High-Speed Twin Roll Casting of Thin Aluminum Alloy Strips Containing Fe Impurities

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In this work, the mechanical properties of roll-cast recycled aluminum alloy were investigated. Fe was added to 6111 aluminum alloy to simulate recycled aluminum alloy. The Fe content was varied between 0.14 and 1.02 mass%. A high-speed twin roll caster was used because it exhibits better cooling characteristics than the conventional twin roll casters. The strip was cast at a speed of 60 m/min and the resulting strip microstructure was not columnar, but equiaxed or globular. When the Fe content was 0.4 mass%, the Fe content does not appear to exert any influence on the tension test results after T6 heat treatment, and after a 180-degree bending test no cracks occurred on the outer surface.

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1. Introduction

From an environmental standpoint, reducing automobile weight is a very important goal. The use of aluminum alloys instead of steel offers a practical way of solving this problem. However, sheets of aluminum alloy used for automobile body work are very expensive. Therefore, in order to make the use of aluminum alloys for automotive bodywork applications cost effective it is necessary to develop a low cost aluminum alloy sheet. There are two ways to reduce aluminum alloy sheet costs: either adopting a more economical process or using recycled aluminum alloys. Of course, during recycling, the Fe content increases resulting in degradation of the mechanical properties. One method of improving the mechanical properties of recycled aluminum alloy is through rapid solidification. The twin roll caster can achieve both effects, i.e. rapid solidification and offer an economic process. Therefore twin roll casting is a suitable method for economically producing strips from recycled aluminum alloy, although there have been reports voicing some concern over roll casting recycled 6000 series aluminum alloy.¹²

Recycled aluminum alloy displays higher Fe impurity concentrations and because the intermetallics crystallize with the Fe, the ductility of the recycled aluminum alloy decreases. However, when the size of the intermetallics is reduced, their influence on the ductility decrease becomes smaller. Rapid solidification is a useful technique for creating fine intermetallics. Because the cooling rate of the twin roll caster is very high, it is useful for reducing the influence of impurities in the intermetallics. However, the casting speed of conventional twin roll casters for aluminum alloy (CTRCA) is slower than 10 m/min, resulting in a low productivity and as a result the casting speed must be increased in order to improve processing costs. A high cooling ability is the preferred method for reducing the size of impurities and rendering them harmless. A high-speed twin roll caster (HSTRC) was used in this study to achieve a high cooling rate. Some additional devices for increasing the cooling rate were also introduced to the HSTRC. The cooling rate of the HSTRC is higher than that of the CTRCA when these devices are installed. In addition, the HSTRC is able to improve low productivity. In the present study, strip casting of Fe added to 6111 aluminum alloy, which was used to model recycled aluminum alloy, was processed using a the high speed twin roll caster and the resulting mechanical properties of the strip were investigated.

2. High Speed Twin Roll Caster

A high speed twin roll caster (HSTRC) was used in the present study and a schematic illustration of the HSTRC is provided in Fig. 1. In order to increase the cooling rate of the strip, some devices were installed on the HSTRC. HSTRC is a vertical type twin roll caster. The nozzle, which was added to the original HSTRC design, is useful for increasing the heat transfer between the roll and the melt using the hydrostatic pressure of the melt head. The higher the melt head, the better the heat transfer. The oscillation of the meniscus at the tip of the nozzle degrades the strip surface. However, the hydrostatic pressure prevents the meniscus

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Fig. 1 High speed twin roll caster (HSTRC).
from oscillating. Therefore, the addition of the nozzle also improves the strip surface. The nozzle precisely controls the solidification length, which is not influenced by the bouncing of the meniscus on the melt surface; this allows for a uniform strip thickness. Thus, installing the nozzle improves heat transfer, the strip surface and the strip thickness.

