Semisolid casting with ultrasonically melt-treated billets of Al-7mass%Si alloys

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Abstract: The demand for high performance cast aluminum alloy components is often disturbed by increasing impurity elements, such as iron accumulated from recycled scraps. It is strongly required that coarse plate-like iron compound of β-Al_5FeSi turns into harmless form without the need for applying refining additives or expensive virgin ingots. The microstructural modification of Al-7mass%Si alloy billets with different iron contents was examined by applying ultrasonic vibration during the solidification. Ultrasonically melt-treated billets were thixocast right after induction heating up to the semisolid temperature of 583 ℃, the microstructure and tensile properties were evaluated in the thixocast components.

Globular primary α-Al is required to fill up a thin cavity in thixocasting, so that the microstructural modification by ultrasonic melt-treatment was firstly confirmed in the billets. With ultrasonic melt-treatment in the temperature range of 630 ℃ to 605 ℃, the primary α-Al transforms itself from dendrite into fine globular in morphology. The coarse plate-like β-Al_5FeSi compound becomes markedly finer compared with those in non-treated billets. Semisolid soaking up to 583 ℃, does not appreciably affect the size of β-Al_5FeSi compounds; however, it affects the solid primary α-Al morphology to be more globular, which is convenient for thixocasting. After thixocasting with preheated billets, eutectic silicon plates are extremely refined due to the rapid solidification arising from low casting temperature. The tensile strength of thixocast samples with different iron contents does not change much even at 2mass% of iron, when thixocast with ultrasonically melt-treated billets. However, thixocast Al-7mass%Si-2mass%Fe alloy with non-treated billets exhibits an inferior strength of 80 MPa, compared with 180 MPa with ultrasonically melt-treated billets. The elongation is also improved by about a factor of two in thixocastings with ultrasonically melt-treated billets for all iron contents of Al-7mass%Si alloys, for example, the elongation of 11% in thixocast of Al-7mass%Si-0.5mass%Fe alloy with ultrasonically melt-treated billets, 5% in that with non-treated billets.

Key words: cast Al-Si alloy; ultrasonic radiation; thixocasting; α-Al; iron compound

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The recycling of aluminum alloy components plays an important role in realizing a sustainable society. With increasing recycled scraps, mixing and thickening impurity elements in the recycling of aluminum alloy components lead to a serious problem, because the cast components are expected to exhibit their higher performance. That is a reason why virgin ingots containing low iron as an impurity element are supplied to some of highly secured automotive components, instead of manufacturing with recycled ingots. A crystallized plate-like iron compound, β-Al_5FeSi, is known to grow in amount and size with increasing iron content in cast Al-Si alloys[1]. The developed β-Al_5FeSi compounds cause Al-Si alloy components to be brittle due to their plate-like morphology [2]. It has been reported that the β-Al_5FeSi compounds can be turned into harmless forms by refining additives containing manganese, as well as through supplying virgin ingots containing low iron [1, 3, 4]. However, there exists the possibility of reflecting new difficulties owing to excess manganese in recycling. Application of a large number of expensive virgin ingots is also not desirable from a viewpoint of energy consumption.

Besides the employment of manganese additives or virgin ingots, the application of ultrasonic vibration has been reported to be effective for the grain refinement of Al-Si alloys [5-8], so

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that it is expected that the plate-like β-Al_5FeSi compounds can be turned into be harmless forms by ultrasonic melt-treatment during the solidification[8]. Ultrasonic radiation is also expected to improve the fluidity for filling a thin wall cavity through the crystallization of fine globular primary α-Al [9]. Thixocasting firstly proposed by Flemings et al. [10] is widely known to improve the performance of cast Al-Si alloy components. The thixocasting is characterized by modifying its microstructure, lengthening the mold life due to the relatively low casting temperature, high precision in size and also decrease in shrinkage defects. It has been reported that the primary α-Al in hypoeutectic Al-Si alloys should be globular to maintain the appropriate fluidity of preheated billets at the semisolid temperature for thixocasting [11-15].

