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Effect of Fe-rich intermetallics on the microstructure and mechanical properties of thixoformed A380 aluminum alloy

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ABSTRACT

The effect of α-Fe and β-Fe intermetallics concentration and morphology as well as α-Al morphology on the microstructure and mechanical properties of thixoformed and gravity cast A380 alloy was reported. The α-$Al_{15}Si_2(Fe,Mn)_3$ intermetallic particle was observed polyhedral morphology in thixoforming while it was observed Chinese script morphology in conventional gravity casting. The β-Al_5FeSi particle was solidified in the form of small plate in thixoforming while it was solidified in the form of needle-like in gravity casting at the grain boundaries of α-Al. The mechanical properties of the alloys have been enhanced by thixoforming compared with the conventional cast condition.

1. Introduction

Eutectic and near eutectic Al–Si alloys are widely used in casting industry due to superior abrasion and corrosion resistance, low thermal expansion coefficient and high strength/weight ratio [9,23]. There is an application area including components such as cylinder blocks, cylinder heads and pistons because of the features [3]. It is known that iron is the most common and harmful impurities in aluminum casting alloys. On the other hand, in pressure die casting alloys, iron is a desired element because it helps to prevent the transfer to mold of the molten alloys. Eutectic composition of Al–Si–Fe alloy is composed of about 0.8–1.1 wt% Fe. When iron is alloyed in these levels, the molten metal does not show tendency of dissolution with the steel mold. Thus, the higher iron content of the alloy reduces the solution potential for the components of the casting machine and dies [16]. Iron must be separated from molten aluminum. As it is not economical, some strategies have been developed to eliminate the negative effects of iron. The negative effects of iron are generally associated with the formation of iron-rich intermetallics during solidification [7,11]. Fe is mainly precipitated in the form of α-Fe ($Al_{15}Si_2(Fe,Mn)_3$) or β-Fe (Al_5FeSi) crystals. On the other hand, the intermetallic of iron-containing is composed in several forms. The morphology of α-Fe and β-Fe can be changed according to the solidification [18]. The iron-containing intermetallics in Al–Si alloys are both of the so-called α-phases form in Chinese script-like morphology and sometimes even as polyhedral crystals. Polyhedral version of α-Fe has a more compact and blocky form [21].

Mechanical properties of near-eutectic and eutectic Al–Si casting alloys do not only depend on the chemical composition. However, dendritic α-Al morphology and other intermetallics in the microstructures have important effects on the microstructural properties. The morphology and size of eutectic silicon, the morphology and composition of intermetallic compounds reveals a significant effect on mechanical properties. In this study, feed stock production with cooling slope casting and then semi-solid forming changed the morphology of intermetallics. Semi-solid forming process consists of basically two steps. First step is feed stock production of rosette-type microstructure and second step is the feed stock forming by pre-heating at appropriate semi-solid temperature. The process is called thixoforming. Semi-solid slurries exhibit rheological behaviors and this is called thixotropy [4–6,8]. The heating to semi-solid range accelerated the globalization of dendritic α-Al phase and also the production of uniformly distributed Fe-containing intermetallic compounds.

There are some theories about the relationship between microstructures and mechanical properties for aluminum alloys. Therefore, it is necessary to pay particular attention to examine mechanical properties considerably affected from microstructure. The aim of this search is to investigate the intermetallic compounds and mechanical properties obtained from thixoforming and conventional gravity casting.

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Table 1
Chemical composition of A380 alloy using in this work (%).

