Proceedings of the 12th International Conference on
Aluminium Alloys, September 5-9, 2010, Yokohama, Japan
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pp. 2186-2191

Microstructure and Deformation Properties of AA5352/Al-6%Mg Sheet Produced by the Direct Chill Casting Fusion^{TM} Process

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Aluminum alloys containing high Mg levels are of interest from the perspective of their high strength and elevated temperature ductility. However, they present processing difficulties due to the rapid oxidation of the alloys at hot rolling temperatures and high rolling loads. Cladding a high Mg alloy sheet with an alloy that has the potential to mitigate some of these problems is of considerable commercial interest, particularly if there is no severe cost penalty. The Direct Chill Casting Fusion^{TM} is a method of producing clad sheet very cost effectively, and in this paper some initial results are reported on double sided clad sheet consisting of AA5352 on the surface and Al-6Mg-0.6Mn (wt.%) in the core. AA5352, with its low Mg level of 2.2 wt. %, has a much lower strength than the core alloy and is more resistance to oxidation. The microstructure of this clad package, as well as some mechanical properties at various gauges and temper conditions are presented, and the potential of such an approach discussed.

Keywords: *Al-Mg alloy, Fusion, microstructure, deformation properties.*

1. Introduction

The 5000 series Al-Mg alloys are used in a range of applications, from automotive sheet to can ends. The alloys provide a wide range of strength from solute and grain size strengthening [1], and they have good formability due to their high work hardening rates [2]. However, the commercial alloys are limited to Mg levels less than 5 wt.% because at high Mg levels the alloys are very susceptible to oxidation at elevated temperatures, complicating heat treatment and hot rolling, and the alloys are susceptible to edge cracking. In spite of these issues, there is an interest in increasing the Mg level to provide added strength while maintaining good formability, and Al-6 wt.% Mg alloys have been studied for armor [3] and superplastic forming applications [4]. Cladding a high Mg alloy would protect it from the environment, simplifying heat treatment and improving rollability without too greatly sacrificing strength. Unfortunately, the usual process of roll bonding to manufacture high Mg containing packages is not viable because of the oxidation behavior. The recently developed Fusion^{TM} technology [5], in which clad ingots are produced by direct chill casting, provides a means of producing clad high Mg alloys.

2. Experiments

The material, clad both sides, was Fusion^{TM} cast as (400 × 1600) mm cross section ingot, homogenized at 525°C and then hot rolled to 10mm gauge plate. The cladding consisted of AA5352 [Al-2.2 wt.% Mg-0.45 wt.% (Fe+Si)] at the 10% level in both sides. The core of the alloy was Al-6 wt.% Mg-0.6 wt.% Mn. The cladding alloy AA5352 has a typical yield strength of about 90MPa, UTS of 190MPa and a tensile elongation of 25%, so it is a relatively soft alloy. In addition, with its Mg level of 2.2 wt.%, it has reasonable oxidation behavior and is much more forgiving from a processing perspective than the 6 wt.% Mg core. After measuring the tensile and fracture properties of the 10mm plate, it was cold rolled by 50, 71 and 90% thickness reductions before annealing at different temperatures to assess the grain size range achievable and the grain structure thermal stability.

3. Results

The clad ingot was hot rolled without undue difficulty, and the hot rolled plate microstructure is shown in Fig. 1. The interface is sound and clean with no indication of defects. The plate is essentially recrystallized, with fairly equiaxed grains through the thickness, but the grain structure becomes more elongated in the core alloy towards the centre of the plate. As expected, the intermetallics are fibred along the rolling direction (RD). The stress-strain curve is serrated, characteristic of Al-Mg alloys, and Table 1 shows the tensile properties after hot rolling, as well as after different degrees of cold rolling. The yield stress increases with an increasing level of cold rolling, from 150MPa to 450MPa, but saturates after about 71% cold rolling. The increase in yield stress is accompanied by a decrease in the tensile elongation, from 28% to 2.5% after 90% cold reduction.

