Light Metals 2015
Edited by: Margaret Hyland
TMS (The Minerals, Metals & Materials Society), 2015

HIGH STRENGTH ALUMINUM ALLOY SHEETS FABRICATED BY TWIN ROLL CASTING FOR AUTOMOBILE APPLICATION

Hyoung-Wook Kim[1], Yun-Soo Lee[1], Min-Seok Kim[1], Cha-Yong Lim[1]
[1]Korea Institute of Materials Science; 797 Changwondaero; Changwon, Gyeonnam, 641-831, Korea

Keywords: Aluminum, Twin roll casting, Rolling, Strength, Elongation

Abstract

In order to fabricated high strength aluminum sheets with reasonable cost, several Al-Mg and Al-Zn-Mg-Cu alloy strips were successfully fabricated by the twin roll casting with a proper operating condition. The strips had good workability during subsequent warm/cold rolling processes due to the fine cast structure. The final annealed sheets have good mechanical properties at ambient temperature. The tensile strength and elongation of annealed Al-10wt%Mg sheet are about 400MPa and 30%, respectively. The tensile strength and yield strength of Al-Zn-Mg-Cu alloy sheet after the aging at paint baking condition (180°C x 30min) are 480MPa and 350MPa, respectively. The developed aluminum alloy sheets have a superior strength to commercial aluminum alloy sheets used for automotive body structures.

Introduction

Weight lightening of automobile has been an important issue to reduce energy consumption and CO2 emission. A lot of light metals like aluminum alloys and magnesium alloys have been developed to replace a steel, but its strength is still not enough to meet the needs of automotive manufacture.[1,2] Moreover, the cost for light weightening of the vehicles should be considered. Twin roll strip casting has been well known as a cost effective process to make an aluminum thin strip directly from the melt [3-5]. In addition, a high cooling rate of twin roll strip casing could improve the mechanical properties by refining cast structure in several aluminum alloys. However, a conventional twin roll strip casting process has disadvantages like a limitation of alloy composition and low mechanical properties due to inhomogeneity in microstructures and chemical compositions through the sheet thickness. Particularly, it is more difficult in high strength aluminum alloys with high contents of alloying elements [6-10]. Al-Mg alloys have a favorable combination of strength and formability as well as good corrosion resistance and weldability, and therefore of interest in light weight structural application. Also, minor alloying element addition such as Mn increase strength of Al-Mg base alloys by refining grain size and precipitation of fine Al-Mn particles [11]. Al-Zn-Mg-Cu alloy have the highest strength among aluminum alloys and has been used for airplane structural parts, the alloy sheets can be anticipated to present more lightweight vehicle structure. In order to make a high strength Al alloy sheet with reasonable cost for automobile application, several high strength aluminum alloy sheets were fabricated by twin roll casting and rolling process in this study. Newly designed Cu-Cr twin rolls were used to get sufficiently cooling rates and optimum process parameters such as roll speed and melt temperature were determined [8-11]. After special warm/cold rolling and annealing treatment to control microstructure, the sheets have high strength and good formability. A possibility of the sheets for the automobile body application was discussed on the basis of the mechanical properties of the fabricated sheets in present paper.

Experimental procedure

A special strip caster with Cu-Cr twin rolls cooled by water circulation was designed to get a high cooling rate at the roll gap. The roll diameter was 300mm and roll gap was 4mm. The roll surface was grounded by emery paper and coated by graphite powder. Molten Al alloy was transferred to the roll gap through tundish and ceramic nozzle. The nozzle was set basically to keep the contact length between melt and rolls at 35mm. The contact length was changed to reduce a surface crack of the strip. [9, 12] The melt was cooled by the rotating twin rolls and solidified into thin strip with the thickness of 4-5mm and the solidification was completed in the roll gap. The Al-Mg alloys and Al-Zn-Mg-Cu alloys were melted in an electric melting furnace and transferred to the rolls at 680°C. The casting speed was changed from 3m/min to 5m/min by controlling the rotating speed of the rolls, the optimum speed was decided to get sound strip about each alloys. Al-Mg cast strip was annealed at 450°C for 10 hours to reduced Mg segregation and the annealed strip cold rolled to 1mm thick sheet. In case of Al-Zn-Mg-Cu sheets, the cast strips were annealed at 400°C for 1 hour and rolled to 2 mm thick sheets at 250°C. The hot rolled strip was rolled to 1 mm thick sheet at ambient temperature. The cold-rolled sheets were annealed at various temperatures for 1 hour and quenched at water to investigate the effect of annealing temperature on microstructure and mechanical properties. The microstructure of the cast strips and rolled sheets was observed by an optical microscope after the mechanical polishing and electro-chemical etching. The tensile specimens of the rolled sheets were prepared according to ASTM E8M, the tensile properties of the annealed sheets were evaluated by an Instron 4201 tensile testing machine at ambient temperature.