Si	Fe	Cu	Mn	Mo	Zn	Cr	Ni
8.163	0.972	2.987	0.170	0.144	0.737	0.0181	0.196

2. Experimental procedure

In this work, A380 aluminum alloy parts were produced by semi-solid forming process. In addition, A380 aluminum alloy parts were produced by means of conventional gravity casting. The chemical composition of the alloy was shown in Table 1. The ingots obtained from cooling slope casting were thixoformed at semi-solid temperature. The cooling slope casting was carried out at a pouring temperature of 615 °C. The slope of inclined plate was 60° and the length of inclined plate was 350 mm. The required semi-solid temperature for thixoforming is 567 °C according to DSC diagram. At this temperature the suitable solid fraction (f_s) value for thixoforming is about 0.4–0.5 solid fraction [6]. The ingots with the diameter of Ø 30 mm and a length of 40 mm were adapted to induction coil for reheating in semi-solid temperature. The ingot temperature was controlled with a K-type thermocouple during heating process. The ingots were held for 5 min at semi-solid temperature of 567 °C and then thixoformed by a 20 ton hydraulic press. The thixoformed sample was shown in Fig. 1. Conventional gravity casting was carried out at 700 °C. The parts obtained from thixoforming and gravity castings were prepared metallographically for microstructural examination and etched in 0.5% HF solution. Microstructural examinations were performed by optical microscopy (OM) and scanning electron microscopy (SEM). Energy dispersive X-ray spectroscopy (EDX) was used to identify the intermetallics. Morphology of the α-Al phase and the intermetallic compounds show the difference in the specimens obtained from thixoforming and gravity casting. In order to investigate the effect of processing conditions on the mechanical properties of A380 alloy, 10 sets of samples were used for tensile tests. Dimensions of tensile specimen were 22 mm gauge length and 8 mm diameter (Fig. 2), and the specimens were tested at room temperature at a tension speed of 2 mm/min. The hardness HB of the specimens was then investigated. Hardness values represent the average value of at least 5 test results.

Fig. 1. The thixoformed sample from A380 alloy.

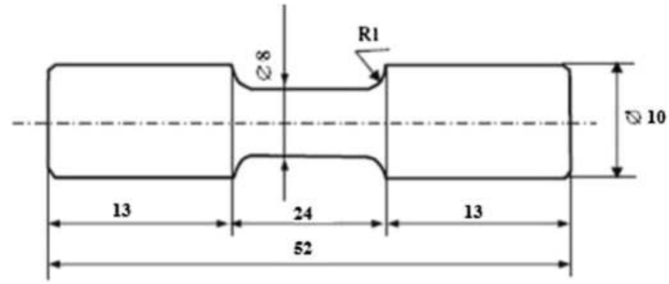

Fig. 2. Tensile test specimen.

3. Results and discussion

The microstructure of slope cast sample before thixoforming was investigated in detail by authors in the previous works [6,14]. The microstructure obtained from gravity casting in Fig. 3a has a typical dendritic structure, surrounded by a eutectic phase. Fig. 3b shows the microstructure of sample obtained from thixoforming. While α-Al grain structure has a globular form, Al–Si eutectic structure is quite fined. SEM studies and EDX analysis were performed in order to determine chemical composition of intermetallics with different shapes. When the sample obtained from

