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EFFECT OF AS-CAST STRIP THICKNESS AND REDUCTION PRIOR TO SOFT ANNEALING ON THE FORMABILITY OF TWIN-ROLL CAST 5754 SHEETS

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Abstract

5XXX aluminum alloys are preferred in automotive applications owing to their high strength, good formability and corrosion resistance. However, these alloys are mostly produced by direct chill casting and there is a limited number of attempt for twin-roll cast (TRC) 5754. With the motivation of the fact that microstructure and properties of sheets produced via TRC are highly influenced by casting parameters and cooling gradient originated throughout the strip thickness, this study investigates the effects of as-cast strip thickness and amount of cold rolling ratio prior to soft annealing on the microstructural evolution as well as mechanical properties of 1 mm thick TRC 5754 sheets. Microstructural characterizations were conducted by optical and SEM examinations on as-cast samples and after intermediate annealing as well as soft annealing performed at final gauge. Mechanical properties of final products processed by different routes were determined by tensile tests and forming limit diagrams.

Introduction

With development of new environmental legislations triggered by global warming, reducing the emissions of vehicles has been gaining much attention. One way of providing the required emissions is to reduce the overall weight of the vehicles. At this point, owing to their superior specific strength, good formability, corrosion resistance as well as recyclability, use of aluminum alloys instead of steels is preferred to build lightweight vehicles [1-5]. However, deformation characteristics of aluminum alloys are different than those of steels and thus successful forming of aluminum alloys in stamping forming is challenging since fracture occurs before necking instability due to their low ductility [2]. On the other hand, this drawback of aluminum can be eliminated by introducing suitable alloying elements. Among the aluminum alloys, high Mg containing 5xxx series possesses enhanced strength and reasonable formability together.

High Mg containing 5xxx wrought aluminum alloys are mainly produced by direct chill casting followed by repetitive hot rolling and if needed cold rolling [6]. Direct chill casting is an expensive technique since numerous thermo-mechanical steps such as scalping, homogenization annealing as well as hot rolling are required [3]. On the other hand, twin roll casting, where liquid metal transforms directly to 3-7 mm thick strip with the combination of casting and hot rolling, can reduce greenhouse emissions and the manufacturing cost of high Mg containing 5xxx aluminum alloys through reduced capital, energy consumption, operating costs and scrap rate when compared with direct chill casting [3,5-8]. However, since the number of thermo-mechanical steps are less than those in direct chill casting due to lower as-cast strip thickness, it is challenging to obtain homogeneous microstructure and good formability [5].

The motivation of this study is to increase the formability of twin roll cast 1 mm thick 5754-O through changing as-cast strip thickness and amount of reduction prior to soft annealing. The effects of as-cast strip thickness and amount of cold rolling ratio prior to soft annealing on the microstructural as well as mechanical properties of 1 mm thick twin roll cast 5754 sheets were investigated.

Experimental Studies

In this study, 5754 aluminum alloy was cast at strip thicknesses of 5.5 mm and 7.0 mm utilizing industrial scale Novelis twin roll caster. Table I lists the chemical compositions of the samples used in this study.

Table I. Chemical compositions of the alloys.

As-cast strip thickness, mm	Element, wt. %					
	Si	Fe	Mn	Mg	Cr	Ti
7.0	0.11	0.17	0.06	2.93	0.07	0.03
5.5	0.09	0,16	0.08	2.81	0.07	0.02

Samples were processed to achieve 1 mm O temper by the combinations of cold rolling and annealing. In order to determine the effect of reduction amount prior to soft annealing, intermediate annealing was conducted on 4.0 mm and 2.5 mm thick samples at 350°C for 6h in a batch type industrial scale furnace. After intermediate annealing, samples were cold rolled to 1 mm and soft annealed at 350°C for 4h to achieve O temper. Table II summarizes different downstream processes conducted in this study.

Table II. Downstream processes followed in this study.

