of Al−7Si−0.3Mg−0.8Fe alloy [J]. Materials Science and Engineering A, 2007, 460−461: 561−573.

[23] JIANG Wen-ming, FAN Zi-tian, DAI Yu-cheng, LI Chi. Effects of rare earth elements addition on microstructures, tensile properties and fractography of A357 alloy [J]. Materials Science and Engineering A, 2014, 597: 237−244.

添加铍对 A380 铝合金显微组织、硬度和拉伸性能的影响

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摘 要：研究铍对 A380 铝合金显微组织、硬度和拉伸性能的影响。采用传统的铁模铸造制备含铍和不含铍的 A380 合金。采用扫描电镜和光学显微镜研究合金的显微组织，采用拉伸试验和硬度测试研究合金的力学性能。研究样品的断口形貌，揭示添加铍对断裂机制的影响。结果表明，板状 β 中间相转变为相对无害的汉字状 Be−Fe 相，共晶 Si 相由片状相变为细小相。拉伸强度和伸长率分别从 207 MPa 和 3.7%增加至 295 MPa 和 4.7%。此外，随着铍含量的增加，A380 合金的硬度减小。不含铍的 A380 合金拉伸样品表现为脆性断裂，而含铍合金具有细小韧窝和少量脆性断面。此外，由于添加铍细化了析出相，合金的硬度降低。

关键词：铍添加；A380 铝合金；硬度；拉伸性能；断口形貌

(Edited by Yun-bin HE)