論 文

Beryllium Effects on the Microstructure and Mechanical Properties of A356 Aluminium Casting Alloy

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Abstract

Microstructure of A356 aluminum alloys cast in the permanent mold was investigated by optical microscope and image analyzer, with particular respect to the shape and size distribution of iron intermetallics known as β-phase (Al_5FeSi). Morphologies of the β-phase was found to change gradually with the Be:Fe ratio like these. In Be-free alloys, β-phase with needlelike morphology was well developed, but script phase was appeared when the Be:Fe ratio is above 0.2:1. With the Be:Fe ratios of 0.4:1-1:1, script phase as well as Be-rich phase was also observed. In case of higher Be addition, above 1:1, Be-rich phase was observed on all regions of the specimens, and increasing of the Be:Fe ratios gradually make the Be-rich phase coarse. It was also observed that the β-phase with needlelike morphology was coarsened with increase of the Fe content in Be-free alloys. However, in Be-added alloys, length and number of these β-phases were considerably decreased with the increased Be:Fe ratio. Beryllium addition improved tensile properties and impact toughness of the A356 aluminium alloy, due to the formation of a script phase or a Be-rich phase instead of a needlelike β-phase. The DSC tests indicated that the presence of Be could increase the amount of Mg which is available for Mg_2Si precipitate hardening, and enhance the precipitation kinetics by lowering the ternary eutectic temperature.

1. Introduction

Al-Si alloys are widely used in many applications because of their good mechanical properties, light weight, and good castability. The as-cast microstructure of these alloys consists of a primary phase, aluminium or silicon, and a eutectic mixture of these two elements. Depending on the purity of base material, the Al-Si-Mg alloys contain varying amounts of impurity elements such as iron, copper, and zinc. In addition, copper and magnesium are often added as alloying elements to increase strength and hardenability of the material. But the impurities and alloying elements partly go into solid solution in the matrix and partly form intermetallic particles during the solidification process.

Iron is the most deleterious impurity element in cast aluminium alloys due to its role in the formation of the brittle intermetallic compound, Al_5FeSi (β-phase). The volume percent and size of the β-phase are strongly influenced by the iron content, solidification rate, and melt superheat temperature [1-2]. As a result of it, mechanical properties are decreased with increasing of iron content. The iron contamination is due to the usage of steel tools in the foundry during preparation of the alloy and remelting or recycling of the scrap [3]. Therefore neutralization of the negative influence of iron on the mechanical properties of aluminium casting alloys is very important.

It has been well established that the addition of certain alloying elements such as Mn, Cr, Ni, and Co can change the morphology of the iron intermetallics from the deleterious needlelike morphology to a less harmful script morphology [1-2, 4-5]. But studies about the effect of Be for neutralizing deleterious β-phase are very few and inconclusive. It was reported that small amounts of Be (5-10 ppm) are sometimes added in premium quality castings to reduce oxidation of molten metal and to enhance elongation [6-8]. In the case of larger amounts additions (0.04~0.07%), Be transforms large needle of iron intermetallics to small equiaxed shaped crystals, thus improving strength and ductility[3, 6, 9]. Accordingly, A357, B358 and 364 alloys contain

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※본 논문은 헝가리 부다페스트에서 개최된 제63차 국제주물대회에서 한국대표 논문으로 발표된 내용임.

Be of the order of 0.02-0.3% to improve the mechanical properties [10].

The objective of this study is to clarify and to establish the Be effects on the morphology of β-phase and on the mechanical properties as a function of Be:Fe ratios, by counteracting the deleterious effects of Fe. As mentioned earlier, decrease in mechanical properties is mainly due to the presence of β-phase in the Fe containing alloys. Therefore, to neutralize the harmful effects of Fe, formation of β-phase is to be prevented or the shape, size and distribution of β-phase should be so altered as to improve the mechanical properties.

2. Experimental Procedure

Chemical composition of the A356 hypoeutectic Al-Si alloy used is shown in Table 1. 12 kg of prealloyed A356 ingots was prepared and then remelted in an electrical resistance furnace in a graphite crucible. Fe and Be were added to the melt in the form of Al-50Fe and Al-5Be masteralloy, respectively. The melt was held for 20 minutes to facilitate dissolution of Be. It was then degassed with nitrogen gas for five minutes, and eutectic Si was modified with Na salt mixture and then poured at 750°C into 35 mm (permanent mold, which was preheated to 300°C. Cast specimens with size of 220 mm×35 mmϕ, were prepared under 30 different conditions.

Table 2 shows the content of Fe and Be in as-cast specimens. The specimens were solution treated at 540°C for 6 hours, and quenched in water at 20°C, and then artificially age hardened at 140°C for 6 hours before measuring the mechanical properties.

Table 1. Chemical composition of A356.2 hypoeutectic Al-Si ingot (wt.%)

Si	Mg	Fe	Ti	Ni	Cr	Mn	Al
7.10	0.34	0.07	0.14	0.003	0.002	0.001	Bal.

Table 2. Contents of Fe and Be in the fabricated specimens (wt.%)

Group		A	B	C	D	E	F
No.	Fe	0.09	0.121	0.21	0.33	0.50	0.68
1	Be	0	0	0	0	0	0
2	Be	0.02	0.07	0.06	0.04	0.02	0.03
3	Be	0.03	0.13	0.08	0.07	0.04	0.06
4	Be	0.07	0.19	0.24	0.14	0.09	0.14
5	Be	0.16	0.35	0.59	0.34	0.24	0.36

The as-cast and aged specimens were polished and then etched with modified keller's solution for 10 seconds, and the microstructures were examined by using optical microscopy (HFX-IIA, Nikon, Japan) and scanning electron microscopy (X-650, Hitachi, Japan). The tensile properties were evaluated with the test specimens fabricated by ASTM E8 subsize specification [11] under the cross head speed of 2 mm/min. The impact toughness was also measured with the test specimens machined by ASTM E23 subsize specification [12]. For an interpretation of the mechanical properties with the microstructure, fracture surface of the test specimen were examined with both an optical and a scanning electron microscope. The size and distribution of β-phase was measured in detail by using image analyzer.

In order to investigate the Be effects on the kinetics of Mg_2Si precipitation and on the ternary eutectic temperature, the Differential Scanning Calorimetry (DSC) studies were carried out by using TA Instruments (TA 910 thermal analyzer). The DSC runs were made at a heating rate of 10°C/min over the temperature range from 20°C to 600°C.