Results and discussion

Twin roll strip casting

Casting defects; Twin roll casting has been used for making aluminum strip with low-cost. Commercial application of the process mainly applied for low and medium strength aluminum alloy strip like 1100, 3003, 8011 which have low alloy content. In case of high strength aluminum alloy having high content of alloying element, the casting process should be controlled more carefully to prevent segregation and surface defects. Several kind of Al alloy strip with high content of alloying element were fabricated by a horizontal twin roll caster with Cu-Cr alloy cooling roll. In first trial to make thin strip of Al-Mg alloy, there were a various defects on the strip surface after twin roll casting as shown in Figure 1. The main reason of the crack formation was grain boundary segregation of Al_8Mg_5 phase during the solidification as shown in figure 1, so that the roll separating force during the casting process should be diminished as possible to prevent the crack formation and propagation along the grain boundaries.

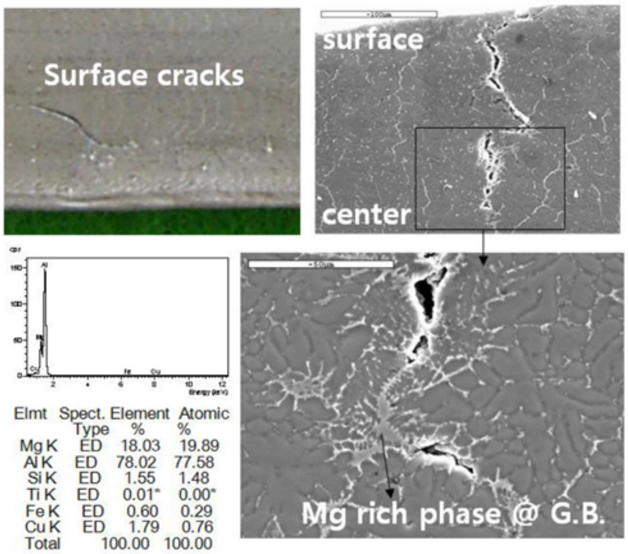

Figure 1 Surface crack and crack path during casting in Al-5.5wt%Mg-0.02Ti alloys

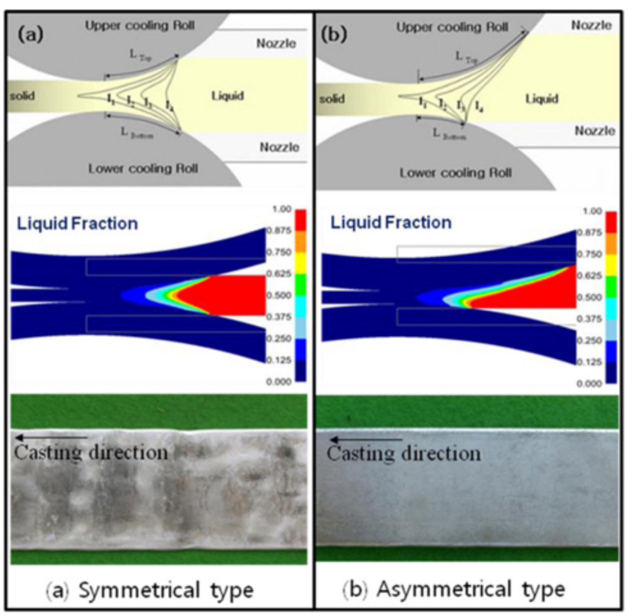

Figure 2 Solid liquid interface during strip casting and cast strips according to nozzle shape; (a) symmetrical type (b) asymmetrical type.[9]

Nozzle shape; In order to reduce the roll separating force, One possible solution is to use an asymmetrical nozzle. In twin roll casting, symmetrical type ceramic nozzle was usually used as shown in Figure 2 (a). However, several aluminum alloys having high content of alloying elements required a special shape nozzle to minimize the surface crack as mentioned before. In Figure 2 (b), the contact length of the upper cooling roll (L_{top}) is twice of that of the lower cooling roll (L_{bottom}), that is, the contact length of the lower roll and upper roll were 30mm and 60mm, respectively. The separating force of the cast process using the asymmetrical nozzle was lower than that of the process using the symmetrical nozzle in spite of the larger contact area between the cast roll and Al melt. Additionally, the solid and liquid interface during the solidification was formed asymmetrically as shown in figure 2 (b). In addition, the center segregation might be reduced in case that the L/S interface (Liquidus line) was shaped like I_4 in figure 2 (b). Figure 2 also shows the cast strips fabricated by twin roll strip casting with different type nozzle. The surface cracks and wavy marks were diminished remarkably by using asymmetrical type nozzle, which came from lower roll separating force and smaller fluctuation of roll separating force during roll casting in spite of larger contact area between the rolls and Al melt. Therefore, using an asymmetrical type nozzle is one possible way to make a crack-free cast strip of high strength Al-Mg alloy.