In the present study, both the modification of primary α-Al to be globular and the refinement of β-Al_5FeSi compounds are brought into hypoeutectic Al-Si alloys containing different amounts of iron by ultrasonic melt-treatment, without applying manganese additives or using virgin ingots. Thixocasting was carried out with billets preheated up to the semisolid temperature to examine the microstructure and tensile properties. The present study is focused on the conformity to the sustainable society, that is, the contribution to the wider applications of recycled aluminum alloys along with modifying the performance of recycled aluminum alloy components through the thixocasting with ultrasonically melt-treated billets.

1 Experimental procedure

Al-7mass%Si(AI-7Si) alloys with iron contents (mass%) of 0.04, 0.2, 0.5, 1.0 and 2.0 were prepared by a series of Al-10Fe master alloy additions. The alloys were heated up to 750 ℃ in an air atmosphere and then degassed by argon injection for 1.8 ks. Al-Si-Fe alloy of 890 g was poured at 630 ℃ into a graphite coated stainless steel container, which was 71 mm in diameter and 90 mm in height, to produce billets for thixocasting. The apparatus of the ultrasonic melt-treatment is schematically shown in Fig.1. Ultrasonic radiation was continuously applied to the molten Al-Si alloy from the pouring temperature of 630 ℃ to the semisolid temperature of 605 ℃. In solidified billets with and without ultrasonic melt-treatment, the microstructure was observed at the center of the billets using an optical microscope.

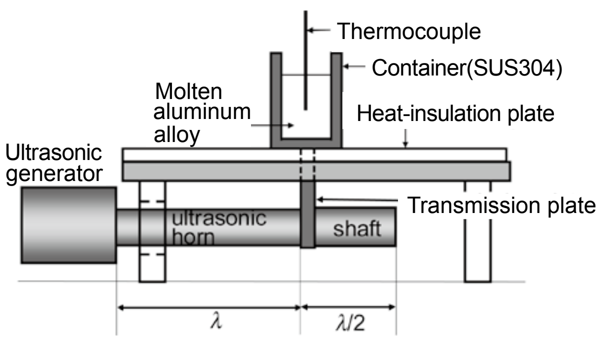

Fig.1: Schematic of experimental setup for preparation of thixocasting billet with ultrasonic vibration system

After heating up to the semisolid temperature of 583 ℃, all billets, both prepared with and without applying ultrasonic radiation, were thixocast using a pressure casting machine, in which the punch traverse speed was 290 mm·s^{-1}, the casting force was 680 kN and the mold preheat temperature was 200 to 290 ℃, to produce a typical component, as shown in Fig. 2. Microstructure observation and tensile tests were performed with the thixocast specimens without any heat treatment. A tensile specimen of 4 mm in width and 3 mm in thickness, as shown in Fig. 2, was prepared by wire-cut electrical discharge machining.

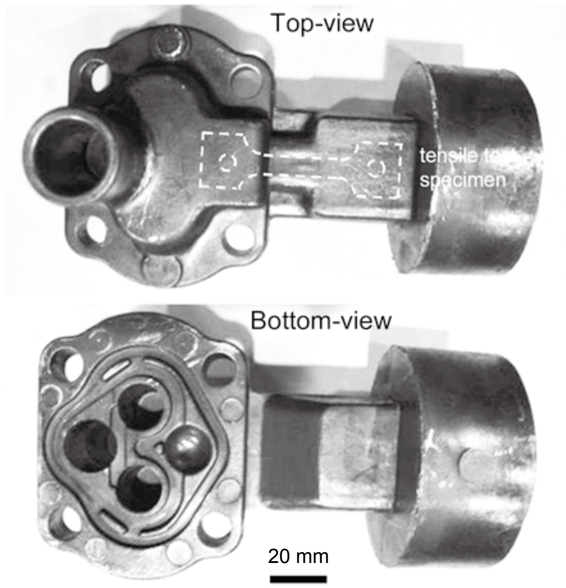

Fig. 2: Thixocast component and sampling of tensile test specimens by wire-cut electrical discharge machining