3. Results and Discussion

3.1 Microstructures

The major purpose of this study is to clarify, through microstructure observation, and to establish the influence of Be on the morphology of iron intermetallics as a function of Be:Fe ratios in A356 alloy.

Fig. 1 shows typical microstructures of high Fe containing (0.68%) alloys at as-cast conditions. β-phases with needle shape are shown in interdendritic regions (Fig. 1a). The needlelike β-phase was formed during solidification of alloys containing Fe. The β-phase is in the shape of very thin platelets, so that in section they appear as long needles. On the other hand, beryllium addition forms new phases with altered morphologies, such as script phase (Fig. 1b) and Be-rich phase (Fig. 1c). The β-phase, script and Be-rich phase are not dissolved during T_6 heat treatment as shown in Fig. 2. As these script and Be-rich phase were solidified at higher temperature

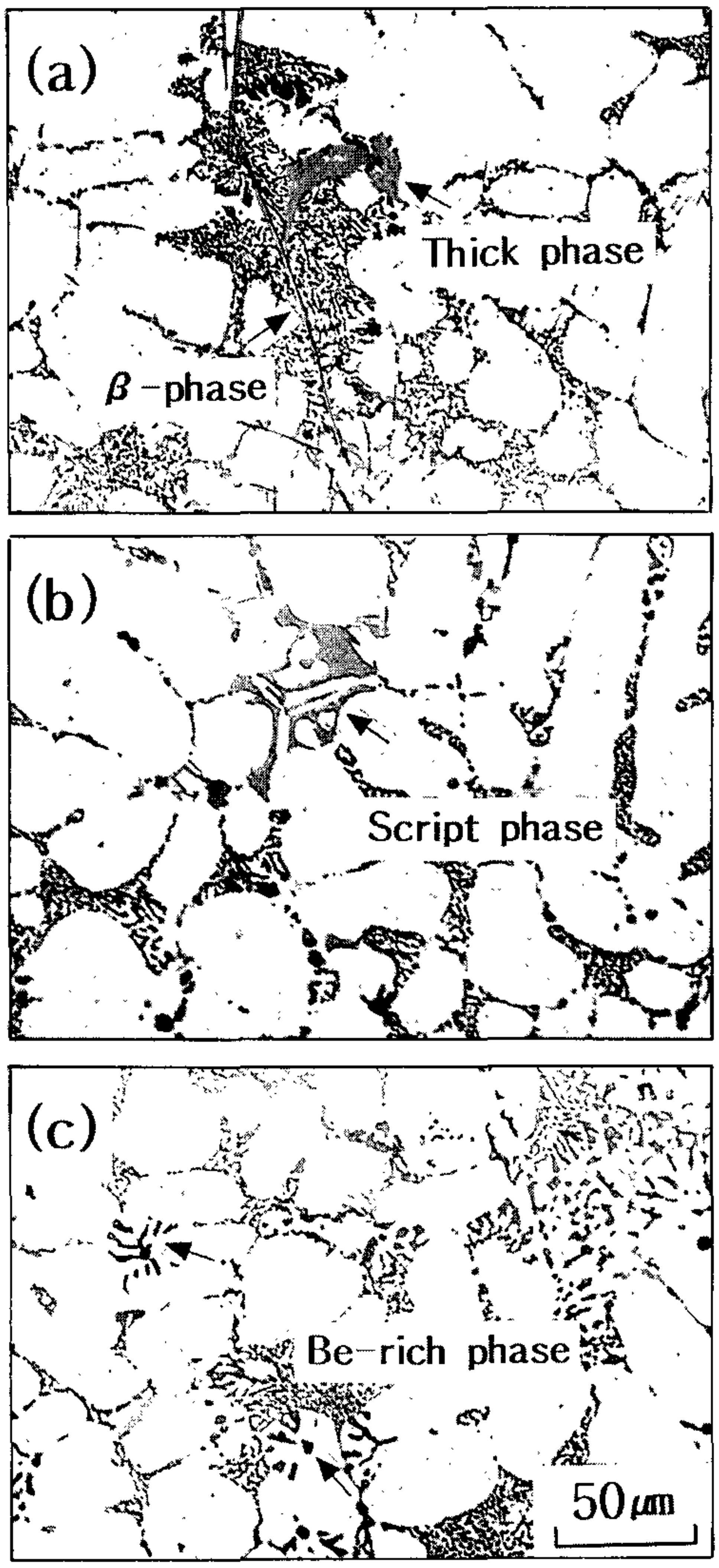

Fig. 1. Optical micrographs of as-cast specimens contained 0.68% Fe.