Roll separating force; Twin roll casting is a combination of casting and rolling process. During twin roll casting, the melt is solidified to strip between two cooling rolls and incompletely solidified strip is deformed by rolling, so that the roll separating force give a great effect on the strip quality. At the low roll separating force, various casting defects like shrinkage and inhomogeneous solidification mark exist on the surface due to insufficient cooling induced by imperfect contact between melt and roll. Meanwhile, at high roll separating force, large cracks appear the whole strip surface due to low formability of the cast strip at high temperature as shown in figure 3(a). The roll separating force can be controlled by roll rotating speed. In our experiment about Al-5.5wt%Mg-0.02Ti alloy, the optimum roll separating force per unit strip width was 100-130Kg/mm. The Al-5.5wt%Mg-0.02Ti strip with good surface quality could be fabricated as shown in Figure 3 (b). In case of other Al-Mg alloy and Al-Zn-Cu-Mg alloy, similarly, the optimum roll separating force determined and strips with good surface were successfully fabricated by twin roll casting.

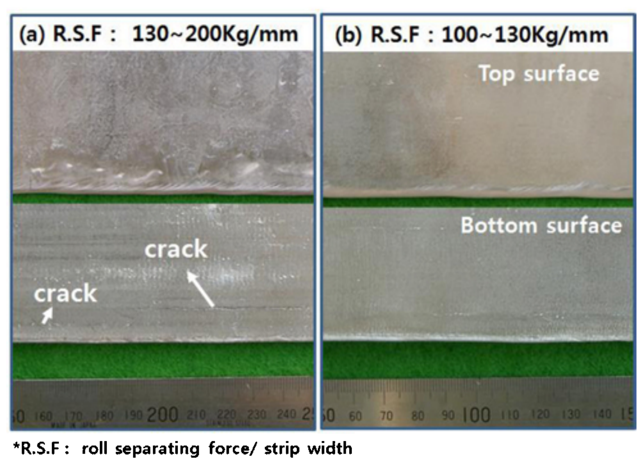

Figure 3 Al-5.5wt%Mg-0.02Ti cast strips under the different roll separating force normalized by strip width; (a) 130-200Kg/mm, (b) 100-130Kg/mm

Properties of Al-Mg alloy sheets

Microstructure: Figure 4 is the microstructures at the center and edge of Al-5.5wt%Mg-0.02wt%Ti strip. The microstructure of the strip consists of fine grain with the size below 20um and very fine dendrite in grain. The grain size and second dendrite arm spacing (DAS) were much finer at subsurface rather than at thickness center due to high cooling rate near surface. Microstructure at the center and edge of the strip was similar in grain size and dendrite arm spacing (DAS). The Mg content through the sheet thickness was analyzed by SEM-EDS. Figure 5 presents the content of Mg through the strip thickness. Mg content at sheet center was slightly higher than at the subsurface as shown in Figure 5(a). The strip was annealed at 450^{o}C for 10hrs to reduce the solute segregation. After the annealing treatment, the content of Mg solute at center was reduced, so that more homogeneous distribution of Mg solute was obtained through the strip thickness as shown in figure 5(b).

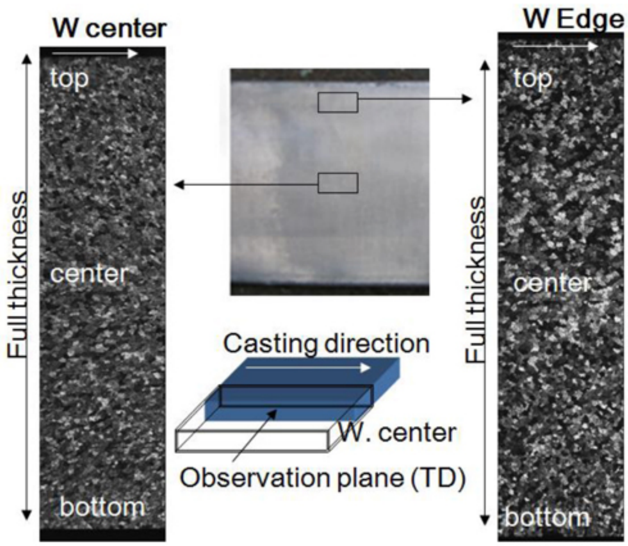

Figure 4 Microstructure of Al-5.5wt%Mg-0.02Ti cast strips at strip center and edge in width.