2 Results and discussion

2.1 Microstructure of ultrasonically melt-treated billets

Figure 3 shows typical microstructures of ultrasonically melt-treated and non-treated billets. The coarse dendritic primary α-Al solid solution in non-treated billets as in Fig. 3(a) is turned into fine globular morphology by ultrasonic melt-treatment. However, the dendritic morphology of primary α-Al is not well defined in the higher iron content of 2mass%Fe shown in Fig. 3(b). When iron was added into Al-7mass%Si alloy as an impurity, the developed plate-like β-Al_5FeSi compounds are recognized, as shown in Fig. 3(b). The size and amount of β-Al_5FeSi compounds increase in non-treated billets with increasing iron content. Especially, in the high iron content of Al-7Si-2Fe alloy shown in Fig. 3(b), without applied ultrasonic melt-treatment, the well developed enormous β-Al_5FeSi compounds of over 1 mm in size are crystallized in billets. However, even these enormous plate-like β-Al_5FeSi compounds are turned into fine globular morphology by the ultrasonic melt-treatment. Ultrasonic radiation in molten Al-

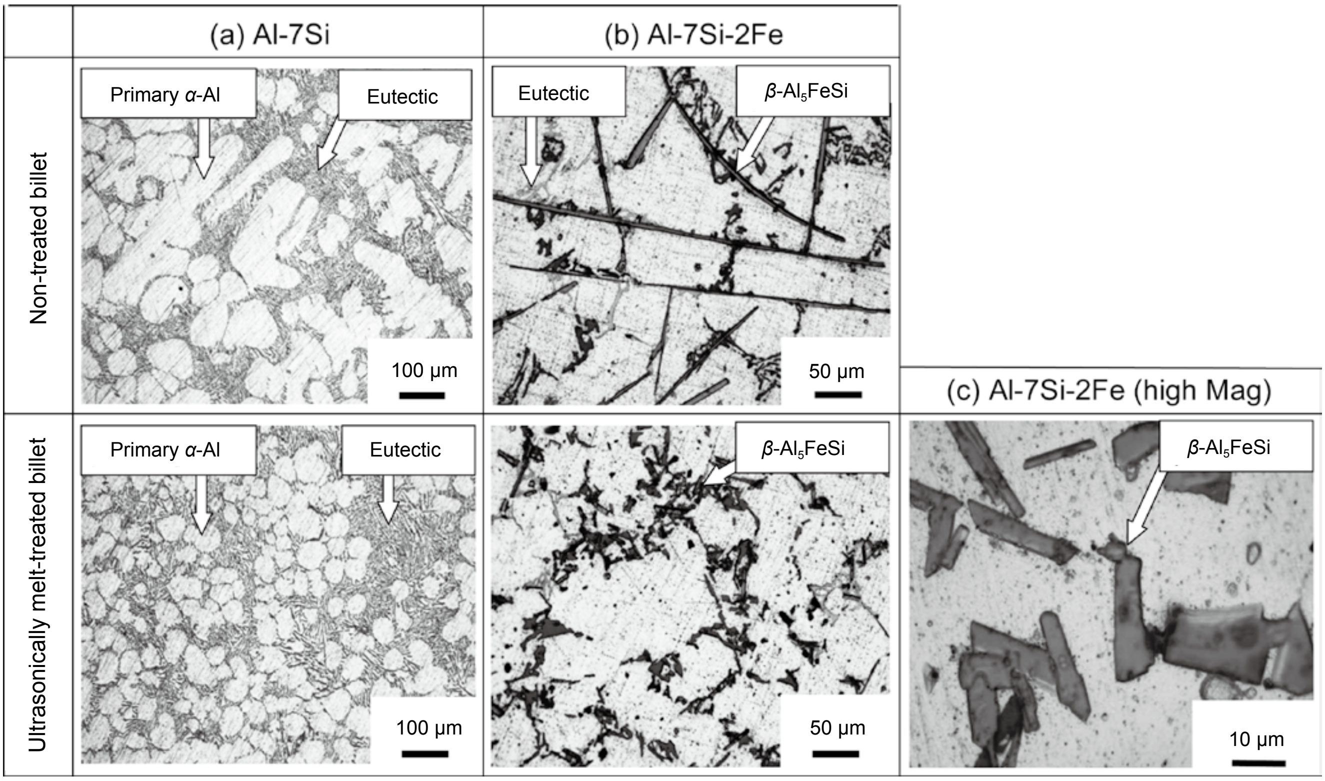

Fig. 3: Typical microstructures of (a) Al-7mass%Si alloy and (b) Al-7mass%Si-2mass%Fe alloy without and with ultrasonic melt-treatment, respectively, solidified in the temperature range of 630 to 605 ºC, (c) highly magnified microstructures of part of (b) with ultrasonic melt-treatment

7Si-2Fe alloy during the solidification gives a marked effect on the refinement of β-Al_5FeSi compounds, as shown in the highly magnified photo of Fig. 3(c).

The acoustic cavitation and streaming generated in molten metal affect the nucleation and growth of both primary α-Al and β-Al_5FeSi compound, and also affect the amount of α-Al during the solidification with ultrasonic radiation. The refining mechanism of the plate-like β-Al_5FeSi compound by ultrasonic melt-treatment was studied by X-ray diffraction, that is, alternative nucleation of α-Al_8Fe_2Si instead of the crystallization of β-Al_5FeSi just as with manganese additives[1], or