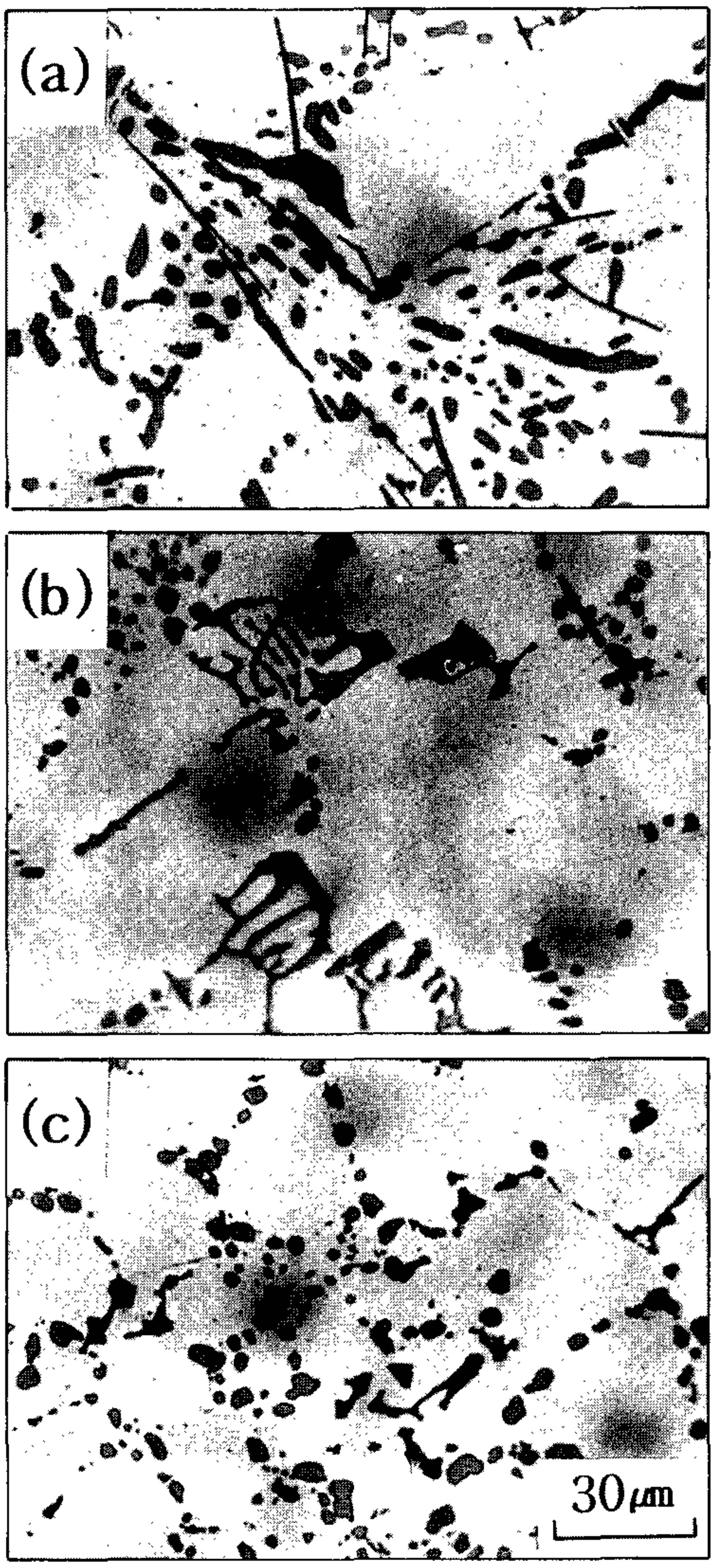

Fig. 2. Optical micrographs of T_6 heat treated specimens contained 0.68% Fe.

than the β-phase [13], the script and Be-rich phase seem to be more stable. These phases were analyzed using an electron microprobe method by many investigators. Granger *et al.* [14] and Tan *et al.* [15] have investigated composition and identification of these phases. The needlelike morphology (β-phase) is found to be Al_5FeSi or $Al_9Fe_2Si_2$, and the thick morphology shown in Fig. 1a is $Al_{10}Si_4Mg_4Fe$ or $Al_8Si_6Mg_3Fe$. Murali *et al.* [9] have reported the Be-rich phase is $BeSiFe_2Al_8$. As mentioned earlier, the β-phase is mostly observed in the interdendritic regions and it seems to be formed by ternary eutectic reaction. In the alloy with Fe impurity and with Be addition, the script and Be-rich phases are observed inside the primary Al-dendrites. Thus the Be-rich phase was reported to be formed by a peritectic reaction [9].

The effect of Be addition on the morphology of iron intermetallics is shown in Fig. 3 as a function of Be:Fe ratios. From this figure we can recognize the fact that the morphologies of iron intermetallics change gradually with the Be:Fe ratios. In Be free alloys, the β-phase with needlelike morphology was well developed. However, the needlelike morphology changed gradually with increasing of the Be:Fe ratios

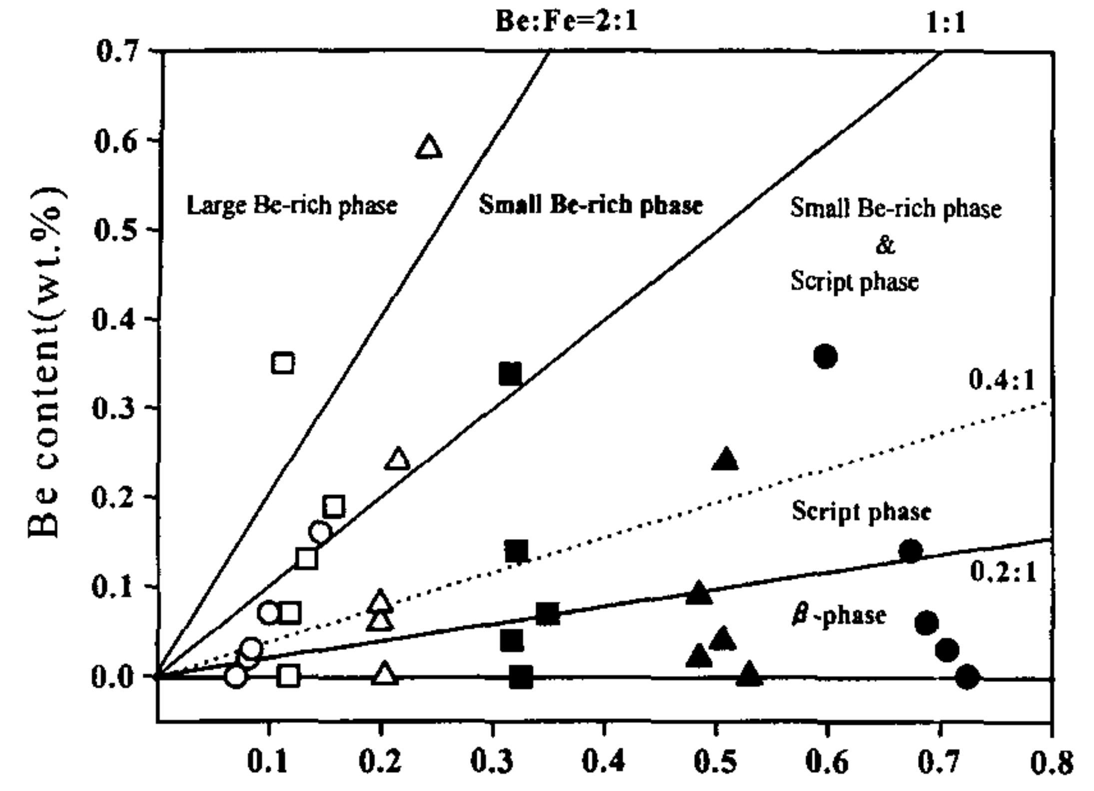

Fig. 3. Effect of Be addition on the morphology of iron intermetallics.

in the following way. When Be:Fe ratio is above 0.2:1, script phase first appeared. Script phase as well as Be-rich phase is also observed with Be:Fe ratios of 0.4: 1-1:1. In case of higher Be addition, that is, above 1:1, Be-rich phase is observed on all regions of the specimens. Increasing of the Be:Fe ratios gradually make the Be-rich phase coarse. This is considered to be due to the fact that the Fe impurity to be crystallized into needlelike intermetallics is tied up by Be added, and new phases containing Be and Fe are crystallized into script or Be-rich phases, because the script or Be-rich phase is crystallized earlier than needlelike β-phase during solidification [13].