In order to increase the cooling rate, a copper roll was used instead of a steel roll. Because the thermal conductivity of copper is about eight times higher than that of steel, a copper roll is preferred for rapid solidification. The roll diameter is 300 mm and the width is 100 mm. The roll is water-cooled from the inside. Lubricants become heat resistant between the roll and the melt and between the roll and the strip. Eliminating lubricant improves heat transfer. In the conventional twin roll caster for aluminum alloy (CTRCA), the lubricant is used to prevent the strip from sticking to the roll. However, a steel roll is used in the CTRCA and the temperature of the roll surface influenced the sticking behavior. The temperature of the copper roll surface is lower than that of the steel roll, so the copper roll temperature does not reach the threshold necessary for sticking. Therefore, the strip does not stick to the copper roll.

The rolling load of the HSTRC is from ten to a hundred times smaller than that of the CTRCA. A small rolling load also helps to prevent the sticking of the strip. However, the rolling load of the HSTRC is large enough to obtain sufficient heat transfer between the roll and the strip. The rolling load should be set in the range of 0.1 to 0.5 kN/mm (per unit width).

Low temperature casting was introduced in the HSTRC. When molten metal is poured from the crucible to the cooling slope, the superheat of the molten metal is 15 K. After passing through the cooling slope, the superheat is further decreased down to 5 K. The cooling slope is made from mild steel and is water-cooled from the inside. BN was sprayed on the surface of the cooling slope as a lubricant. The cooling slope length is 300 mm, the width is 100 mm, and the inclination angle is 60 degrees.

3. Experimental Conditions

The 6111 aluminum alloy is one of the typical 6000 series alloys processed for automobile plates. The Fe content is restricted to less than 0.4 mass%. The Fe content of original 6111 is 0.13 mass%, and for these experiments, the Fe content was modified to 0.43, 0.62, 0.81 and 1.02 mass%. 2.7 kg of aluminum alloy was melted in an electric furnace. Before every casting, the roll surface was polished using #1200 emery paper. One roll was rigidly attached, while the other roll was supported by a spring. At the start of the casting, the roll gap was set at 1.0 mm and the roll gap varies along the strip thickness for the casting. The roll speed was set to 60 m/min. In comparison, the roll speed of CTRCA was slower than 10 m/min. Therefore, the proposed casting speed is very high. The rolling load was 0.14 kN/mm (per unit width). The mechanical properties of the strip were investigated using a tension test and a 180-degree bending test. The cast strip was cold rolled down to 0.5 mm, and T4 or T6 heat treatment was performed before the tension test. The 180-degree bending test was performed on a T4 heat treated specimen at 1.0 mm thickness. The T4 and T6 heat treatment conditions are described below. For T4 heat treatment, the as-cast strip was cold-rolled down to 0.5 or 1.0 mm without homogenization and intermediate annealing. The cold-rolled strip was kept at 813 K for four 14.4 ks, and then water-quenched. After T4, the strip was kept at 433 K for 21.6 ks. The gauge length and width was 20 and 10 mm, respectively, for the tension test piece. The microstructures of the as-cast and the T6 heat treated strip were metallographically observed.