Process number	As-cast strip thickness, mm	Intermediate annealing	Soft annealing
1	7	4.0 mm, 350°C -6h	1.0 mm, 350°C -4h
2		2.5 mm, 350°C -6h	
3	5.5	4.0 mm, 350°C -6h	
4		2.5 mm, 350°C -6h	

Microstructural and mechanical characterization of the samples were conducted. Microstructural characterization was carried out by optical microscope examinations on the cross sections of as-cast and annealed samples after preparing the samples according to standard metallographic methods. Mechanical properties of the samples were determined by hardness measurements, tensile tests and forming limit curves (FLCs). Hardness measurements were conducted on polished cross sections of as-cast samples utilizing a micro hardness tester with a Vickers indenter under an indentation load of 10 g. Tensile tests were performed on as-cast strips and 1.0 mm soft annealed samples at room temperature on

Zwick tensile test machine at a nominal cross speed of 10 mm/min with a 50 mm extensometer. In order to determine plastic anisotropy ratios and strain hardening exponent, longitudinal and transverse strain gauges were utilized during tensile tests of soft annealed 1.0 mm thick rectangular dog-bone samples prepared in 0°, 45° as well as 90° to the rolling direction. Plastic anisotropy ratios and strain hardening exponent values were measured at plastic strains between 4 and 6 %. Results of tensile tests were evaluated by averaging the results of 5 successive tensile tests.

Forming limit curves (FLCs) were determined based on Nakajima model. As shown in Figure 1, blanks with six different geometries (radius) were employed for FLCs to obtain different strain paths. In order to calculate the strain values, during forming tests, 10 pictures of samples in a second were captured. Strains calculated from 5 different sections taken on the last pictures just before failure were used for FLCs. Forming studies were performed three times for each geometry. Therefore, each point in the FLCs were the average of 15 measurements.

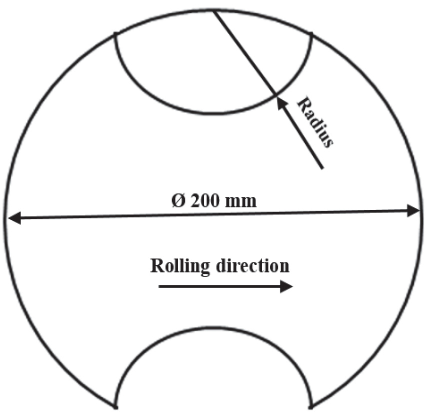


Figure 1. Blank geometries used in forming tests.
Radius: 0 mm, 35 mm, 45 mm, 50 mm, 55 mm, 85 mm.

Results and Discussion

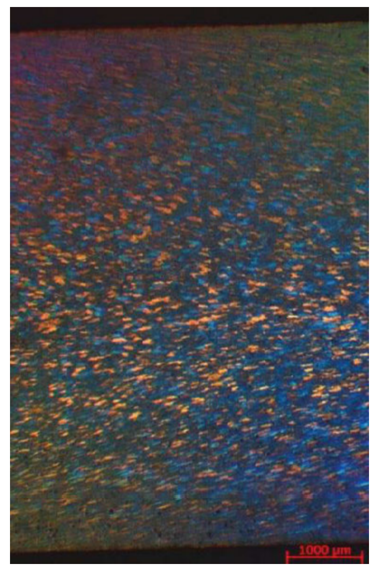
Mechanical properties of as-cast strips are given in Table III. Tensile tests results have revealed that as-cast strip thickness has no significant influence on mechanical properties.

Table III. Mechanical properties of as-cast strips.

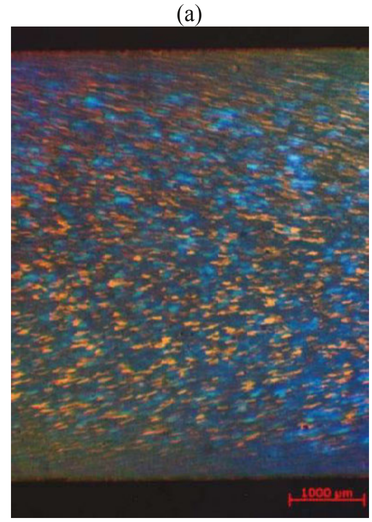
As-cast strip thickness, mm	Yield strength, MPa	Tensile strength, MPa	Elongation A50, %	Hardness, $HV_{0.01}$
7.0	157	226	9.5	79±8.8
5.5	162	228	9.9	77±12.5

Typical etched cross sectional optical microscope images of 7.0 mm and 5.5 mm thick as-cast strips are shown in Figure 2. As expected, grain sizes of as-cast strips increase gradually from outermost surfaces to mid-plane due to gradient in solidification rate. As can be seen in the cross sectional images of etched samples, 7.0 mm thick as-cast strip exhibits slightly finer grain structure when compared to that of 5.5 mm thick as-cast strip.