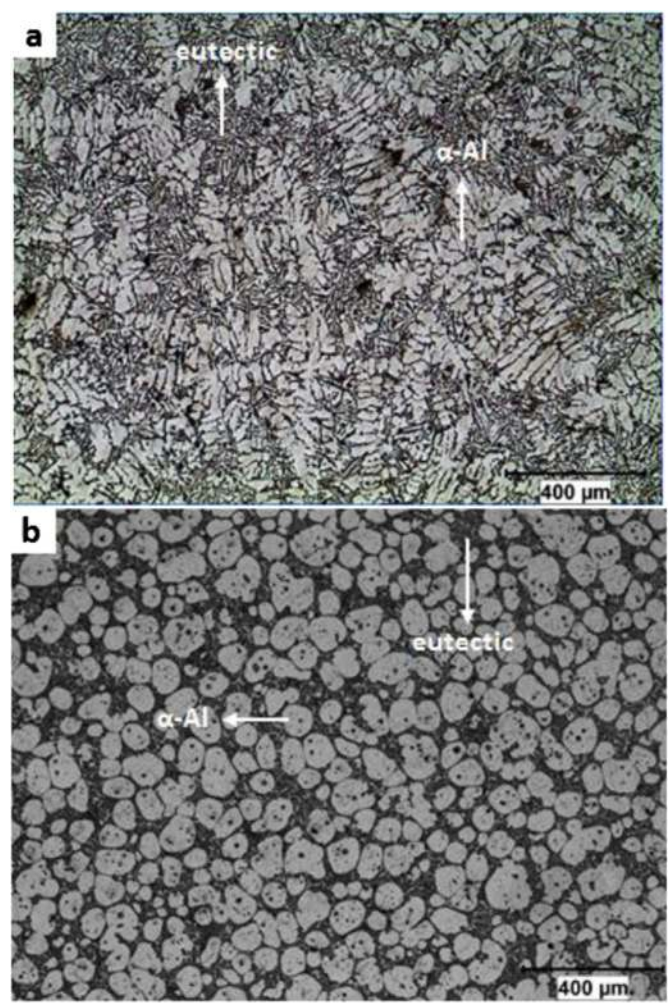

Fig. 3. The microstructure of A380 alloy obtained from (a) gravity casting and (b) thixoforming.

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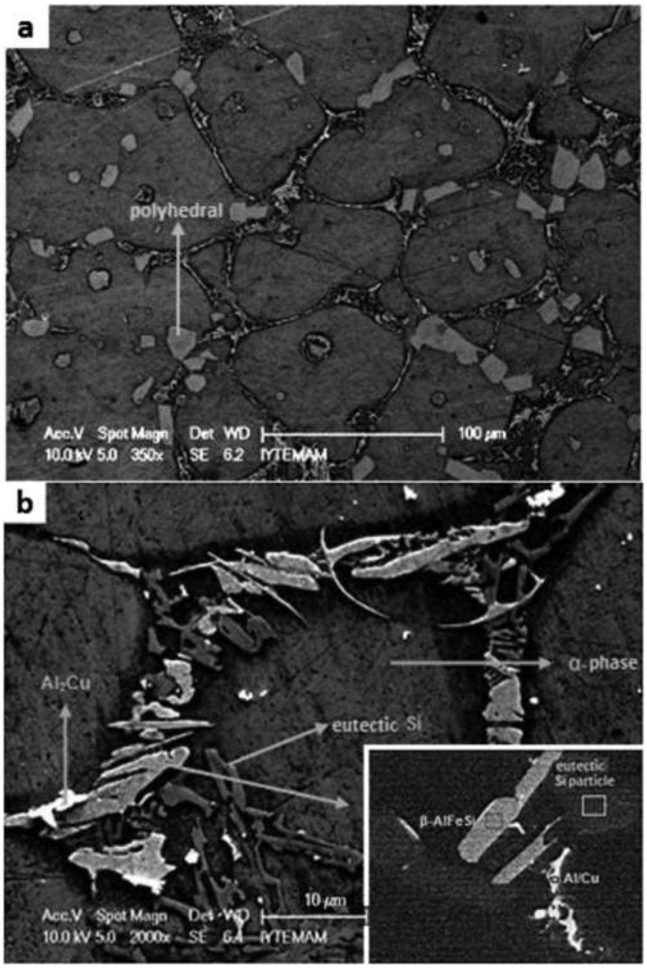

Fig. 4. SEM images showing the presence of phases and intermetallic compounds taken from thixoforming; (a) low-magnification, (b) high-magnification.

thixoforming was examined, it was observed that polyhedral, plate or particle-shaped intermetallics with different character occurred as well as α-Al phase and eutectic-Si (Fig. 4a and b). Intermetallic's formula was calculated by using the chemical compositions. The calculated formulas by means of stoichiometry were listed in Tables 2–4. The EDX analysis results obtained from α-Al and eutectic-Si were given in Table 2. According to stoichiometry, it was verified that these phases were α-Al and Si. Some polyhedral intermetallics have formed inside α-Al in the thixoformed state (Fig. 4a). Semi-solid metal is created by partial melting of solid feed stock before forming. After forming process, this partial melting regions may be move from grain boundaries into the alpha-Al phase by the effect of pressure.

Table 2
EDX analysis of the phases of A380 alloy.

Phase	Element	Wt. (%)	Calculated
α-Al	Al	95.55	Al
	Si	0.69	
	Fe	0.87	
	Mn	0.44	
	Cu	1.39	
Eutectic Si particle	Al	1.58	Si
	Si	95.70	
	Fe	0.25	
	Cu	0.44	

Table 3
EDX analysis of the intermetallic compounds obtained from thixoforming.