Microstructural observations near the fractured surface indicate that cracks nucleate preferentially in the β-phase rather than in the eutectic Si particles (Fig. 4a), although the eutectic silicon phases are considered to be the most important crack initiator for Al-Si alloys with low Fe content. The iron intermetallics with needlelike morphology (β-phase) is considered to be most detrimental due to its stress raising potential at the needle tips [16]. Moreover, as β-phase is intermetallic compound, it is very hard and brittle, and have a relatively low bond strength with matrix. As shown in Fig. 4b and Fig. 4c, porosity and eutectic silicon are observed around β-phase, and these seem to be contributed to the low bond strength of β-phase with matrix.

The size and the amount of Al_5FeSi (β-phase) depends strongly on the Fe content and the solidification rate [8]. Fig. 5 shows the maximum length of β-phase as a function of iron content in this alloys. The results indicate that for a constant solidification rate, the length of β-phase increase with the Fe content. However, the maximum length of β-phase is decreased by addition of Be. Therefore, in order to estimate the effects of Be and Fe content on

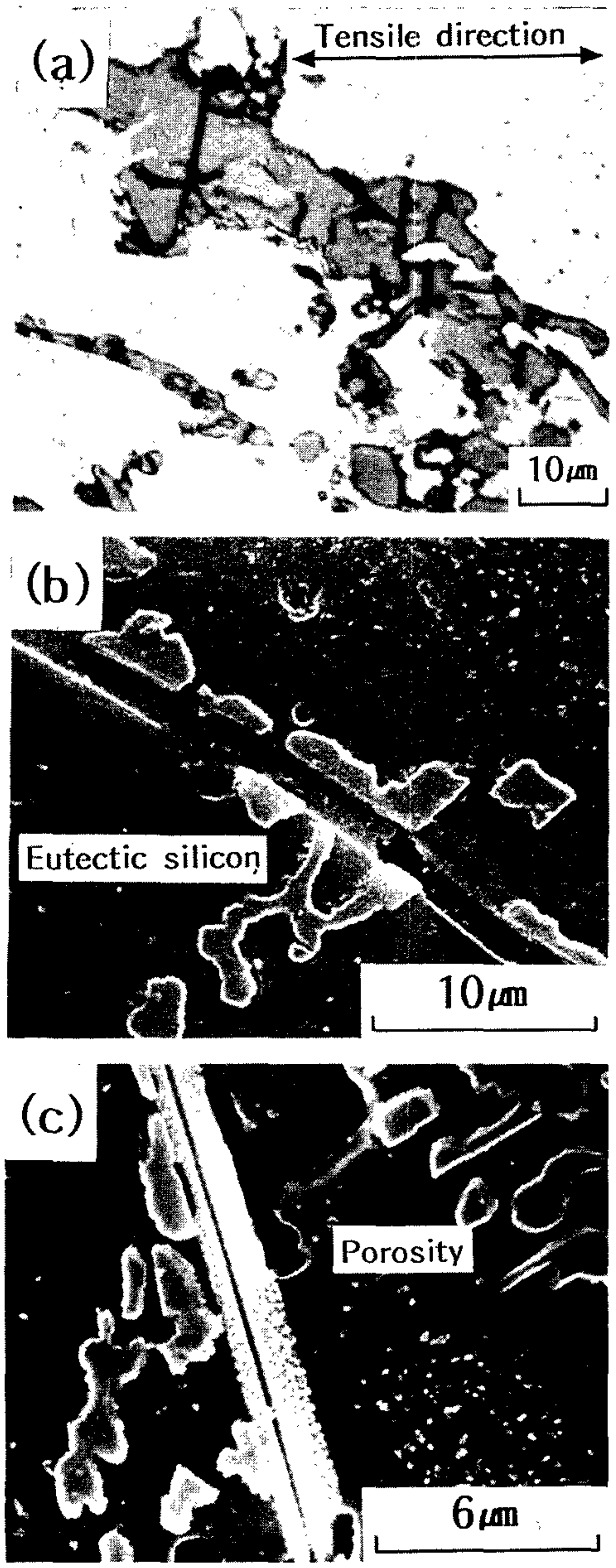

Fig. 4. (a) Optical micrgrph of crack initiated β-phase near the fractured surface, (b) scanning electron micrographs for porosity and (c) eutectic Si near the β-phase.