simple refinement of β-Al_5FeSi compound without any phase transformation. There are no appreciable differences between diffraction peaks of β-Al_5FeSi and the strongest peak of α-Al_8Fe_2Si, as shown in Fig. 4. Consequently, the phase transformation of β-Al_5FeSi to α-Al_8Fe_2Si does not occur in the ultrasonic melt-treatment of molten Al-7Si-2Fe alloys during the solidification.

Ultrasonic radiation was stopped before reaching the eutectic temperature, so that the morphology of eutectic silicon in ultrasonically melt-treated billets is still needle-like, which is the same as that in non-treated billets. With an increase in iron content, since the alloying element of silicon is consumed for the crystallization of β-Al_5FeSi compounds before reaching the eutectic temperature, it is expected that the area percentage of eutectic region decreases in the microstructure solidified with ultrasonic radiation.

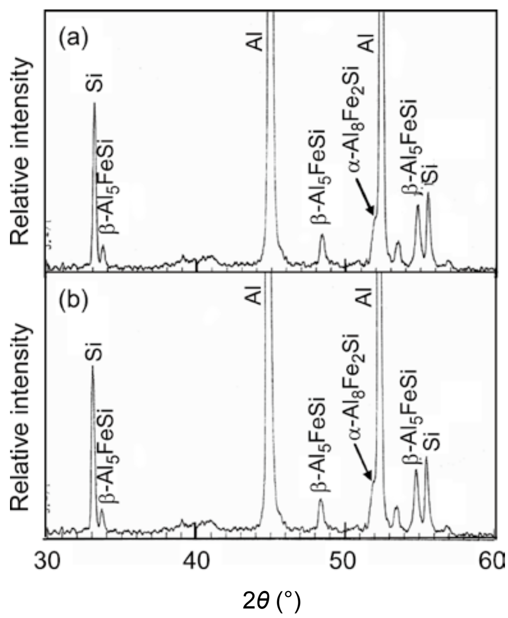

Fig. 4: Typical X-ray diffraction patterns (Co-K$_\alpha$ radiation) of Al-7mass%Si-2mass%Fe alloy (a) without and (b) with ultrasonic melt-treatment, respectively, solidified in the temperature range of 630 to 605 ºC

2.2 Change in microstructure in thixocasting

The change in microstructure of billets by heating up to the semisolid temperature of 583 ℃ was studied prior to the thixocasting. The microstructure of Al-7Si-2Fe alloy billets quenched from 583 ℃ is typically shown in Fig. 5. The microstructure of non-treated billets in Fig. 3(b) turns into distinct globular morphology of primary α-Al surrounded by the eutectic region after the heating, as shown in Fig. 5. The influence of ultrasonic radiation on the morphology of α-Al, which was not well defined in Al-7Si-2Fe billets of Fig. 3(b), becomes more distinct after the heating, that is, the primary α-Al has a finer globular morphology compared with that in non-treated billets. With heating up to the semisolid temperature of 583 ℃, however, there are no appreciable changes in size and distribution of β-Al_5FeSi compounds refined by ultrasonic radiation.