Phase	Element	Wt. (%)	Calculated	Shape and color
β-Fe	Al	57.94	Al_5FeSi	Small plate, light gray
	Si	26.37		
	Fe	9.38		
θ-Al/Cu	Al	53.11	Al_2Cu	Particle, white
	Cu	38.51		
α-Fe	Al	58.51	$Al_{15}Si_2(FeMn)_3$	Polyhedral, dark gray
	Si	10.09		
	Fe	18.31		
	Mn	6.90		

According to EDX analysis of thixoformed alloy, chemical equation of Al–Si–Fe–Mn bearing intermetallic with polyhedral-shaped as shown in Fig. 4a was recommended as α-$Al_{15}Si_2(FeMn)_3$ (α-Fe) in Table 3. Al–Fe–Si bearing intermetallics occurred in the shape of small plate and consist of β-Al_5FeSi (β-Fe) formula (Table 3). In general, they formed at the grain boundaries (Fig. 4b). Al–Cu bearing binary compound is θ-Al_2Cu phase in the shape of particle. When the SEM microstructure of the alloy obtained from gravity casting was examined, it was seen that intermetallics of characteristic Chinese script-shaped occurred. It was determined that this intermetallics obtained from Al–Si–Fe–Mn elements and α-$Al_{15}Si_2(FeMn)_3$ formula was calculated. In the literature Mohamed et al. [12], proposes that the α-Fe intermetallic has $Al_{12}Si_2(FeMnCu)_3$ formula in Chinese-script morphology, Liu and Kang [10] and Barbin et. al. [1] propose that the α-Fe intermetallic has $Al_{15}Si_2(FeMn)_3$ formula in Chinese-script morphology, Shabestari and Parshizfard [15], Shabestari and Ghanbari [16], Timelli and Bonollo [22] and Warmuzek et. al. [19] asserted that the α-Fe intermetallic has $Al_{15}Si_2(FeMn)_3$ formula in polyhedral morphology. While α-Fe with this composition consisted in the form of Chinese script in gravity casting (Fig. 5), α-Fe consisted in the form of polyhedral in thixoforming (Fig. 4a). Dinnis et al. [2] emphasized the solidification in order to explain the morphology of α-Fe. Hence, the solidification as primary phase of α-Fe plays an important role. If α-Fe phase solidifies before α-Al phase, it is formed in polyhedral morphology [2]. In A380 alloys, when the solidified temperatures of phases at cooling rate between 0.2 and 5 K s^{-1} were observed, the solidified temperature of Al-FCC phase is almost 610 °C and α-Fe ($Al_{15}Si_2(FeMn)_3$) phase is almost 567 °C [17], and so, in semi-solid forming process, the primary phase is α-Fe.

Wang et al. [18] and Dinnis et al. [2] reported that α-Fe formed the convoluted arm structure when the α-Al phase primarily solidified. In this study, α-Al phase is the primary phase during gravity casting because it firstly nucleates during solidification. Alloy elements flourish on grain boundaries by inducing throughout the solidification direction and α-Fe phase is formed in Chinese script morphology when it reaches the suitable composition. During thixoforming, it is known that partial melting develops along grain boundaries with increasing temperature, while α-Al is still at solid

Table 4
EDX analysis of the intermetallic compounds obtained from gravity casting.

Phase	Element	Wt. (%)	Calculated	Shape and color
β-Fe	Al	49.02	Al_5FeSi	Needle, light gray
	Si	21.42		
	Fe	21.42		
θ-Al/Cu	Al	47.25	Al_2Cu	Thin plate, white
	Cu	43.03		
α-Fe	Al	55.74	$Al_{15}Si_2(FeMn)_3$	Chinese script, dark gray
	Si	8.43		
	Fe	22.85		
	Mn	6.30		