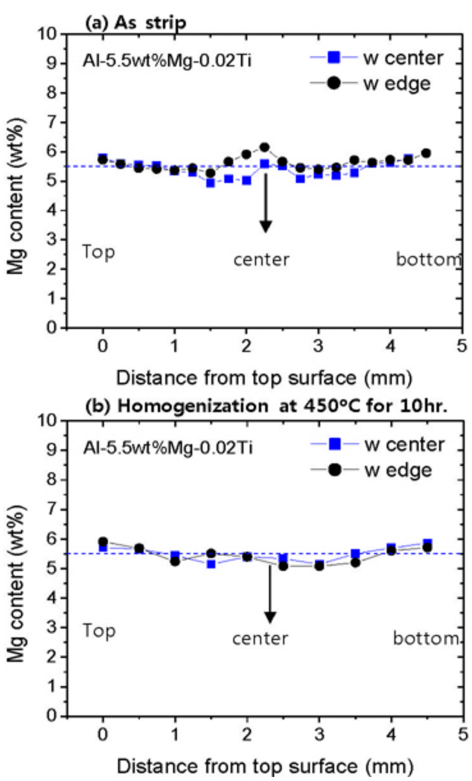

Figure 5 Mg contents through thickness; (a) before annealing and (b) after annealing at 450^{o}C for 10hours.

Tensile properties: The homogenized strip could be rolled from 4.4mm thick to 1mm by cold rolling without severe cracks. The cold rolled sheet was annealed again at 400^{o}C and 450^{o}C to increase formability. Figure 6 is tensile properties of Al-5.5wt%Mg-0.02Ti sheets annealed at different temperature. In case of the sheets annealed at 400^{o}C (Figure 6 (a)), the tensile properties of the sheet were different according to the tensile direction. Tensile strength and yield strength along the rolling direction were 320MPa and 151MPa respectively and the total elongation was 27%. Tensile strength was slightly decreased at transverse direction (90^o to the rolling direction). Meanwhile, the elongation was much decrease at the same direction. That is, the sheets had a strong anisotropic tensile elongation. The anisotropy of the elongation was much improved in the specimen annealed at 450^{o}C. The tensile strength and yield strength along the rolling direction were 281MPa and 122MPa respectively and the total elongation was 28%. The tensile properties at other directions were similar with at rolling direction. Thickness of cast strip fabricated by twin roll casting was very thin compared to commercial DC casting slab, so that the rolling reduction is not enough to control the sheet properties. Therefore, the final rolling reduction and annealing temperature should be considered to minimize such a kind of anisotropic properties.

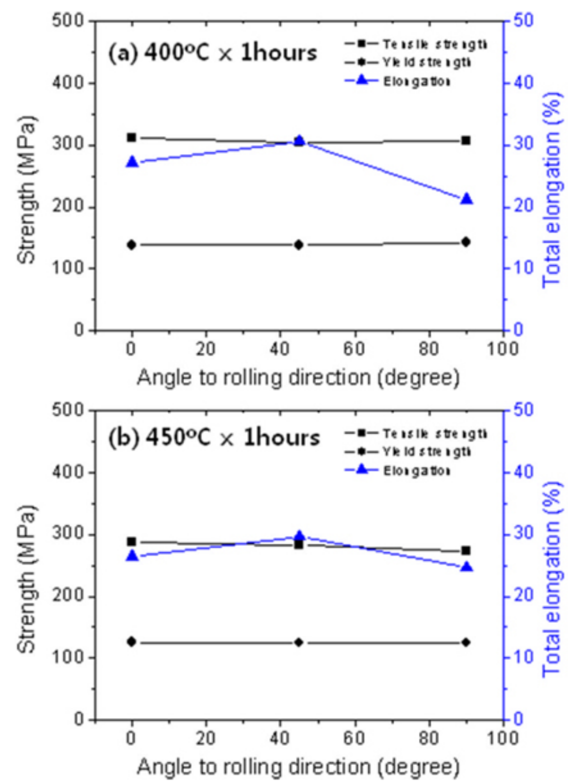

Figure 6 Tensile properties of Al-5.5wt%Mg-0.02Ti sheets annealed at ; (a) 400^{o}C and (b) 450^{o}C for 1hour.