4. Results and Discussion

4.1 Strip casting 6111 strip with Fe additions

The original and modified 6111 were cast into the strip at a speed of 60 m/min. The roll casting ability increased as the Fe content increased. Continuity of the strip was improved by the addition of Fe. For the high-speed twin roll caster (HSTRC) used in the present study, casting of mushy solidification type aluminum alloy was easier than skin formation solidification type aluminum alloy. The modified 6111 became closer to the mushy solidification type alloy as the Fe content was increased. This indicates that there is no problem in the high speed roll casting of recycled 6111. Figure 2 shows the surface of the as-cast strip. The width of the strip was the same as that of the roll. Ripple marks generated by the conventional twin roll caster for aluminum alloy (CTRCA) were not present on the surface. This is an advantage of the HSTRC. The oscillation of the meniscus was inhibited by the hydrostatic pressure of the molten metal. As a result, ripple marks did not occur. Fe content influenced the metallic luster of the strip surface. As the Fe content increased, the metallic luster decreased. This can be attributed to the strip temperature when it leaves the roll, which became respectively higher with increasing Fe content. The strip can not be cooled enough to exhibit metallic luster. However, there were no problems for continuously casting the modified 6111 strip. When the solidification length was set longer, the strip surface exhibited metallic luster as the cooling time lengthened and the strip was sufficiently cooled. The Fe impurities did not influence the strip surface. Figure 3 shows influence of Fe content on the strip thickness. The thickness decreased gradually as the Fe content increased. The reason for this was the improved fluidity of the alloy in the semisolid condition as Fe content increased. However, the Fe content did not influence the thickness distribution of the strip cross-section. The as-cast strip could be cold-rolled down to 0.5 mm without homogenization or intermediate annealing. On the other hand, cracks occurred when the ingot cast using an insulator mold was cold-rolled without homogenization. This suggests that the roll-cast strip had good ductility due to the higher cooling rate used. The cooling rate of the strip cast by the HSTRC is estimated at about 4000 K/s near the surface, and about 1000 K/s in the middle of the thickness direction.

The cooling rate of strips cast by the CTRCA was usually lower than 1000 K/s. Therefore, the cooling ability of the HSTRC is better than that of the CTRCA. No differences were apparent in the surfaces of the original 6111 strip and the modified 6111 strip after cold rolling, with both of these
surfaces exhibiting metallic luster. The surface of the strip after cold rolling is shown in Fig. 4.

4.2 Microstructure

Figure 5 shows microstructure in cross-section of the as-cast strip. It is clear that the microstructure created by the high cooling rate is very fine. The microstructure is not uniform in the thickness direction. Specifically, the center area is different from the other areas. The microstructure of the strip cast by CTRCA usually has a columnar structure. The HSTRC though, did not produce a columnar microstructure and there was no apparent interface in the center between the upper and lower solidification layers like for the
CTRCA. The level of Fe content did not affect this tendency.

The characteristics of the strip cast by the HSTRC are described below. An enlarged view of the microstructure cross-section is shown in Fig. 6. The microstructure of the center area resembled a spherical structure. This structure is typical for low superheat or low solidification rate semisolid casting. The microstructure for the other areas was a duplex structure containing both dendritic and a globular structures. Globular crystals that existed in the dendritic structure were crystallized on the cooling slope. Figure 7 shows the grain interface of the ingot cast using the insulator mold and of the strip cast by HSTRC. Al–Fe–Si intermetallics were observed at the grain interface. However, there were not large Al–Fe–Si intermetallics found in the microstructure of the roll cast strip, like in the ingot cast metal. The intermetallics containing Fe in the roll cast strip became very small due to the high cooling rate. The HSTRC proved very capable of creating intermetallics with fine impurities. Figure 8 shows

![Fig. 6 Enlarged view of microstructure of the cross-section in Fig. 5. (a) center area of Fig. 5(a), (b) near surface of Fig. 5(a) (c) center area of Fig. 5(b), (d) near surface of Fig. 5(b)](image)

![Fig. 7 Intermetallic of as-cast strip and as cast ingot of 6111 including 1.02 mass% Fe. (a) as cast strip (b) as cast ingot)](image)

![Fig. 8 Microstructure of the cross-section of the strip after cold rolling and T6 heat treatment. (a) 0.13 mass% Fe (b) 0.43 mass% Fe (c) 0.62 mass% Fe (d) 0.81 mass% Fe (e) 1.02 mass% Fe)](image)
the microstructure after T6 heat treatment. The grain size was smaller than 20 μm and a difference in the microstructure between the center and the other areas of the as cast strip was resolved. A small non-uniformity of the microstructure in the thickness direction still existed. The intermetallic and the result of the line analysis are shown in Fig. 9. The Fe content of this specimen was 1.02 mass% and the intermetallic included Fe and Si. This was the Al–Fe–Si intermetallic. The intermetallic including Fe was smaller than 3 μm, and was not acicular but globular. Fe content influenced the number of the intermetallics but did not influence their size. The intermetallics became very small due to the rapid solidification by the HSTRC and cold-rolling. The intermetallics were nearly uniformly distributed in the thickness direction.