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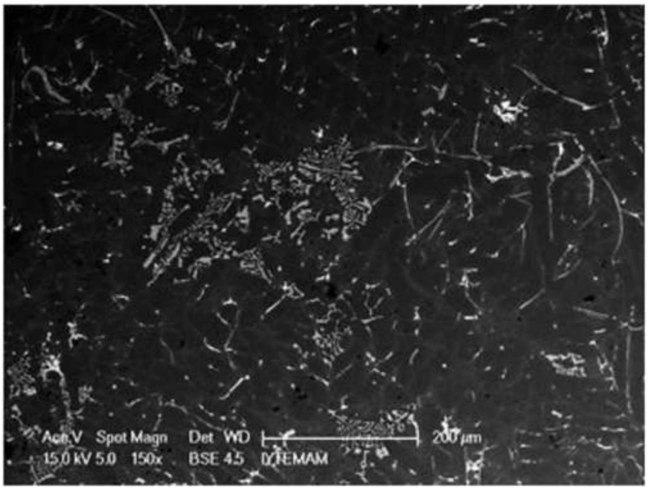

Fig. 5. Back-scattered image showing the microstructure of A380 alloy taken from gravity casting.

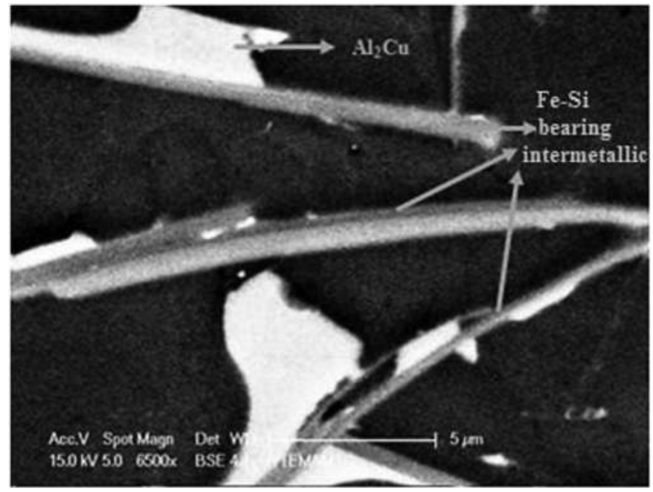

Fig. 7. SEM images showing the presence of intermetallics taken from gravity casting.

state. During solidification, α-Fe intermetallics arise from liquid grain boundary as a primary phase. Therefore, it has a polyhedral morphology. The intermetallics in gravity casting and thixoforming was compared by examining Figs. 4 and 6. Al_2Cu phase is about 4–10 μm, Chinese script-like phase is about 120 μm and β-Fe phase is about 60 μm in gravity casting sample. In thixoforming process, it was seen that Chinese script-like morphology transformed to the polyhedral α-Fe morphology and α-Fe was about 15–20 μm. Besides, after thixoforming, it was found that Al_2Cu phase did not changed dimensionally and was about 4–7 μm, β-Fe phase was finer and about 10–12 μm.

When the detailed photograph was examined for the Chinese script-shaped intermetallic as shown in Fig. 6, it was seen that many cracks emanated on the intermetallic. It was thought that this situation was due to internal tensions which comprised the shrinkage of conventional cast-material during cooling. However, in the semi-solid forming process, there is no question in the formation of shrinkage compared to conventional casting. Ozdemir et al. [13] noted that thixoforming avoided internal defects such as microcracks due to applied pressure during the process. While β-Al_5FeSi intermetallic occurred needle-like-shaped in the gravity casting as shown in Fig. 7, it occurred as small plate-shaped due to applied high pressure in the thixoforming as shown in Fig. 4b. Mohamed et al. [12] propounded that the needle-like morphology of β-Al_5FeSi intermetallic created a harmful effect on ductility; it had the upgrading potential of tension and constituted the weak bond strength within the matrix. As thixoforming process decrease the intermetallic sizes and decrease its harmful effect. As the gravity casting microstructure was considered, it was observed that intermetallics aggregated in specific regions and they were not homogenously distributed in the matrix (Fig. 5).