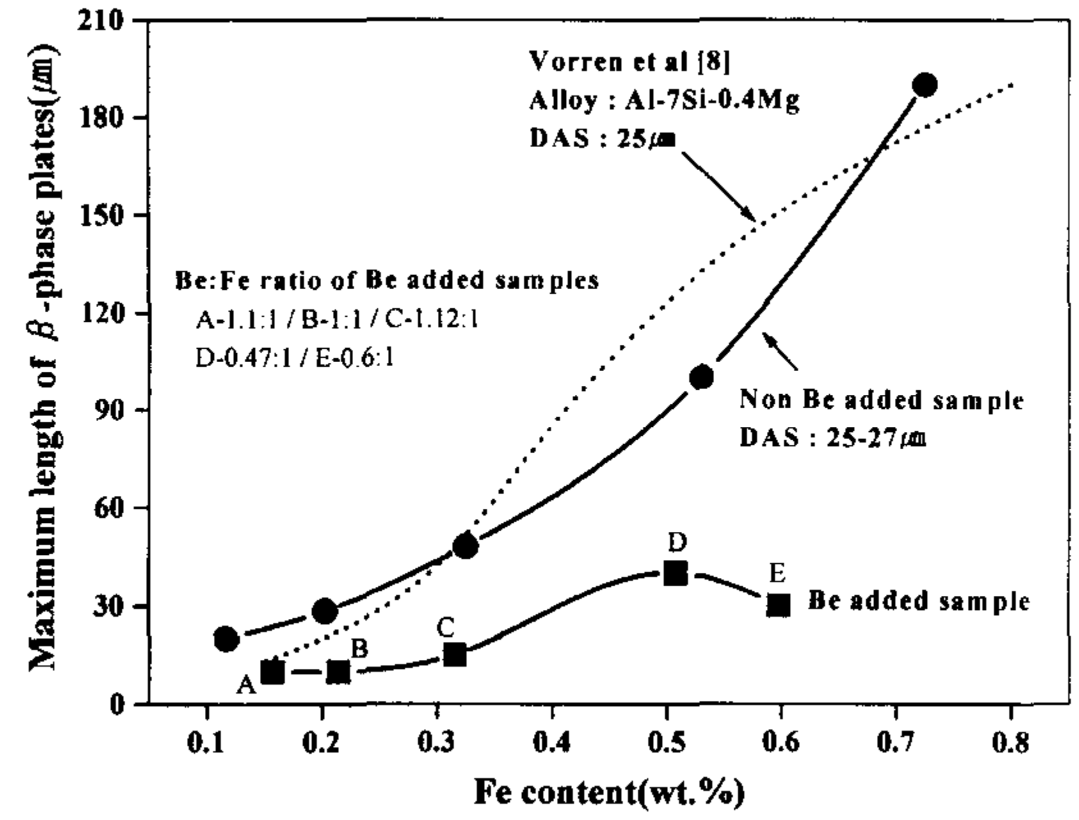

Fig. 5. Variation of the maximum length of β-phase for A 356 alloy with various amount of Fe.

the β-phases, both the frequency and the length of β-phase were measured by using image analyzer, and shown in Fig. 6. With an increase in Fe content from 0.09 to 0.68%, the amounts (counts) and length of the β-phase are increased. However, as the Be:Fe ratios increased, the amounts and the length of β-phase are markedly decreased. Especially for higher Be:Fe ratio (usually Be:Fe = 1:1), β-phase does not remain in the matrix. This phenomenon indicates that the β-phases with needlelike morphology change to the other phases such as a script or a Be-rich phase by Be addition. Modified phases by Be addition seem to play a positive role for mechanical properties.

3.2 Mechanical Properties

Addition of Mn, Cr, and Co to the Fe-containing aluminum alloy[1, 3, 5, 17] is found to be beneficial, as it neutralizes the detrimental effect of Fe on the mechanical properties. But studies about the Be effect for neutralizing deleterious β-phase are very few and inconclusive. In this study, variation of mechanical properties with the microstructure, particularly as a function of Be:Fe ratios, are evaluated.

Fig. 7 and Fig. 8 show effects of Be addition on the tensile strength and Charpy impact toughness of this alloy with different Be and Fe content after T_6 heat treatment. An increase in Fe level from 0.09 to 0.68%

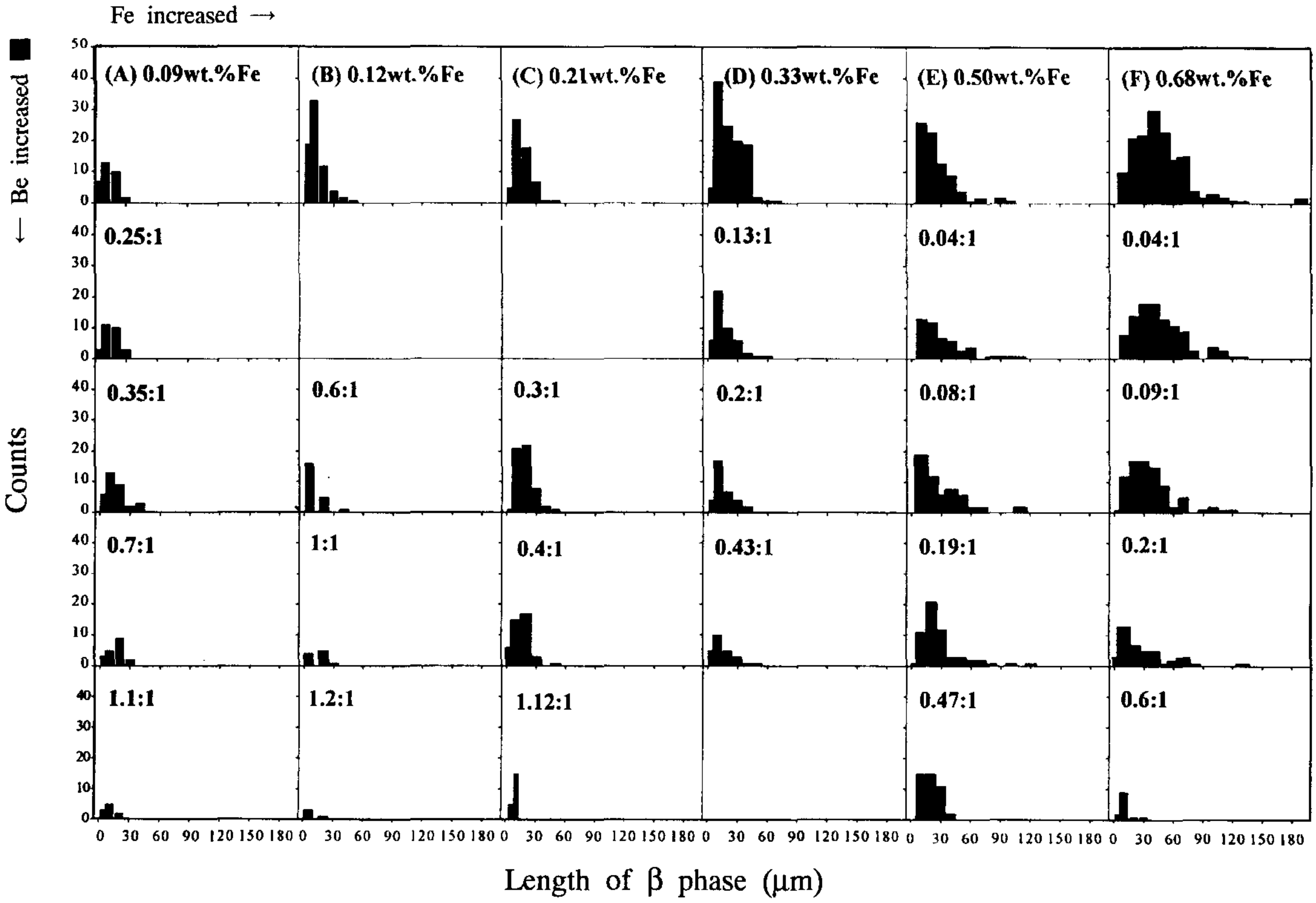

Fig. 6. Effect of Be addition on the size and distribution of β-phases as a function of Be:Fe ratio.