Figure 3 shows typical etched microstructures of all processes after intermediate annealing. Microstructures of samples have revealed that intermediate annealing at 350°C for 6h is sufficient for fully recrystallization at 4.0 mm and 2.5 mm. However, after intermediate annealing conducted at 4.0 mm and 2.5 mm, strips produced from 7.0 mm thick as-cast strips show finer grains when compared to those of produced from 5.5 mm thick as-cast strips. This result can be attributed to higher amount of cold rolling prior to intermediate annealing as well as smaller grain structure of 7.0 mm thick as-cast strip. At the same time, for a constant as-cast strip thickness, after intermediate annealing, 2.5 mm thick samples exhibit finer grains when compared to those of 4.0 mm thick samples. This observation can also be attributed to increased amount of reduction for 2.5 mm thick samples at a constant as-cast strip thickness.



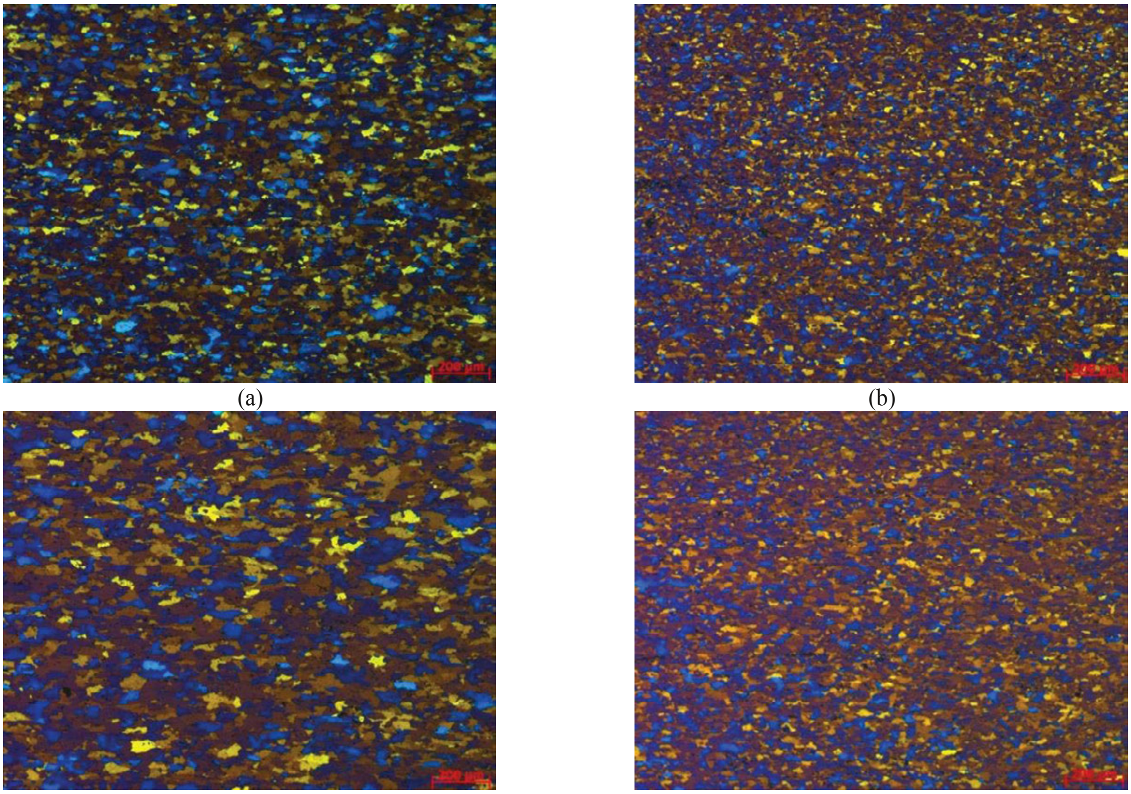
(a)



(b)

