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Significance of Rapidly Solidified Aluminum Alloy Strips for High Quality Recycling

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Significance of rapidly solidified aluminum alloy strips fabricated by a twin-roll strip caster was demonstrated for high quality recycling of widely-used conventional aluminum alloys. An A356 aluminum alloy was cast into a plate using the strip caster equipped with a pair of water-cooled copper rolls. The estimated cooling rate of the cast product was 500~4000K/s. The rapid cooling rate resulted in refined solidification structure. A cold-rolled sheet produced from the strip-cast plate exhibited improved formability compared to the reference material fabricated by conventional method. The rapidly solidified cast strip of a 6063 aluminum alloy with high Fe content was cold-rolled and heat-treated to form a thin sheet. Increase in Fe content resulted in refined grain size. Detrimental effect of Fe was not evident except for reduced precipitation hardening.
Key words: Recycling, Aluminum alloy, Twin-roll caster, Rapid solidification, Mechanical properties

1. INTRODUCTION

The incentive for the recycling of material is particularly strong in the case of aluminum because remelting of scrap requires only 3~5% of the energy needed to produce the same weight of primary aluminum from the ore bauxite. Conventional scrap remelting, however, tends to downgrade the alloys so that they are used almost exclusively for foundry castings. There is a need to accommodate more aluminum scrap in cast billets to be used for producing wrought alloys.

The strip casting is a direct plate producing method from the alloy melt. In the 1930s and 1940s, the development of continuous strip casting began on industrial scale. There was great enthusiasm for strip casting, with the idea of avoiding investment in hot-rolling mills in 1950s and 1960s. However, cast strip could not match the quality of strip produced by conventional hot-rolling, especially for hard alloys and for products with high quality requirements.

Recently, however, strip casting has gained new impetus. Used beverage can (UBC) recycling is much more efficient if UBC can be transformed into canstock in decentralized locations, in so called "mini-mills" [1].

Advantages of strip casting in this case are as follows. (i) the equipment is small-scale, relatively simple and cheap, (ii) the plant can be located close to the can-making plant, (iii) the whole cycle from liquid metal to finished canstock ready for the can-making plant takes place no more than a day.

Considering these advantages, strip casting is also applicable to recycling of aluminum alloy scrap for automotive use.

Solidification of the starting product is important since the initial solidification structure controls mechanical, physical and chemical properties of the final product. Rapid solidification can be achieved by using a newly developed twin roll strip caster. Rapid solidification can provide (i) grain refinement, (ii) supersaturation of relatively insoluble elements and (iii) fine and homogeneous distribution of secondary particles.

The present study aims to demonstrate the importance of fine solidification structure of roll cast strips for high-quality recycling of aluminum alloys using widely-used commercial A356 and 6063 aluminum alloys.

2. HIGH SPEED TWIN ROLL CASTER

Since the introduction of the Hunter vertical casters nearly 50 years ago both the equipment and the casting techniques have evolved gradually, but there has been little or no change in the underlying process technology. In twin-roll casting, molten metal is fed onto water-cooled rolls. Solidification begins when the molten metal contacts the water-cooled casting rolls, and due to the progressively reducing dimension of the roll bite, the solidifying metal is forced to remain in contact with the rolls. Once solidification is completed, the material undergoes a degree of hot working before leaving the roll bite [2].

At present, the vast majority of commercial twin-roll casters produce sheet aluminum of around 6mm thick. There is, however, great interest in producing strip at thinner gages because this will allow increases in productivity as well as improvements in materials properties [3]. One of the major challenges for the twin-roll casting production route is to improve both physical and mechanical properties of the sheet while achieving high productivity. Thin strip casting (1-4mm thick) has shown potential for high increases in productivity as well as for improvement of materials properties, and therefore has attracted great interest.

Figure 1 shows a vertical-type twin roll caster used in the present study, which has been called as Hydrostatic Pressing Twin Roll Caster (HPTRC) [4].

By using the present caster, a thin cast strip, which is thinner than 2mm, can be fabricated at a high speed of 30 to 120m/min. Characteristics and resultant merits of the present caster are as followings.