Effects of Mg contents: Al-Mg alloy have high strength and elongation by solid solution hardening, so that large amount of solute Mg in Al matrix may be improve the strength and formability. In order to increase the strength and formability, Al-Mg alloy sheets with high content of Mg were fabricated by twin roll casting and rolled to 1mm in the same way with Al-5.5wtMg-0.02Ti sheets. Figure 7 is the microstructures at center of the sheets with different Mg content. The microstructure were consist of fully-recrystallized and equi-axed grain with the grain size below 42um. The content of Mg did not give a significant effect on the microstructure, the grain sized and shapes were similar in all sheets.

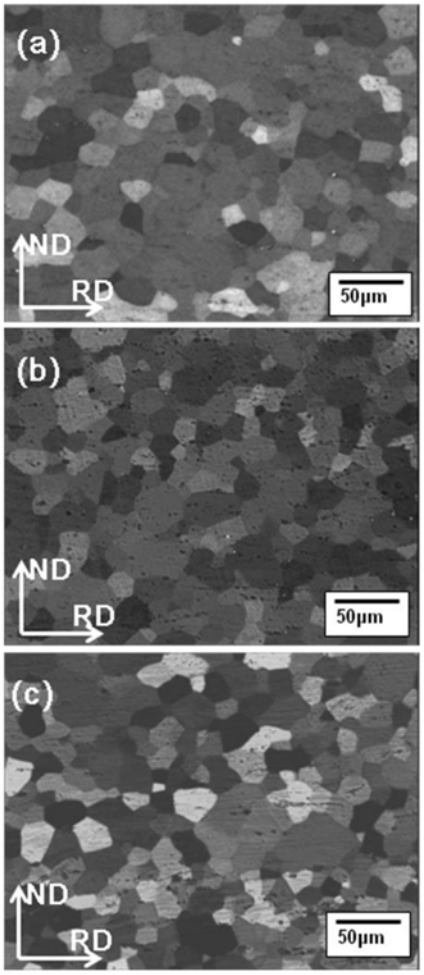

Figure 7 Microstructure of Al-Mg alloy sheets annealed at 450oC for 1hour; (a) Al-5.5wt%Mg-0.02Ti, (b) Al-7wt%Mg-0.02Ti, (c) Al-10wt%Mg-0.02Ti.

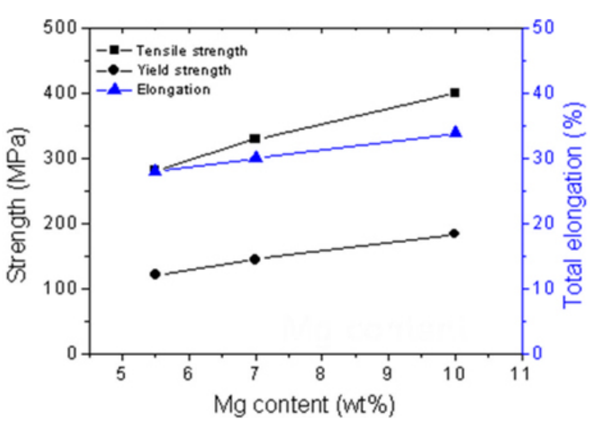

Figure 8 Effects of Mg content on tensile properties of Al-Mg alloy sheets annealed at 450°C for 1hour.

Tensile properties of the annealed Al-Mg sheets with different Mg content were presented in Figure 8. Tensile strength and yield strength of the annealed Al-7wt%Mg-0.02Ti sheet are 329MPa and 145MPa, respectively. Total elongation of the annealed sheets is over 30%. The tensile strength and elongation were increased with increasing Mg content. As shown in Figure 8 (b), tensile strength and yield strength of the annealed Al-10wt%Mg-0.02Ti sheets were about 400 MPa and 184 MPa respectively; furthermore elongation reached to 34%. As a result, tensile strength and elongation of the annealed Al-Mg sheets were affected by the content of Mg solute due to solution hardening by rich Mg solute in Al matrix. In this study, high strength Al-Mg sheets was fabricated successfully by twin roll casting and rolling process, and which show superior strength and elongation to a commercial Al-Mg alloy sheets.