4.3 Mechanical properties

Mechanical properties were investigated using tensile tests and 180-degree bending tests. Figure 10 shows the tensile test results for the T6 heat-treated specimen. The figure shows that the tensile stress and proof stress were hardly influenced by Fe content. Si was used for the Al–Fe–Si intermetallic. The intermetallic including Fe was smaller than 3 μm, and was not acicular but globular. Fe content influenced the number of the intermetallics but did not influence their size. The intermetallics became very small due to the rapid solidification by the HSTRC and cold-rolling. The intermetallics were nearly uniformly distributed in the thickness direction.

by the effect of α-AlFeSi crystallization, therefore, the amount of precipitated Al₂CuMg might be sufficient for precipitation hardening. The elongation did not decrease when the Fe content was smaller than 0.8 mass% and the intermetallic including Fe did not reduce the elongation probably because of the very fine size of the intermetallic, as shown in Fig. 9. Similarly, the addition of Fe did not produce any significant difference in the tension test results for the T4 heat treated specimen. The tensile stress and proof stress increase gradually as Fe content increased and the grain size gradually became smaller as the Fe content increased. The elongation did not decrease as the Fe content increased. Figure 11 shows the tensile test results for the T4 heat treated specimen. The addition of Fe did not produce any significant difference in the tension test results for the T4 heat treated specimen. The amount of the intermetallics including Fe might not influence the result of the tensile test as the intermetallics were very fine.

Figure 12 shows the bending test results. During the manufacturing of an automobile, the hemming process is performed at the end of the plate. It can be estimated whether a plate is suitable for hemming or not. The thickness of the strip was 1 mm and the heat treatment was T4. When the Fe content was smaller than 0.4 mass%, it exerted no influence on the outer surface conditions of the bent strip. When the content of Fe was larger than 0.5 mass%, cracking occurred on the outer surface of the cracks however, were not deep.

Fig. 9 Result of line analysis of roll cast 6111 of 1.02 mass%Fe after cold rolling and T6 heat treatment.

Fig. 10 Tensile test results of T6 heat treatment strip.

Fig. 11 Tensile test results of T4 heat treatment strip.

Fig. 12 Outer surface of T4 heat treatment 1 mm-thick strip after 180-degree bending.
enough to break the strip after bending. The cracking usually occurred on the outer surface after the 180-degree bending of 1 mm-thick 6111 plate of T4 heat treatment. Retrogressive heat-treatment was introduced to improve the cracking. 5) Cracking, however, did not occur in the strip cast by the HSTRC when the Fe content was less than 0.4 mass%. The cast strip’s ability to withstand the hemming process was superior for those processed by the HSTRC than by the conventional process. This might be due to the effect small grains and the intermetallics of the rapidly solidified strip generated by the HSTRC. This indicates the usefulness of the HSTRC for the 6000 alloy series and recycled 6000 alloy series used in automobiles.

5. Conclusion

A strip of 6111 and 6111 with Fe-additions was processed by a high speed twin roll caster (HSTRC) at a speed of 60 m/ min. The 6111 aluminum alloy in which Fe was added as impurity up to a 1.0 Fe mass%, was used to model recycled aluminum alloy. Modified 6111 could be roll cast into strip. The Al–Fe–Si intermetallic of modified 6111 was very fine due to the high cooling rate of the high speed twin roll caster. When the Fe content was lower than 0.8 mass%, the tension test results of the Fe-added 6111 strip did not decrease. In addition, cracks did not occur on the outer surface after a 180-degree bending test when the Fe content was lower than 0.5 mass%. This indicates that the high speed twin roll caster is suitable for improving the mechanical properties of recycled aluminum alloy.

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REFERENCES