The present roll caster is equipped with a pair of water-cooled copper rolls. No lubricant is employed at the roll surface. These facilitate heat transfer from the melt to the rotating rolls. The roll diameter is 300mm. The face width of the roll is 100mm.

A casting nozzle made of heat-insulating material is mounted on the twin roll. Introduction of the nozzle works effectively in many ways as shown below.

The width of the nozzle controls the solidification length, which is the circumferential length of the roll surface, with which the melt contacts. The resultant strip thickness can be kept constant since the solidification length is maintained constant by the nozzle.

Another role of the nozzle is application of hydrostatic pressure to the melt. This is beneficial to improve heat transfer between melt and the roll. Hydrostatic pressure is also useful to prevent the oscillation. Oscillation of meniscus of the molten metal often happens, and this results in periodical undesirable marks on the strip surface.

Separating force applied in the present study is very small in order to prevent sticking of the strip to the roll. Casting temperature of the melt is relatively low in order to promote rapid solidification.

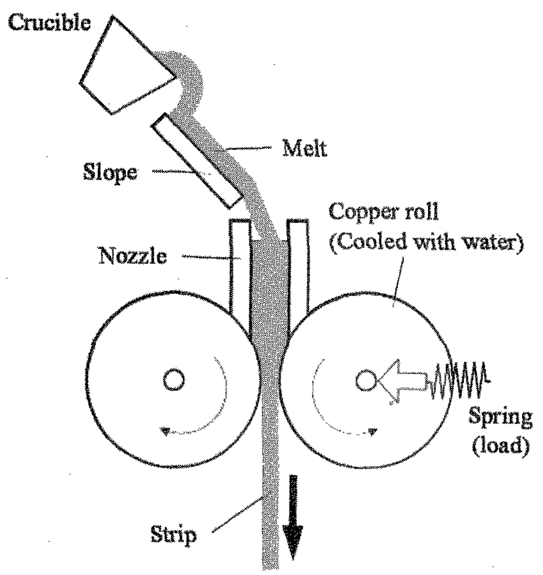

Fig. 1 Vertical-type twin roll caster.

3. HIGH SPEED TWIN ROLL CASTING OF A356 ALUMINUM ALLOY

The material selected in the present study is A356 aluminum alloy, which belongs to the most widely used aluminum-silicon alloy system, as shown in Fig. 2.

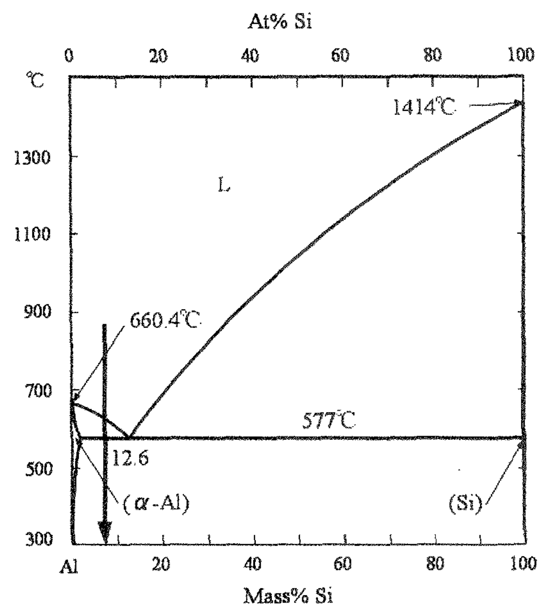

Fig. 2 Al-Si phase diagram.

The hypo-eutectic Al-7%Si-0.4%Mg alloy is commonly specified as a cast aluminum alloy for automotive applications. Figure 3 shows an optical micrograph of the solidified structure of the conventional cast product. Microstructural features of the alloy are characterized by secondary dendrite arm spacing (DAS) of primary aluminum, and morphology and distribution of eutectic Si particles.