<u>Properties of Al-Zn-Mg-Cu alloy sheets</u>

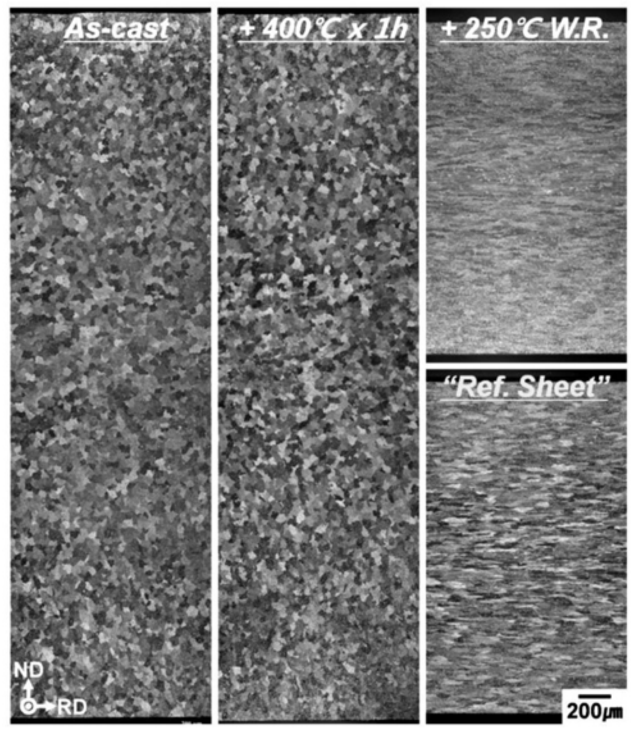

Figure 9 Microstructure of as-casted 7075 strip (a), annealed strip (b), warm rolled sheet(c) and annealed 2mm thick sheets (d).

<u>Microstructure</u>: The Al-Zn-Mg-Cu alloy strip was successfully fabricated by optimizing the process parameters on twin roll casting. The fabicated strips was 7075 alloy which composition was shown in Table 1. The cast strip with the thickness of 4.4mm was annealed at 400°C for 1 hour and rolled at 250°C to the thickness of 2mm by thickness reduction of 30% per pass. Figure 9 shows microstructures of the 7075 strip and the warm rolled sheets. The cast strip was consisted of fine grains with very fine dendrites in garin interior. The microstruture was quitely homogenious in grain size through the whole thickness. The annealed strip at 400°C for 1hour showed good workablility during warm rolling at 250°C, there were no cracks on the rolled sheets . This good workablity is due to the fine grain size and homogeneous microstructure of the cast strip. Commercial 7075 sheets are manufactured by very complex process like Direct chill(DC) slab casting→ scalping→ homogenization heat

treatment→ hot rolling→intermediated annealing→ repeted warm rolling and anealing. Meanwhile, in this work, the 7075 sheets with thickness of 4.4mm was fabricated directly from the melt by twin roll casting. The 7075 sheet with thickness of 2mm could be obtained from the cast strip by simple annealing and warm rolling. The twin roll casting process is very effective to reduce the process cost comparing with conventional DC slab casting and hot rolling process. The hot rolled sheets was annealed again at 400°C for 1hour to increase formability. The 2mm thick annealed sheet was cold rolled to 0.8mm thick sheet without cracks. The cold rolled sheet was annealed finally at diffrent tempertures and quenched in water. The microstructure of the anneald sheets were presented in Figure 10. When the sheet annealed at 400 ℃ for 1 hour, the grains of the subsurface are relatively coarse and elongated rather than those of the center. However, that inhomogeneous microstructure especially in grain size through the thickness could be diminished with increasing annealing temperature as shown in Figure 9. The 7075 sheets annealed at 500°C for 1hour consisted of fine recrystallized and equi-axed grain at sheets center and slight elongated grain at subsurface. The inhomogeneous microstructure through the sheet thickness increased the anisotropy of tensile properties as mentioned in previous reports [8].

Table 1 Chemical composition of 7075 strip fabricated by twin roll casting

Element (wt%)	Zn	Mg	Cu	Fe	Si	Mn	Ti	Cr	Al
7075	5.18	2.27	1.49	0.23	0.11	0.045	0.050	0.22	bal.

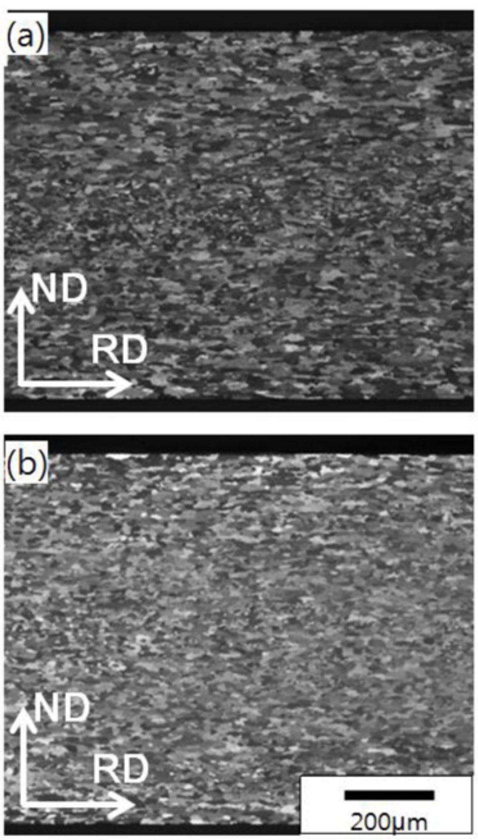

Figure 10 Microstructure of 7075 sheets annealed at (a) 450°C and (b) 500°C.