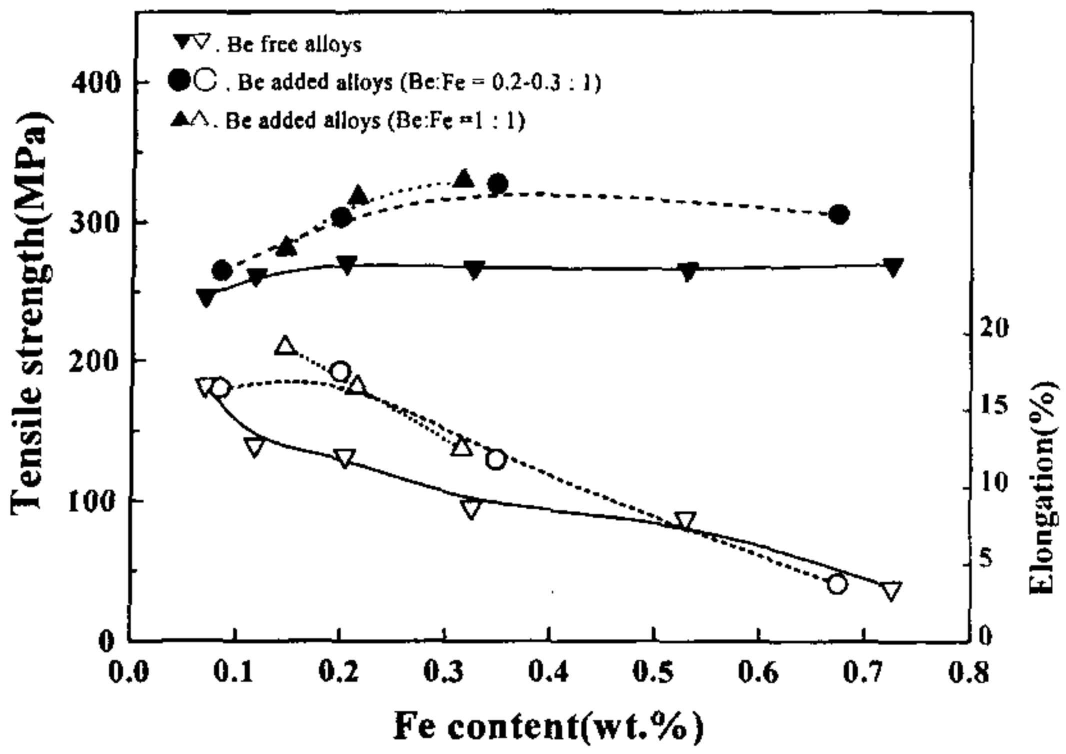

Fig. 7. Variation of the tensile properties with Fe content at T_6-treated condition.

resulted in a marked decrease in elongation and impact toughness, but ultimate tensile strength (UTS) remained almost unchanged. However, Be addition improved tensile properties and impact toughness, due to the formation of a script or a Be-rich phase instead of the needlelike β-phase. Although, the case for the alloys with high Fe content (above 0.5%) and with higher Be:Fe ratios (above 1:1) was not studied, it could be estimated that the mechanical properties of higher amounts of Be containing alloys should be more increased than that of small amounts of Be containing alloys, due to decrease in number and size of the harmful β-phase. Therefore, it could be concluded that the improved mechanical properties of the Be containing A356 casting alloy with high Fe impurity is mainly attributed to the modified shapes and decreased number of the β-phase, as well as their location formed inside primary Al dendrites.

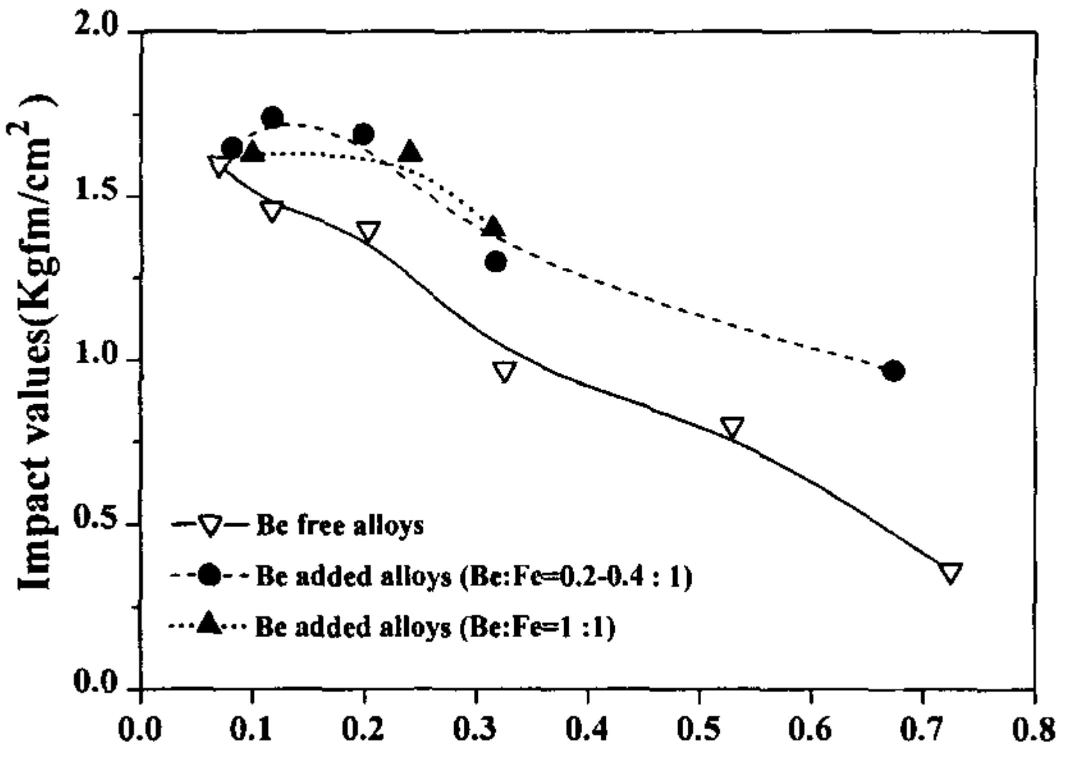

Fig. 8. Variation of the impact toughness with Fe content at T_6-treated condition.