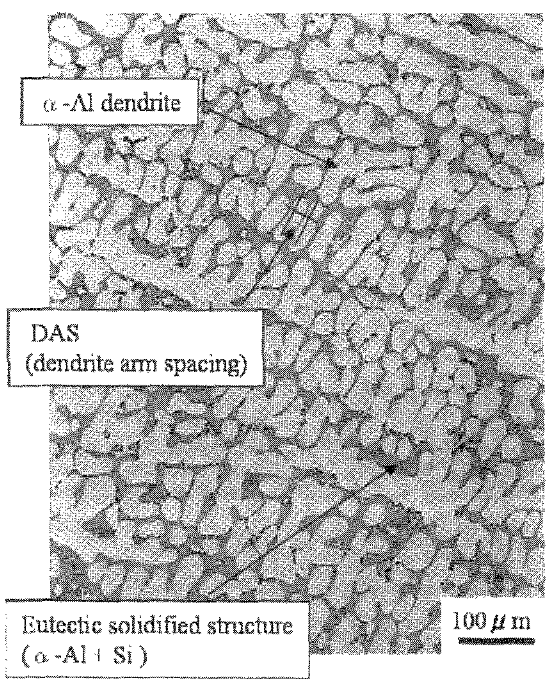

Fig. 3 Solidified structure of A356 alloy.

The alloy was melted at 898K(625℃) and poured into the nozzle through the cooling slope. Roll speed was 90m/min and the resultant thickness of the cast strip was 2mm. For comparison, the alloy was also cast into a conventional permanent mold.

Figures 4 show solidified structure of the cast plate. The twin-roll cast plate exhibits fairly refined primary dendrite and eutectic solidified structure. DAS for the near-surface region (a) and the mid-thickness region (b) was 3μm and 5μm, respectively. In contrast, DAS for the permanent mold cast plate (c) was 30μm.

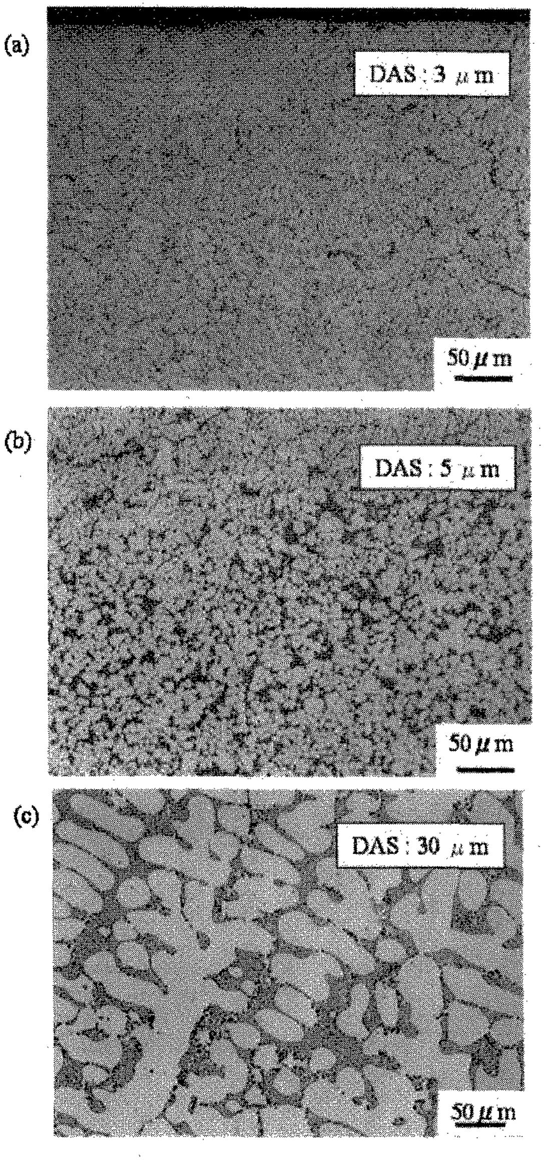

Fig. 4 Solidified structure of the cast plate : (a) Twin-roll cast (near-surface), (b) Twin-roll cast (mid-thickness) and (c) permanent mold cast.

The relationship between DAS and cooling rates has been investigated for A356 alloys so far, as shown in Fig. 5. By using the relationship, cooling rates of the cast strip can be estimated. The estimated cooling rate at the near-surface region is 4000K/s, and it is 500K/s for the mid-thickness region. These are significantly larger than that for the permanent mold cast (2K/s).