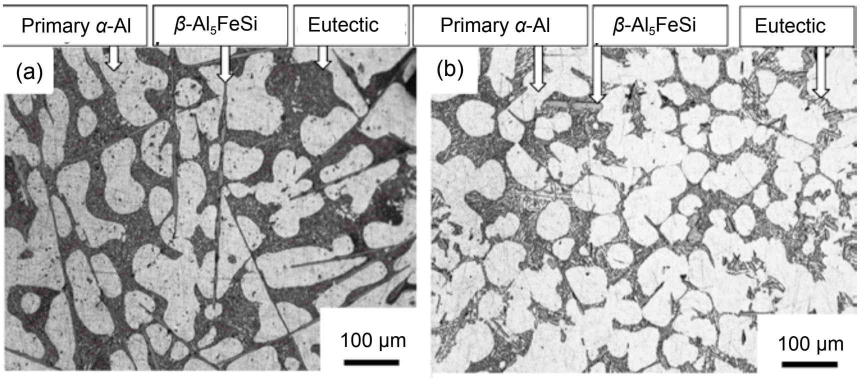

Fig. 5: Typical microstructures of Al-7mass%Si-2mass%Fe alloy billet after induction heating up to 583 °C: (a) without and (b) with ultrasonic melt-treatment

Thixocasting was carried out with billets right after preheating up to the semisolid temperature of 583 ℃. Typical microstructure is shown in Fig. 6, which includes both thixocast samples with ultrasonically melt-treated and non-treated billets. However, globular primary α-Al modified by the ultrasonic melt-treatment is different in diameter and circularity compared with those of non-treated billets, although they slightly grow after preheating up to the semisolid temperature. The microstructure of Al-7Si-0.5Fe alloy shown in Fig. 6(b) is similar to that of Fig. 6(a), except for the crystallization of a small amount of β-Al_5FeSi compound. The primary α-Al becomes larger in non-treated billets with increasing iron content, as shown in Fig. 6(c). As noted previously, there is no appreciable difference in size of refined β-Al_5FeSi after heating up to the semisolid temperature. When non-treated billets were thixocast, the breakage of enormous plate-like β-Al_5FeSi compounds is recognized due to the high casting pressure in thixocasting, as shown in Fig. 6(c), because the size of β-Al_5FeSi compounds becomes larger in Al-7Si alloys when the iron content is increased. In contrast, when ultrasonically melt-treated billets were thixocast, there exists no breakage of β-Al_5FeSi compounds because they have already been refined by the ultrasonic radiation.

The eutectic silicon is markedly modified by thixocasting due to the rapid cooling from the semisolid temperature, the coarse eutectic silicon needles in the billets of Figs. 7(a) are remarkably refined, as shown in Figs. 7(b) and (c). The