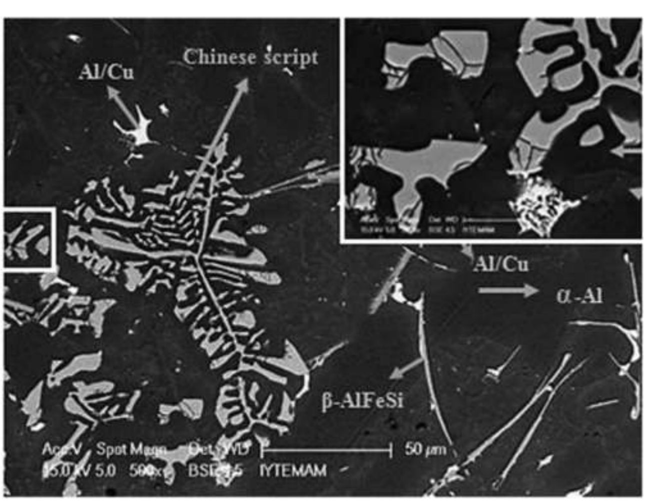

Fig. 6. SEM images showing the presence of the Chinese script-shaped intermetallic compounds taken from gravity casting.

Tensile properties and hardness values were represented in Table 5. It was seen that the results of tensile and hardness test were supported by the microstructure images. Ultimate tensile strength of the alloy produced by thixoforming has increased by 20% in comparison to gravity casting, while yield strength has increased by 27%. It is known that β-Al_5FeSi intermetallic solidifies as needle-like in gravity casting. In particular, the needle-like morphology of β-Al_5FeSi intermetallic led to decrease in the ultimate tensile strength and elongation by increasing the brittleness. The solidification in the form of Chinese script leads to fractures by increasing the internal tension and decreasing the strength. Moreover, the shrinkage of a semi-solid material is significantly reduced as compared with gravity casting; therefore, the formation of fractures can be reduced in thixoforming samples. Whereas, an increase in strength occurred in the thixoforming process because α-Fe solidified as polyhedral-shaped. β-Fe carried out the small-plate morphology in thixoforming. Applied pressure during thixoforming caused increase in primary α-Al phase hardness. Dislocation density has increased owing to applied pressure [20].

4. Conclusions

In this work, the α-Al grains with fine and equiaxed spherical morphology were produced by thixoforming. Coarse dendritic α-Al grains appeared in conventional gravity casting method. Morphology and chemical equation of intermetallic compounds in

Table 5
Mechanical properties of the alloys investigated.

Alloy	Ultimate tensile strength R_m (MPa)	Yield strength R_p (MPa)	Elongation *A* (%)	Hardness (HB)
Thixoformed-A380	240	190	3.5	75
Gravity casting-A380	200	150	2.0	65

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addition to primary crystals were different in thixoforming and gravity casting. β-Al_5FeSi intermetallic had the small-plate morphology and θ-Al_2Cu intermetallic was in the form of particle in thixoforming while β-Al_5FeSi intermetallic had the needle-like morphology and θ-Al_2Cu intermetallic was in the form of thin plate in gravity casting. The α-$Al_{15}Si_2(FeMn)_3$ particle was observed in two diversified morphology. In gravity casting, α-Al phase grew as primary phase. The Chinese script-shaped α-$Al_{15}Si_2(FeMn)_3$ formula intermetallic compound constituted an aggregation and non-homogenous structure in the matrix in gravity cast alloy. In thixoforming, the intermetallics have dissolved and then new intermetallics formed whereas the α-Al phase has solid-state, and therefore, α-$Al_{15}Si_2(FeMn)_3$ particle grew as primary phase. The α-$Al_{15}Si_2(FeMn)_3$ particle resulted in polyhedral morphology in thixoforming alloy. The thixoforming alloys had good mechanical properties compared to conventional casting.