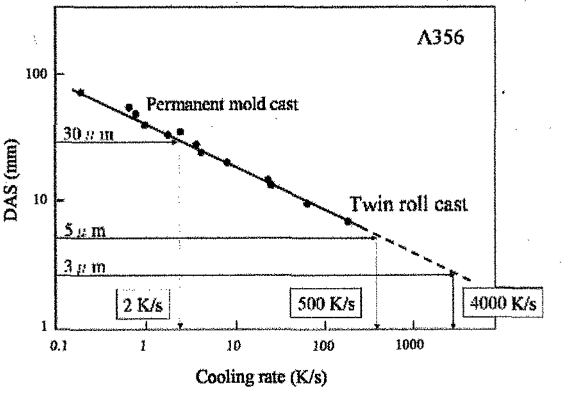

Fig. 5 Relationship between cooling rates and DAS for A356 alloy.

Refined solidification structure is beneficial for mechanical properties of the downstream product. The twin-roll cast plate (2mm thick) was homogenized at 803K(530℃) for 4h and then cold-rolled into a 0.5mm thick sheet. After cold-rolling, it was annealed at 723K(450℃) for 4h. The permanent mold cast plate was also machined into a 2mm thick plate, and then cold-rolled into a 0.5mm thick sheet in the same procedure.

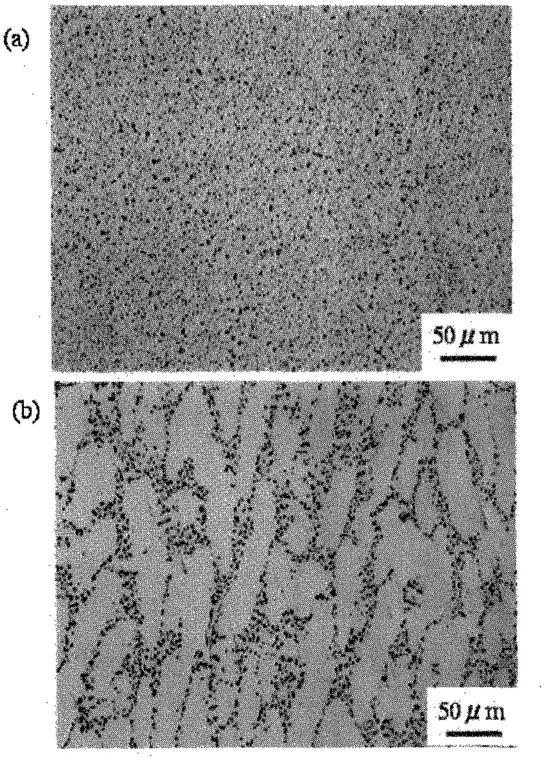

Fig. 6 Microstructure of the sheet surface of the twin-roll cast (a) and the permanent mold cast (b) products.

Figure 6 shows optical micrographs of the sheet surface for the twin-roll cast and the permanent mold cast products. Fine and homogeneous distribution of Si particles are observed for the twin-roll cast product. In contrast, for the permanent mold cast product, Si