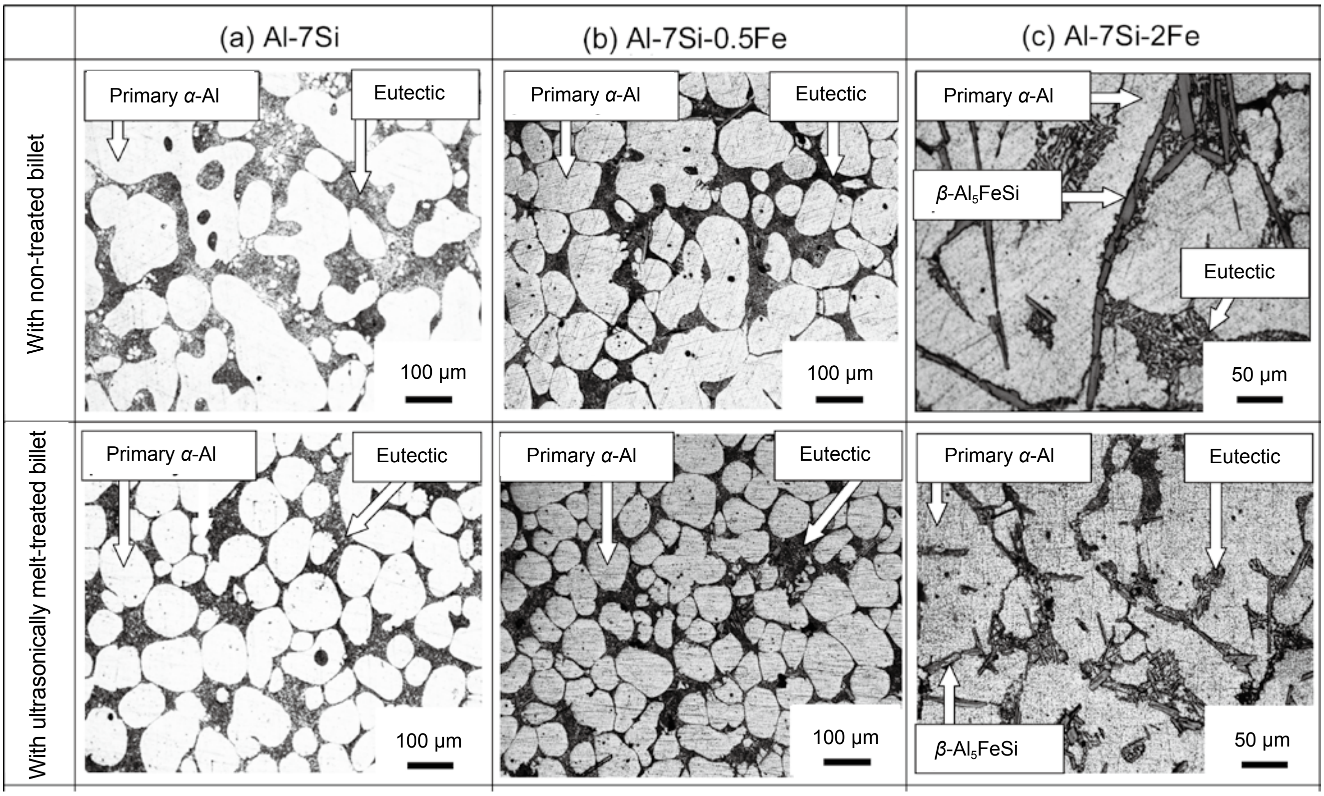

Fig. 6: Typical microstructures of thixocast (a) Al-7mass%Si, (b) Al-7mass%Si-0.5mass%Fe and (c) Al-7mass%Si-2mass%Fe alloy with non-treated and ultrasonically melt-treated billets

refinement of eutectic silicon proceeds through the quenching effect chilled by the cavity surface, since the cooling in semisolid billets shows a lower latent heat expression. Thixocasting of Al-Si alloys is characterized by the refinement of eutectic silicon, so that the sizes of eutectic silicon in Figs. 7(b) and (c) are nearly the same, regardless of the use, or not, of ultrasonic melt-treatment.