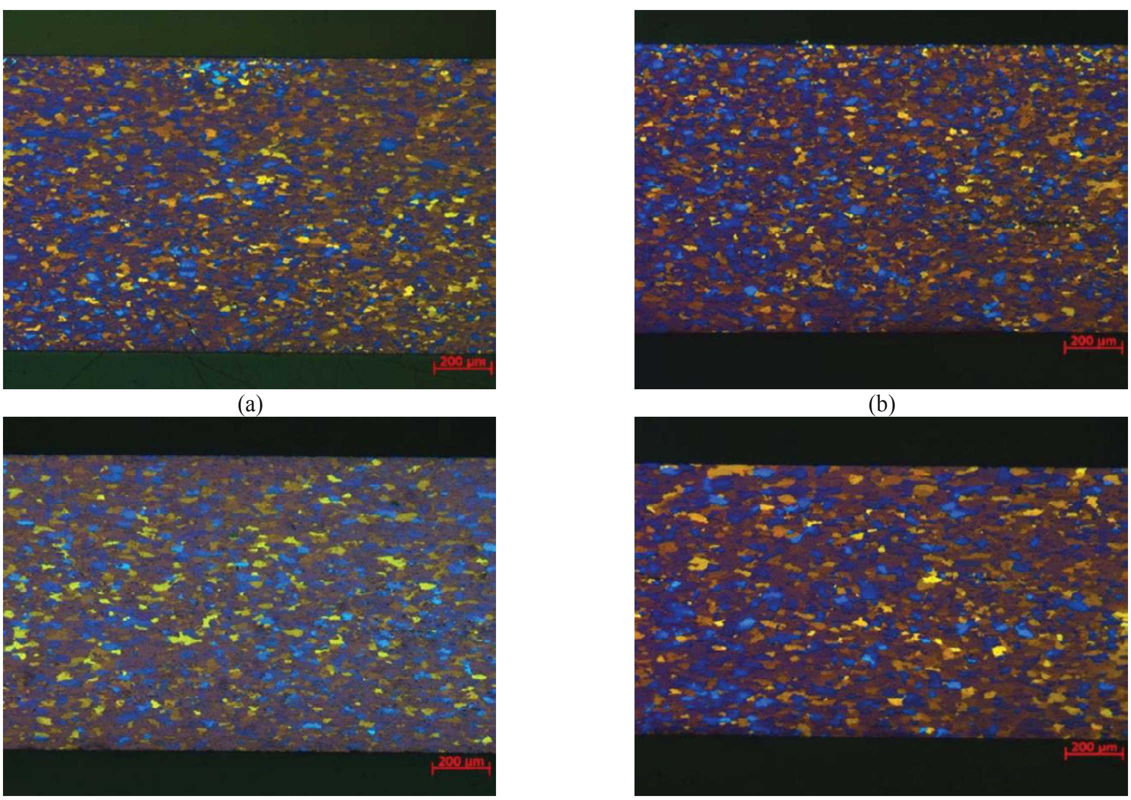
Figure 2. Typical etched cross sectional optical microscope images of (a) 7.0 mm thick and (b) 5.5 mm thick as-cast strips.

Figure 4 represents etched microstructures of 1 mm thick samples after soft annealing. Microstructural investigations revealed that for the same intermediate annealing thickness, increased as-cast strip thickness led to finer grains.



(a) (b) (c) (d)

Figure 3. Etched microstructures of samples after intermediate annealing (a) process 1, (b) process 2, (c) process 3 and (d) process 4.



(a) (b) (c) (d)

Figure 4. Etched microstructures of 1 mm thick samples after soft annealing (a) process 1, (b) process 2, (c) process 3 and (d) process 4.

Table IV. Tensile test results with r and n values.