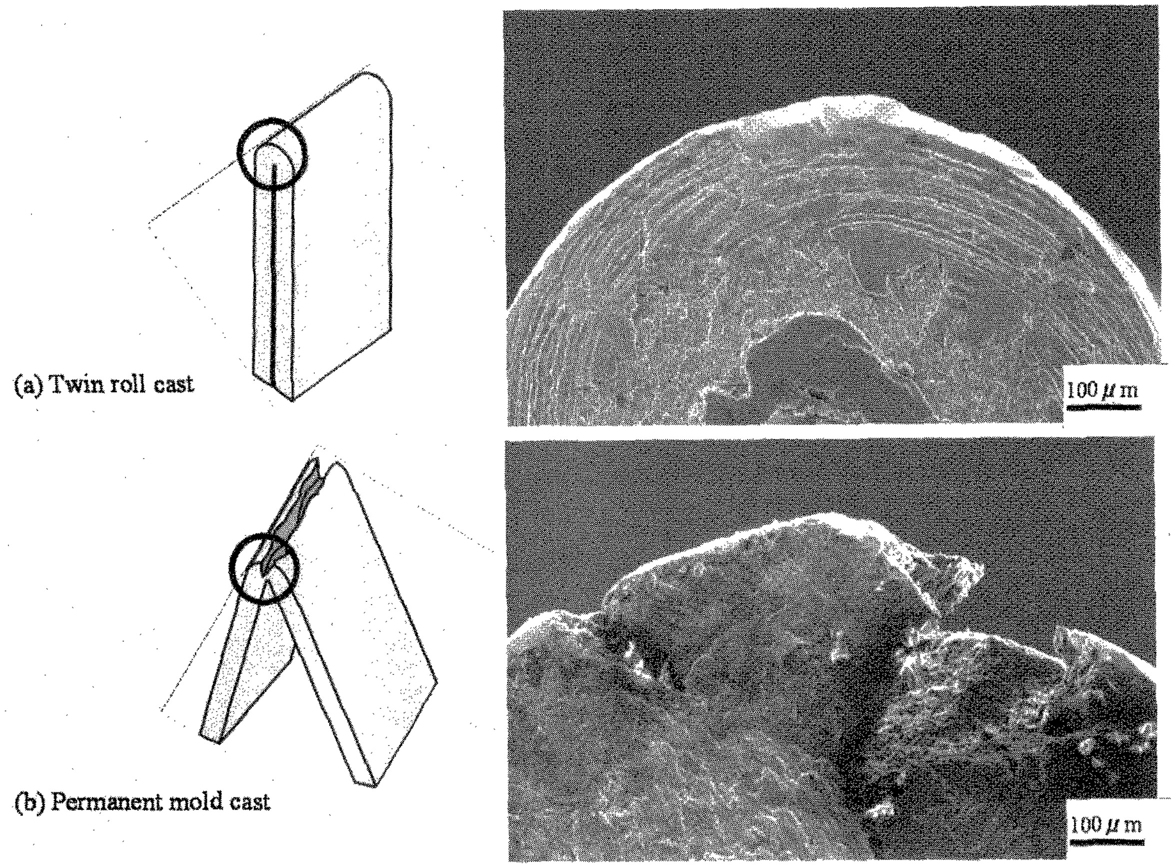

Fig. 7 Bending test results for (a) twin-roll cast product and (b) permanent mold cast product

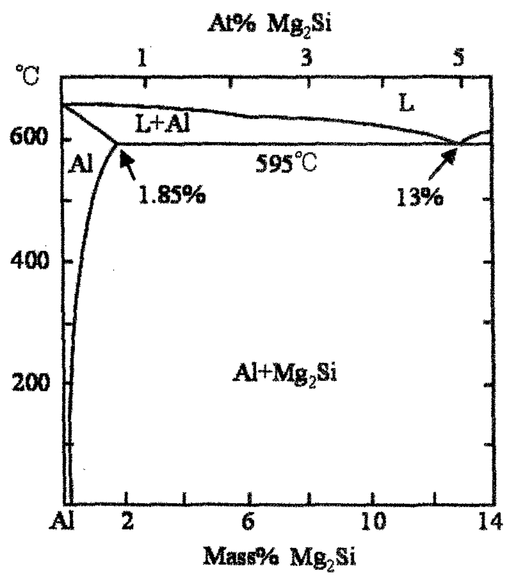

Fig. 8 Al-Mg_2Si phase diagram.