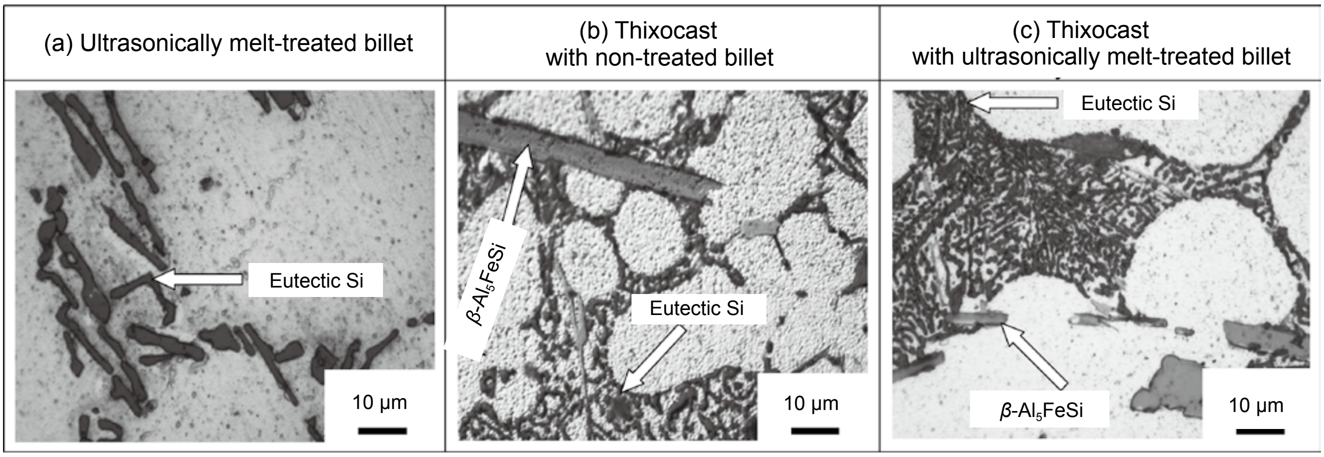

Fig. 7: Typical highly magnified microstructures of Al-7mass%Si-2mass%Fe alloy (a) before thixocasting, and after thixocasting with (b) non-treated and (c) ultrasonically melt-treated billets

2.3 Tensile properties of thixocast samples

Tensile tests were performed with the as thixocast specimens shaped by wire-cut electrical discharge machining, as shown in Fig. 2. The tensile strength of thixocast specimens with ultrasonically melt-treated billets is shown in Fig. 8 as a function of iron content, as well as that with non-treated billets. It is known that the tensile strength and elongation become inferior due to the well developed plate-like β-Al_5FeSi compounds, when the iron content is over 1mass% in Al-7Si alloy. In the case of thixocast samples produced with non-treated billets, the tensile strength of Al-7Si-2Fe alloy decreases suddenly by 40%, although they maintain a constant tensile strength up to the iron content of 1mass%. However, there exists no decrease in tensile strength up to 2mass% of iron in the thixocast samples with ultrasonically melt-treated billets, rather it remains constant. The tensile strength of thixocast Al-7Si-2Fe alloy is clearly improved because of the refinement of harmful enormous plate-like β-Al_5FeSi compounds.

The elongation, which was also measured in tensile tests of thixocast samples, both with and without ultrasonic melt-treatment, is shown in Fig. 9. The elongation decreases linearly with increasing iron content, which is clearly different from the profile of the tensile strength. The elongation of thixocast samples produced with ultrasonic melt-treatment is approximately 2 times higher than that without ultrasonic radiation, regardless of iron content. Especially the marked modification in the elongation is observed in the thixocast samples containing less than 0.5mass% iron, that is, the elongation of over 10%.

The microstructure was observed on the planes perpendicular to the fracture surface of Al-7Si-2Fe alloy in tensile tests; and typical examples are shown in Fig. 10. The fine β-Al_5FeSi compounds are observed close to the fracture surface obtained

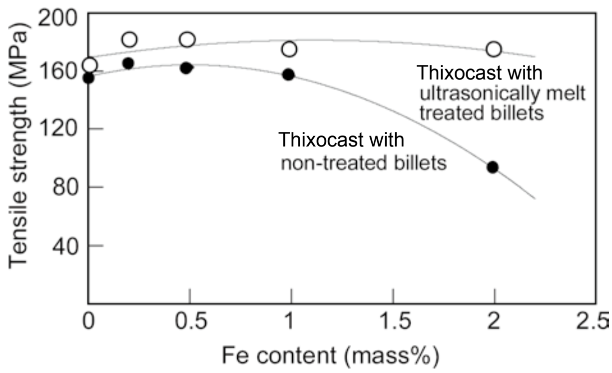

Fig. 8: Change in tensile strength of thixocast Al-7mass%Si alloy with non-treated and ultrasonically melt-treated billets as function of iron content