Process number	Direction	Yield strength, MPa	Tensile strength, MPa	Uniform elongation A50, %	Total elongation A50, %	r	n	$R_{vertical}$	R_{planar}
1	0	101±0.8	210±2.5	15.3±0.71	17.9±0.66	0.85	0.27	0.7350	0.3300
	45	98±1.1	205±3.1	17.4±1.84	20.7±0.94	0.57	0.29		
	90	101±1.6	206±2.7	16.3±1.91	19.5±0.92	0.95	0.30		
2	0	108±0.9	224±1.0	16.0±1.27	18.8±1.22	0.89	0.27	0.7825	0.2650
	45	105±1.7	215±1.1	18.0±1.24	20.1±1.31	0.65	0.28		
	90	107±1.0	216±2.4	16.2±1.32	19.1±0.91	0.94	0.28		
3	0	100±1.0	211±1.0	15.4±1.74	17.8±1.23	0.95	0.28	0.7200	0.3800
	45	96±1.4	202±0.9	16.6±1.23	19.6±0.93	0.53	0.29		
	90	98±0.9	205±0.5	15.5±1.27	18.1±0.89	0.87	0.28		
4	0	99±0.9	214±1.6	15.7±1.05	18.4±0.45	0.98	0.30	0.7725	0.4250
	45	95±1.1	206±1.3	16.7±1.70	20.3±1.86	0.56	0.30		
	90	98±1.0	209±1.1	16.1±0.86	18.0±0.82	0.99	0.30		

Tensile test results of 1 mm thick O temper samples are shown in Table IV with plastic anisotropy ratios (r) and strain hardening exponent (n).

In general, samples possess maximum strength and total elongation values at 0° and 45° to rolling direction, respectively. This trend is comparable with those reported by Jain et al [9].

For samples produced from the same as-cast strip, the r-values of samples taken parallel and perpendicular to rolling direction are much higher than those of taken at 45° to rolling direction. This observation indicates that samples experience higher thinning at 45° when compared with those of other directions. Among the other directions, in general, samples taken perpendicular to rolling direction possess slightly higher r-values. This trend in r-values are in good agreement with those reported by Jain et al [9] and Abedrabbo et al [10], who studied forming performance of 5754 Al alloy. It is interesting to note that samples produced from 5.5 mm thick as-cast strip show slightly higher r-values at 0° and 90° directions where they exhibit lower r-values at 45° direction as compared to those of samples produced from 7.0 mm thick as-cast strip. However, when vertical ($R_{vertical}$) and planar (R_{planar}) anisotropy coefficients were calculated, it was found that samples produced from 7.0 mm thick as-cast strip have relatively higher vertical and lower planar anisotropy coefficients indicating that increased as-cast strip thickness provides resistance to thinning and earing during forming.

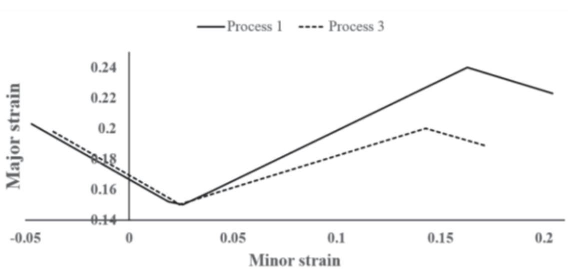


Figure 5. Forming limit curves of 1 mm thick samples produced by processes 1 and 3.

Figure 5 shows FLCs of 1 mm thick samples produced from processes 1 and 3. Along with thick gauge casting, relatively higher deformation (43%) applied prior to intermediate annealing, in the former process, appears to have an influence on the maximum strain before onset of failure at biaxial deformation (ε_{major}, $\varepsilon_{minor}>0$) side of FLCs.

Conclusions

The results of this study can be summarized as follows:

Increased strip thickness in casting leads to finer grain structure without any significant change in mechanical properties of as-cast strips.

Intermediate annealing conducted at 350°C for 6h is sufficient for completing recrystallization of all the samples exposed to the prior deformation ranging from 27-64% from as-cast thickness. Due to higher amount of cold rolling and finer grain structure at as-cast strip thickness, samples produced from 7.0 mm thick strip exhibit finer grains after intermediate annealing. For a constant as-cast strip thickness, increased amount of reduction before intermediate annealing results in fine grained structure after intermediate annealing, regardless of casting thickness.

For the same intermediate annealing thickness, increased as- cast strip thickness leads to finer grains in soft annealed 1 mm thick samples.

Plastic anisotropy values of samples taken 45° to the rolling direction are the lowest when compared to those of other directions indicating that samples experience higher levels of thinning at 45°. Increased as-cast strip thickness results in slightly lower r-values at 0° and 90° directions while higher r-values at 45° direction. However, increased as-cast strip thickness results in higher vertical and lower planar anisotropy coefficients which are favorable for thinning and earing, respectively.

Higher deformation applied prior to intermediate annealing in thick gauge cast material results in higher fracture strains that can be accommodated on biaxial deformation mode.

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