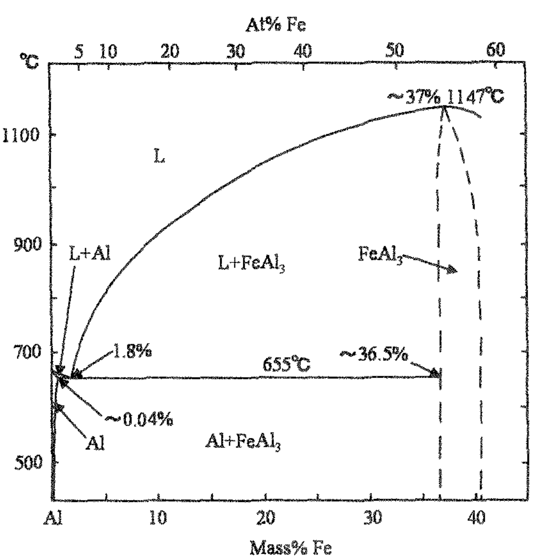

Fig. 9 Al-Fe phase diagram.

particles are segregated being dispersed along the original dendrite branches.

Each sheet was subjected to the 180° bending test as shown in Fig. 7. Cracking took place for the permanent mold cast product. No cracking occurred for the twin-roll cast product. Improved formability is mainly due to the fine and evenly-distributed Si particle structure. It should be mentioned that such a microstructure is originated from the initial rapidly solidified structure produced by the twin-roll casting method.

4. HIGH SPEED TWIN ROLL CASTING OF 6063 ALUMINUM ALLOY WITH HIGH Fe CONTENT

Al-Mg-Si alloys are widely used as medium-strength

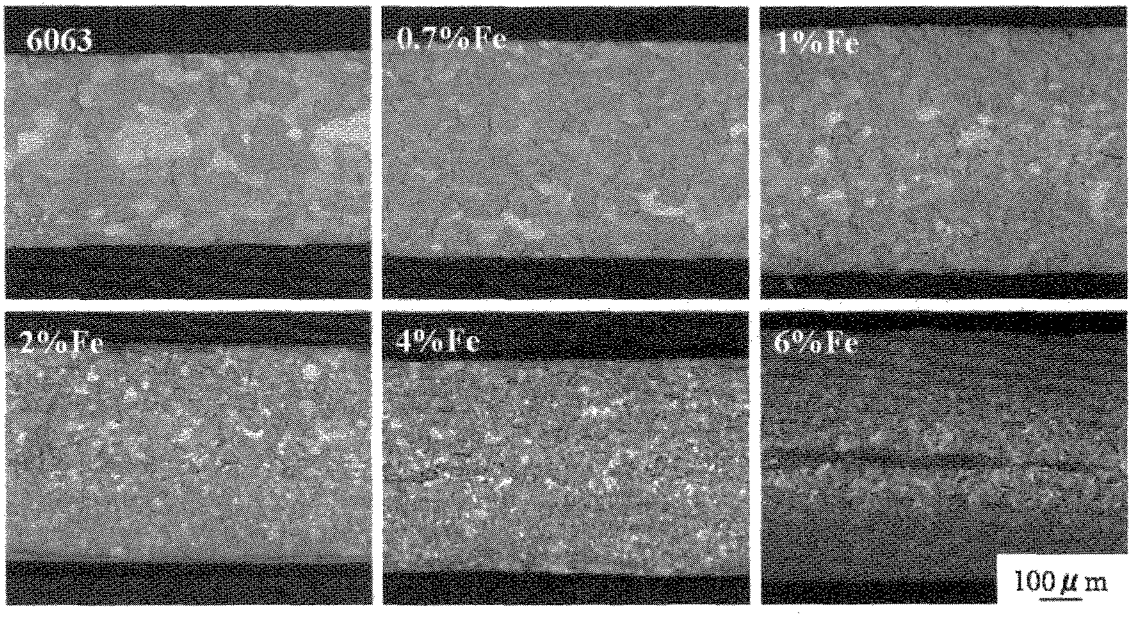

Fig. 10 Transverse section of the sheet.

structural alloys. Magnesium and silicon are added either in balanced amounts to form quasi-binary Al-Mg_2Si alloys, or with an excess of silicon above that needed to form Mg_2Si, as shown in Fig. 8. 6063 belongs to the alloy group with balanced amounts of Mg and Si adding up to between 0.8% and 1.2%. Moderate strength is developed by age hardening and one alloy, 6063, is the most widely used of all Al-Mg-Si alloys. Figure 9 shows the Al-Fe phase-diagram. The impurity limit for Fe is 0.35mass% for 6063 alloys [5].