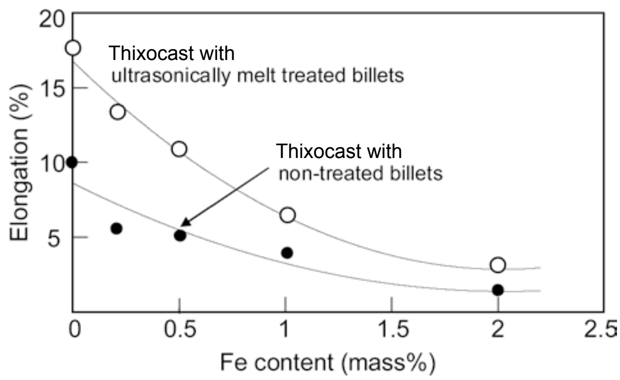

Fig .9: Change in elongation of thixocast Al-7mass%Si alloy with non-treated and ultrasonically melt-treated billets as function of iron content

from sample with ultrasonic melt-treatment; however, cracks do not pass through the β-Al_5FeSi interfaces as shown in Fig. 10(b). In contrast, the β-Al_5FeSi compounds are included at the crack propagation path, as shown in Fig. 10(a), so that the β-Al_5FeSi interfaces seem to invite a crack initiation site and/or a propagation path.

Even if the iron content is 1mass% in Al-7mass%Si alloys, the elongation obtained in thixocastings with ultrasonically melt-treated billets corresponds to that with non-treated billets containing less than 0.5mass%Fe. Since the β-Al_5FeSi compounds become almost harmless forms in thixocast samples by the application of ultrasonic radiation during the solidification, high performance Al-Si alloy components produced with virgin ingots containing less than 0.2mass%Fe can be manufactured through the processing with ultrasonic radiation, that is, the recycled ingots containing 0.5mass%Fe can be supplied to the wide application fields of required high performance.

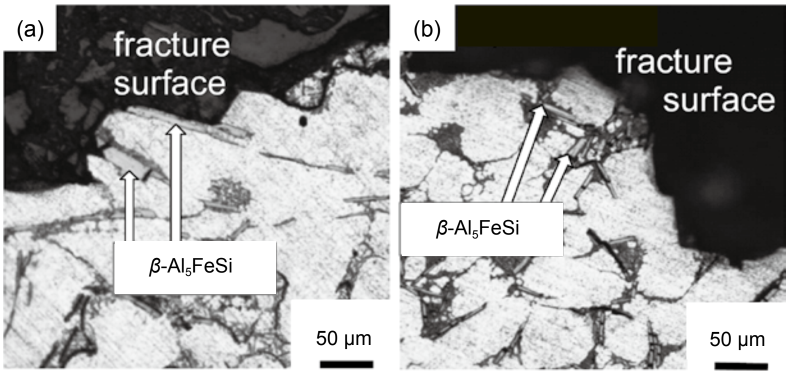

Fig. 10: Optical micrographs showing cross-sectional fracture surface of thixocast Al-7mass%Si-2mass%Fe alloy with (a) non-treated and (b) ultrasonically melt-treated billet

3 Conclusions

Thixocasting of Al-7mass%Si alloys containing different amounts of iron were performed with ultrasonically melt-treated billets to examine the modification in microstructure and tensile properties. The obtained results are as follows:

(1) The microstructure obtained with ultrasonic melt-treatment radiated from the liquid temperature of 630 ℃ to the semisolid of 605 ℃ is characterized by both fine β-Al_5FeSi compound instead of coarse plate-like and fine globular primary α-Al modified from its dendritic morphology.

(2) With heating up to the semisolid temperature of 583 ℃, there is observed no appreciable coarsening in β-Al_5FeSi compounds, and the modification in circularity of primary α-Al along with its slight growth. The eutectic silicon is also refined by the rapid cooling from the semisolid temperature in thixocasting, regardless of the use of ultrasonic melt-treatment.

(3) Recycled ingots can be supplied to the production of high performance Al-Si cast components, because the tensile strength and elongation are remarkably improved through the characteristic microstructures consisting of fine globular α-Al, fine β-Al_5FeSi compound and fine eutectic silicon in thixocastings with ultrasonically melt-treated billets.

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