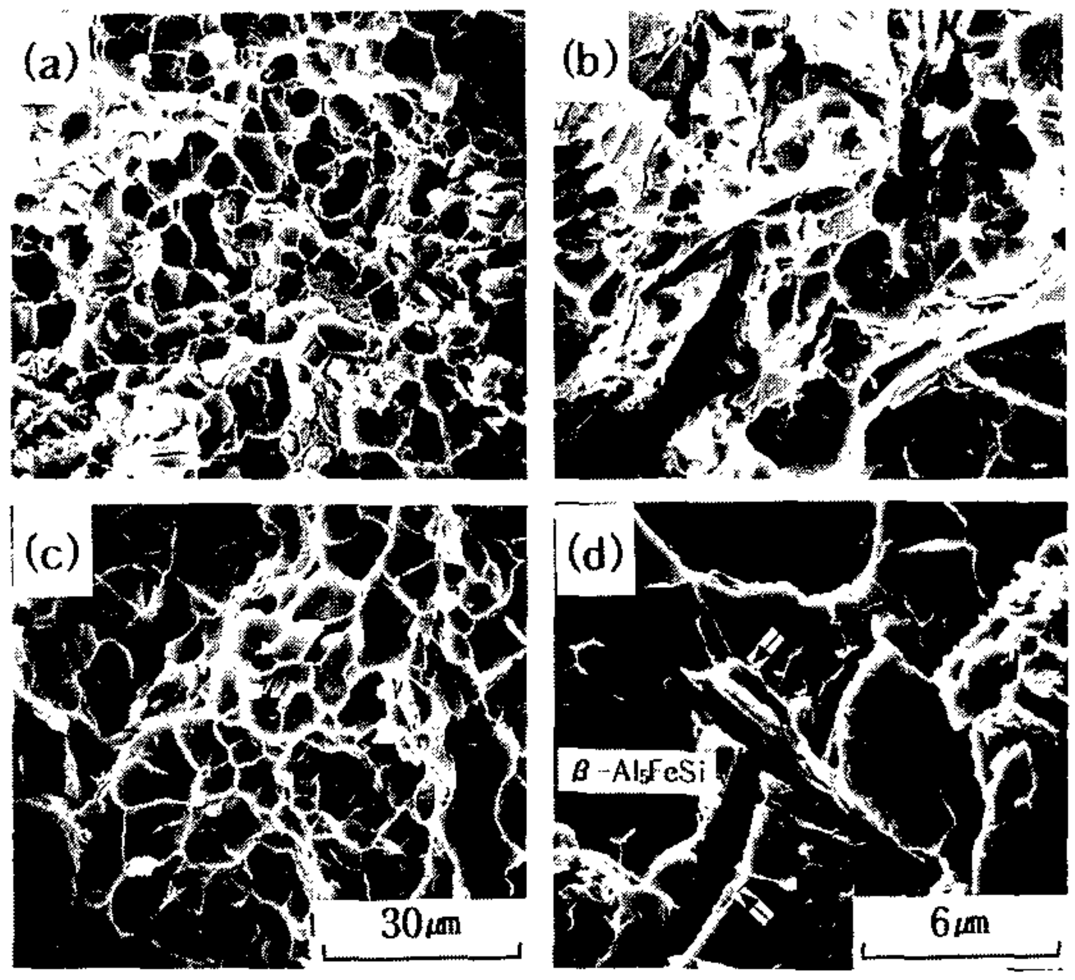

Fig. 9. Fractographs of the test bars with different Fe or Be content; (a) 0.09% Fe, (b) 0.68% Fe, (c) 0.68% Fe and 0.36% Be and (d) higher magnification view of intergranular and brittle cleavage fracture surface of the test bar (b).

According to the fractograph observation, the specimen with low Fe levels (0.09%) shows ductile cellular fracture along with some brittle cleavage fractured areas (Fig. 9a), and the specimen with high Fe levels (0.68%) shows a mixed mode of intergranular and brittle cleavage fracture (Fig. 9b). However, the Be-added specimen with high Fe levels (0.68 %) exhibits ductile cellular fracture, as shown in Fig. 9c. Such a cellular mode fracture is considered to be attributed to the deformation that occurs in the soft matrix (Al dendrites), and occurrence of intergranular and brittle cleavage fracture is most likely to be contributed by the β-phases (Fig. 9d).

In addition, DSC test were performed to evaluate the effect of Be on the kinetics of Mg_2Si precipitation and on the ternary eutectic temperature of the alloy. Fig. 10 shows an exothermic reaction of the Mg_2Si precipitation for alloy A (Al-7Si-0.4Mg-0.11Fe) and alloy B (0.35%Be addition in alloy A) after a high temperature (540°C) solution treatment. From this figure, we can recognize that the alloy B which contain Be has an increased peak area and a lower peak temperature. This means that the addition of Be increased the amount of Mg_2Si precipitate, and enhanced the precipitation kinetics. Also, Fig. 11