Another benefit of the rapid cooling rate was demonstrated by using a 6063 aluminum alloy with high Fe content, which was selected as a model of the scrap-based secondary alloy. It is well known that reduction of detrimental effects of Fe on mechanical properties of 6xxx series alloy is of primary problem for high-grade and closed-type recycling.

As mentioned previously, rapid solidification takes place in twin-roll casting, leading to characteristic features in the microstructure, such as a marked supersaturation of the relatively insoluble elements, fine matrix grain structure, and fine and even distribution of secondary particles. These characteristics will be helpful to minimize the detrimental effect of impurities from scrap.

6063 aluminum alloys with various Fe contents (0.35, 0.7 and 1~6mass%) were strip cast using the twin-roll caster at a roll speed of 60m/min. The rapidly solidified cast strips (thickness: 1.5~2.7mm) were homogenized at 813K(540℃) for 2h, and then cold-rolled into 1mm thick sheets. After annealing at 813K for 1h, they were cold-rolled again into 0.5mm thick sheets. Sheets were homogenized at 813K for 2h and water-quenched. The resultant sheets were naturally-aged (T4) or artificially -aged at 433K(160℃) for 6h (T6).

Figure 10 shows the transverse section of the sheets. It was found that grain size was reduced with increasing Fe content. Dark spots or banded area observed in the mid-thickness region in the sheet correspond to segregated coarse Al-Fe-Si-base intermetallic particles.

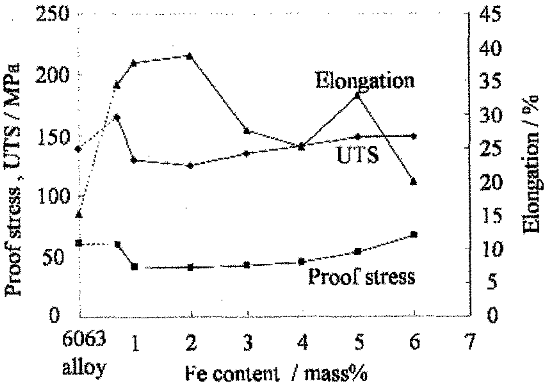

Fig. 11 Tensile properties of the rolled sheet for T4 condition.

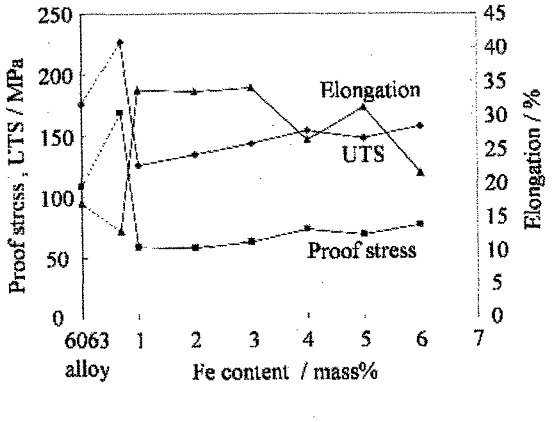

Fig. 12 Tensile properties of the rolled sheet for T6 condition.

Figure 11 shows tensile properties of the rolled sheet for T4 condition. Slight increase in proof stress and UTS is observed with increase in Fe content. Detrimental influence of Fe is not apparent. Tensile properties of the rolled sheet for T6 condition are exhibited in Fig. 12. Reduced age-hardening effect is evident for high Fe materials. This may relate to the increased volume fraction of intermetallic compound particles.

5. SUMMARY

An A356 aluminum alloy was cast into a plate using the strip caster equipped with a pair of water-cooled copper rolls. The estimated cooling rate of the cast product was 500~4000K/s. The rapid cooling rate resulted in refined solidification structure. A cold-rolled sheet produced from the strip-cast plate exhibited improved formability compared to the reference material fabricated by conventional method. The rapidly solidified cast strip of a 6063 aluminum alloy with high Fe content was cold-rolled and heat-treated to form a thin sheet. Increase in Fe content resulted in refined grain size. Detrimental effect of Fe was not evident except for reduced precipitation hardening.

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