Tensile properties: Tensile properteis of the 7075 sheets annealed at 500°C for 1hour are shown in Figure 11 (a). Tensile strength of the sheets is about 370MPa with no relation to tensile direction, the yield strength is slightly high at 45° to rolling direction. The yield strength of the sheets are range from 152MPa to 165Mpa. The tensile elongations was much effected by tensile direction. The elongation at rolling direction is 25%, it decrease to 21% at transverse direction (90° to rolling direction). The main reason of the anisotropic tensile elongation are seem to be the inhomogeneous microstructure through the thickness, especially elongated grain at subsurface as mentioned above. Al-Zn-Mg-Cu alloy sheets are age hardening alloy, so that additional increase in yield strength could be expected during paint bake-hardening process of automobile body structure. The strength of the annealed sheet after bake hardening treatment at 180°C for 30min was tested and the results are presented in Figure 11(b). Tensile strength and yield strength of bake hardened sheet were about 480MPa and 350MPa, respectively, the elongation reduced by 10% after the bake hardening treatment.

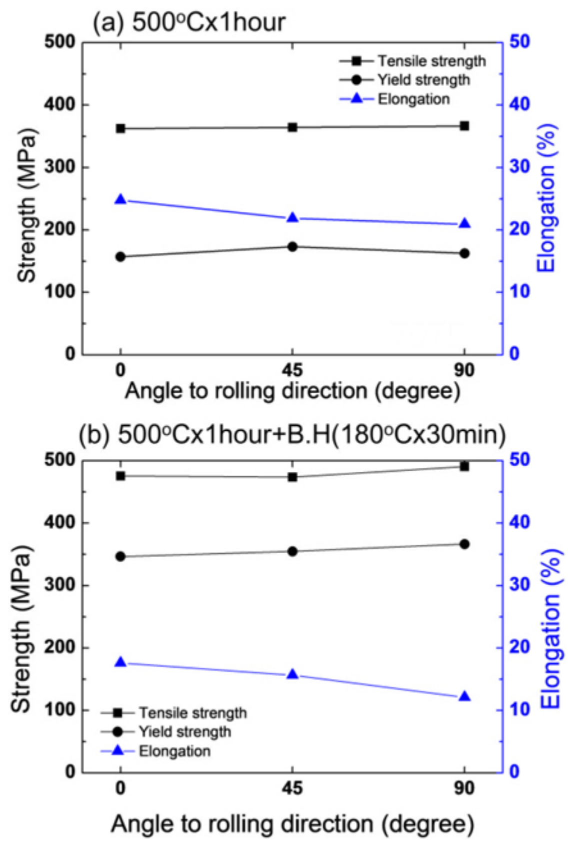

Figure 11 Tensile properties of 7075sheets (a) annealed at 500oC for 1 hour and (b) annealed and aged at 180°C for 30minutes.

Automobile application of the developed sheets

Commercial Al-5.5wtMg sheets have been used for light weight sheet materials to apply several hang on part like hood, door and trunk Lid due to its high strength and formability. The tensile strength and elongation of the sheets were about 280MPa and 30%, respectively. In this paper, The fabricated Al-Mg alloy sheet having large content of Mg have had high strength and high formability. In case of the Al-10wt%Mg-0.02Ti sheet, the maximum tesile strengh is about 400MPa and the elongation is over 30%. The mechanical properties of the alloy sheets is superior to a commercial Al-Mg alloy sheet. The developed Al-Zn-Mg-Cu alloy sheet have very high strength and enough formability and can be used to replace the steel sheets for automobile frame like piller, subframe and so on. The sheets fabricated by twin roll casting have a lot of merit in the view point of mecahnical properties and materials cost for automobile body application. However, there are several remained problems to commerciallize it and to improve several properties like press formability, corrosion properties and so on. More interest will be needed to apply the developed sheets to automobile application.