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References

[1] N.M. Barbin, I.G. Brodova, T.I. Yablonskikh, N.A. Vatolin, Alloying and modification of molten silumin in salt melt, J. Phys. Conf. Ser. 98 (2008) 072014.
[2] C.M. Dinnis, J.A. Taylor, A.K. Dahle, As-cast morphology of iron-intermetallics in Al–Si foundry alloys, Scr. Mater. 53 (2005) 955.
[3] J.U. Ejiofor, R.G. Reddy, Developments in the processing and properties of particulate Al–Si composites, JOM J. Min. Met. Mat. S 49 (1997) 31.
[4] Z. Fan, Semisolid metal processing, Int. Mater. Rev. 47 (2002) 49.
[5] M.C. Flemings, Behavior of metal alloys in the semisolid state, Metall. Mater. Trans. B 22 (1991) 269.
[6] S. Gencalp, N. Saklakoglu, Semisolid microstructure evolution during cooling slope casting under vibration of A380 aluminum alloy, Mater. Manuf. Process. 25 (2010) 943.
[7] W. Khalifa, F.H. Samuel, J.E. Gruzleski, Iron intermetallic phases in the Al corner of the Al–Si–Fe system, Metall. Mater. Trans. A 34 (2003) 807.
[8] D.H. Kirkwood, Semisolid metal processing, Int. Mater. Rev. 39 (1994) 173.
[9] L. Lasa, J.M. Rodrigues-Ibabe, Wear behaviour of eutectic and hypereutectic Al–Si–Cu–Mg casting alloys tested against a composite brake pad, Mat. Sci. Eng. A 363 (2003) 193.
[10] Y.L. Liu, S.B. Kang, The solidification process of Al–Mg–Si alloys, J. Mater. Sci. 32 (1997) 1443.
[11] T.O. Mbuya, B.O. Odera, S.P. Ng'ang'a, Influence of iron on castability and properties of aluminium silicon alloys: literature review, Int. J. Cast. Metal. Res. 16 (2003) 451.
[12] A.M.A. Mohamed, A.M. Samuel, F.H. Samuel, H.W. Doty, Influence of additives on the microstructure and tensile properties of near-eutectic Al–10.8%Si cast alloy, Mater. Des. 30 (2009) 3943.
[13] I. Ozdemir, S. Muecklich, H. Podlesak, B. Wielage, Thixoforming of AA 2017 aluminum alloy composites, J. Mater. Process. Technol. 211 (2011) 1260.
[14] N. Saklakoglu, S. Gencalp, S. Kasman, I.E. Saklakoglu, Formation of globular microstructure in A380 aluminum alloy by cooling slope casting, Adv. Mat. Res. 264-265 (2011) 272.
[15] S.G. Shabestari, M. Ghanbari, Effect of plastic deformation and semisolid forming on iron–manganese rich intermetallics in Al–8Si–3Cu–4Fe–2Mn alloy, J. Alloy Compd. 508 (2010) 315.
[16] S.G. Shabestari, E. Parshizfard, Effect of semi-solid forming on the microstructure and mechanical properties of the iron containing Al–Si alloys, J. Alloy Compd. 509 (2011) 7973.
[17] P. Suwanpinij, U. Kitkamthorn, I. Diewwanit, T. Umeda, Influence of copper and iron on Solidification characteristics of 356 and 380-type aluminum alloys, Mater. Trans. 44 (5) (2003) 845.
[18] E.R. Wang, X.D. Hui, S.S. Wang, Y.F. Zhao, G.L. Chen, Improved mechanical properties in cast Al–Si alloys by combined alloying of Fe and Cu, Mat. Sci. Eng. A 527 (2010) 7878.
[19] M. Warmuzek, W. Ratuszek, G. Sek-Sas, Chemical inhomogeneity of intermetallic phases precipitates formed during solidification of Al–Si alloys, Mater. Charact. 54 (2005) 31.
[20] S. Tahamtan, A. Fadavi Boostani, H. Nazemi, Mechanical properties and fracture behavior of thixoformed, rheocast and gravity-cast A356 alloy, J. Alloy Compd. 468 (2009) 107.
[21] J.A. Taylor, The effect of iron in Al–Si casting alloys, 35th Australian Foundry Institute National Conference, 31 Oct.–3 Nov., South Australia, 2004.
[22] G. Timelli, F. Bonollo, The influence of Cr content on the microstructure and mechanical properties of AlSi9Cu3(Fe) die-casting alloys, Mater. Sci. Eng. A 528 (2010) 273.
[23] M. Zeren, Effect of copper and silicon content on mechanical properties in Al–Cu–Si–Mg alloys, J. Mater. Process. Technol. 169 (2005) 292.

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