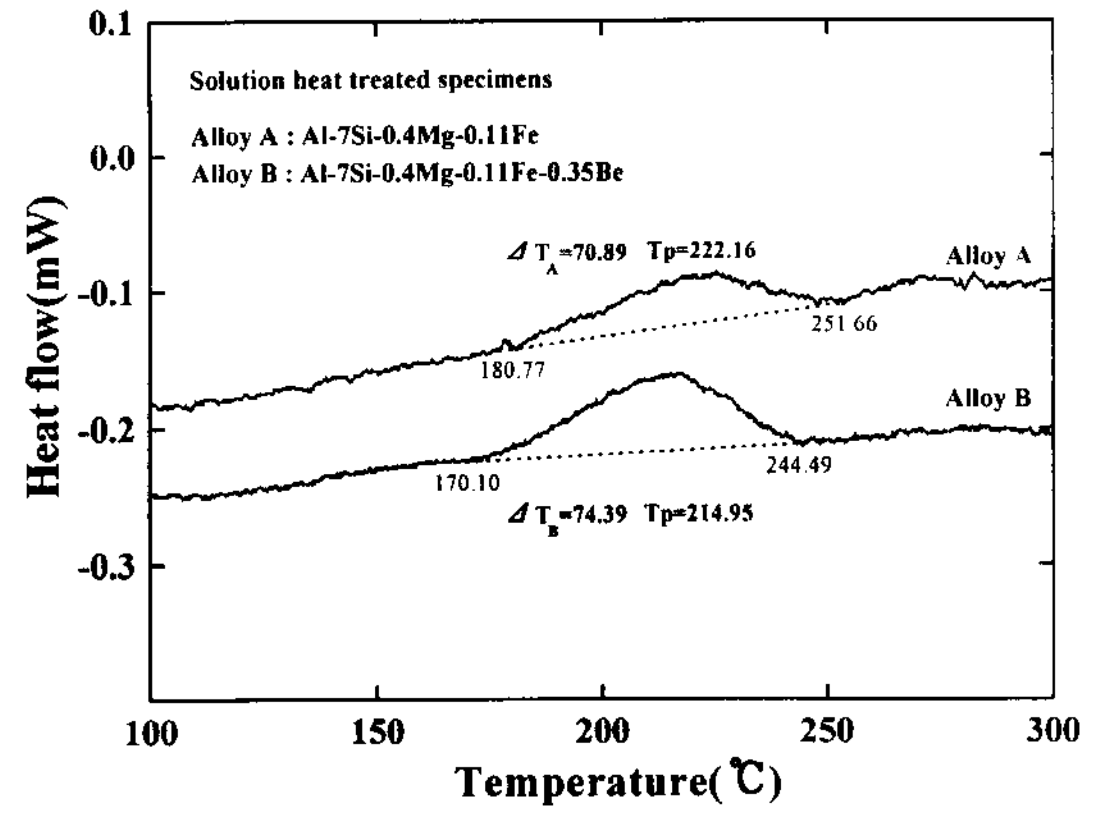

Fig. 10. DSC curves illustrating the effect of Be on the Mg_2Si precipitation.

shows an endothermic reaction of the dissolution for alloy C (Al-7Si-0.4Mg-0.5Fe) and alloy D (0.5% Be addition in alloy C) after T_6 heat treatment. This figure indicates that the addition of Be can lower the ternary eutectic temperature by 4°C. From the results indicated by Fig. 10 and Fig. 11, we can postulate the fact that if solution treatment is performed for the Be-added alloy and the Be-free alloy at the same temperature, the kinetics of Mg_2Si precipitation should be enhanced by lowering the ternary eutectic temperature and the amount of Mg which is available for Mg_2Si precipitation should be increased for the Be-added alloy than for the Be-free alloy. Thus ultimate tensile strength of the Be-added alloy should be higher than that of the Be-free alloy.

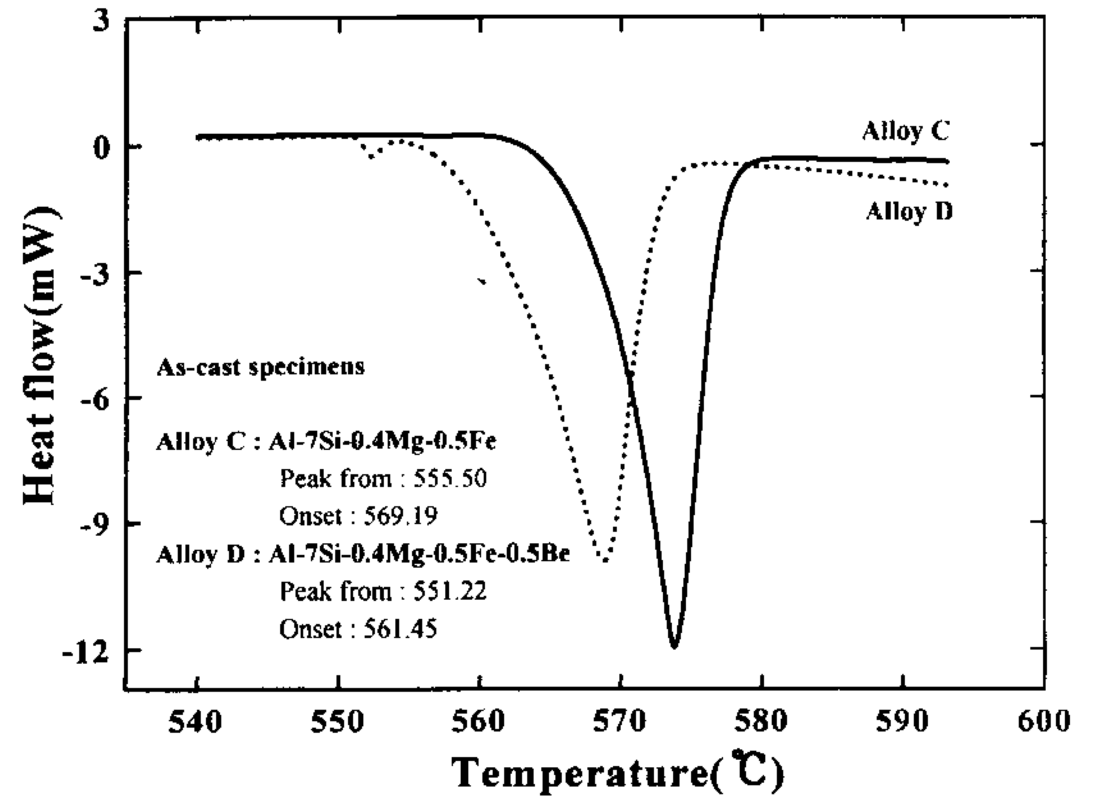

Fig. 11. DSC curves illustrating the effect of Be on the ternary eutectic temperature.

4. Conclusions

1. Addition of Be alters morphologies of the iron intermetallics from needlelike to script morphology, and to Be-rich phase. Needlelike β-phase was seen in the interdendritic regions, while script and Be-rich phase were found to be inside the primary aluminium dendrites in the Be-added alloy.

2. Morphologies of the iron intermetallics change gradually with the Be:Fe ratios. In Be-free alloys, the β-phase with needlelike morphology of β-phase is well developed, but script phase is appeared when Be:Fe ratio is above 0.2:1. With Be:Fe ratios of 0.4:1-1:1, script phase as well as Be-rich phase is also observed. In case of higher Be addition, above 1:1, Be-rich phase is observed on all regions of the specimens, and increasing of the Be:Fe ratios gradually make the Be-rich phase coarse.

3. For a constant solidification rate, the maximum length of β-phase was observed to be increased with the Fe content, but decreased by addition of Be.

4. Addition of Be improved tensile properties and impact toughness, due to the formation of a script or a Be-rich phase instead of the needlelike β-phase.

5. The specimen with high Fe level (0.68%) shows a mixed mode of intergranular and brittle cleavage fracture. However, the Be-added specimen with high Fe level (0.68%) exhibits ductile cellular fracture.

6. Addition of Be can increase the amount of Mg which is available for Mg_2Si precipitation hardening, and enhance the precipitation kinetics by lowering the ternary eutectic temperature.

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