Summary

The optimum process conditions to obtain good surface quality of high strength Al-Mg strips with high content of Mg and Al-Zn-Mg-Cu alloy strip were decided. The high cooling rates reduced the center segregation and refined the grains and dendrites. The proper annealing treatment reduced inhomogeneity of the microstructure and improved tensile properties. The Al-Mg cast strip obtained in this work showed good workability during rolling process, so that Al-Mg sheet with a thickness of 1mm was fabricated successfully by cold rolling without any severe cracks. In annealed Al-10wt%Mg sheets, tensile strength and yield strength were about 400 MPa and 184 MPa respectively, and elongation was over 30%. The 7075 strip was successfully fabricated by horizontal twin roll casting, the strip have a good workability during subsequent hot rolling and cold rolling after annealing at 400°C for 1hour. The annealed 7075 sheets showed high strength of 370MPa and large elongation of over 20%. After aging at 180°C for 30minumtes, tensile strength and yield strength of the 7075 sheets were 480MPa and 350MPa, respectively. The sheets fabricated in this paper have a superior tensile property to a commercial aluminum sheets for automobile body application, so that the developed sheets could be used for automobile applications. Twin roll casting and rolling process with a proper heat treatment might be one of promising way to make high strength aluminum alloy with low cost.

Acknowledgement

This study was supported by a grant from the R&D program for Core Technology of Materials funded by the Ministry of Knowledge Economy, South Korea. The authors thank to Wongkyong Kim and Donga Jo for their many helps to make specimens.

References

[1] W.S.Miller, L.Zhuang, J.Bottema, A.J.Wittebrood, P.De Smet, A.Haszler and A. Vieregge, "Recent development in aluminum alloys for the automotive industry", *Mater. Sci. Eng.*, A208 (2000), 37-49.

[2] J.Hirsch and H.I.Laukli, "Aluminum in innovative light-weight car design" (Paper presented at the 12th international conference on aluminum alloys, Yokohama, Japan, 5 September 2010), 46-53

[3] R. Cook, P.G. Grook, P.M. Thomas, D.V. Edmonds and J.D. Hunt, "Development of twin roll casting process" *J. Mater. Proc. Technol.* 55 (1995) 76-84

[4] M.Yun, S.Lokyer and J.D.Hunt, "Twin roll casting of aluminum alloys" *Mater. Sci. Eng.* , A208 (2000), 116-123

[5] T.Haga, T.Nishiyama and S.Suzuki "Strip casting of A5182 alloy using melt drag twin roll caster" *J. of Mater. Proc. Technol.* 133 (2003) 103-107

[6] S. Kumar, N.H.Babu, G.M.Scamans, Z.Fan and K.A.Q.O'Reilly, "Twin roll casting of Al-Mg alloy with high added impurity content" *Metall. Mater. Trans.* 45A (2014) 2842-2854

[7] Ch.Gras, M.Meredith and J.D.Hunt, "Microdefects formation during the twin-roll casting of Al-Mg-Mn aluminum alloys" *J. of Mater. Proc. Technol.* 167 (2003) 62-72

[8] H.W.Kim, C.Y.Lim and S.B.Kang, "Fabrication of high Mg containing Al-Mg alloy sheets by twin roll strip casting", *Advanced Mater. Research* 29-30 (2007) 83-86

[9] H.W.Kim, J.H.Cho, C.Y.Lim and S.B Kang, "Microstructure and Tensile Properties of Al-(5~10)wt%Mg alloy Sheets fabricated by Twin Roll Casting and Rolling Process"s, *Key Engineering Materials,* Vol.443 (2010) 45-50

[10] Sanjeev Das, N. S. Lim, J. B. Seol, H.W. Kim and C.G. Park, "Effect of the rolling speed on microstructural and mechanical properties of aluminum-magnesium alloys prepared by twin roll casting", *Materials and Design*, 31 (2010) 1633-1638.

[11] H.W.Kim, J.Cho, C.Y.Lim and S.B.Kang, "Effect of Mn content on microstructure of twin roll cast Al-Mg-Mn alloys" (Paper presented at the ICAA 12, Yokohama, Japan, 7 September 2010).

[12] H.W.Kim. S.S.Jeong, C.Y.lim and S.B.Kang, "Microstructure and tensile properties of Al-5.5Mg-0.3Cu alloy sheets fabricated by twin roll casing", (Paper presented at the 11th International Conference on Aluminum Alloys, Aachen, Germany, 22 Sep 2008)

[13] H.W.Kim, J.H.Cho, C.Y.Lim and S.B.Kang, "High strength Al-Zn-Mg-Cu aheets fabricated by twin roll casting", (Paper presented at the Aluminum 2000, Milano, Italy, 16 May 2013)