Table 1: Tensile properties after hot and cold rolling.

	YS (MPa)	UTS(MPa)	Elongation (%)
Hot rolled, 10mm	152	313	28
Cold rolled 50%	361	403	4.6
Cold rolled 71%	453	485	4.5
Cold rolled 90%	443	461	2.5

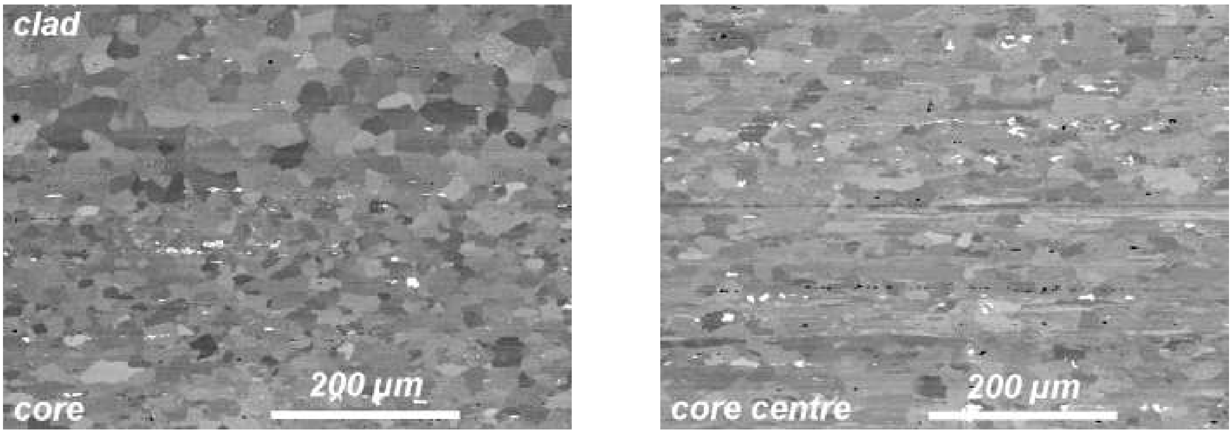

Fig. 1. Microstructure of the 10mm hot rolled plate in the longitudinal section. The RD is horizontal.

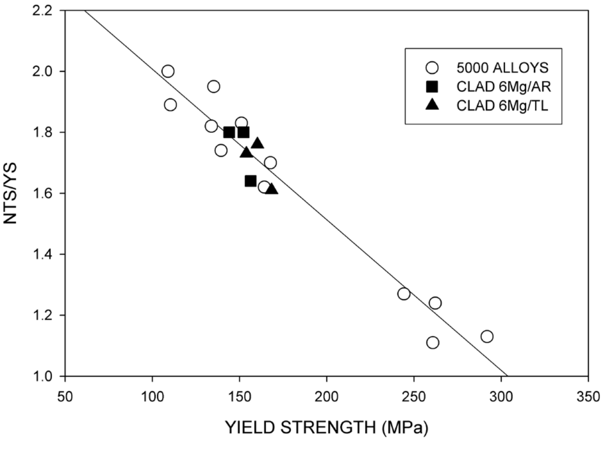

Fig. 2. Notch-yield ratio for different strength Al-Mg alloys.

The fracture toughness of the 10mm plate has been assessed by notch tensile tests [6], the tensile samples were orientated in the RD, transverse direction and 45° orientations with 60° edge notches and a notch-tip radius of 0.25mm. It should be mentioned that the crack from the edge notch was propagating through both cladding and core in a plane perpendicular to the rolling plane. Tests were carried out on both as-rolled plate and after tension leveling. Fig. 2 shows the notch-yield ratio, given by Notched Tensile Strength/Tensile Yield Strength, for the clad package, compared with other 5000 series alloys of different tempers and hence different yield strengths [6]. The notch toughness of the clad package is in good agreement with earlier data.

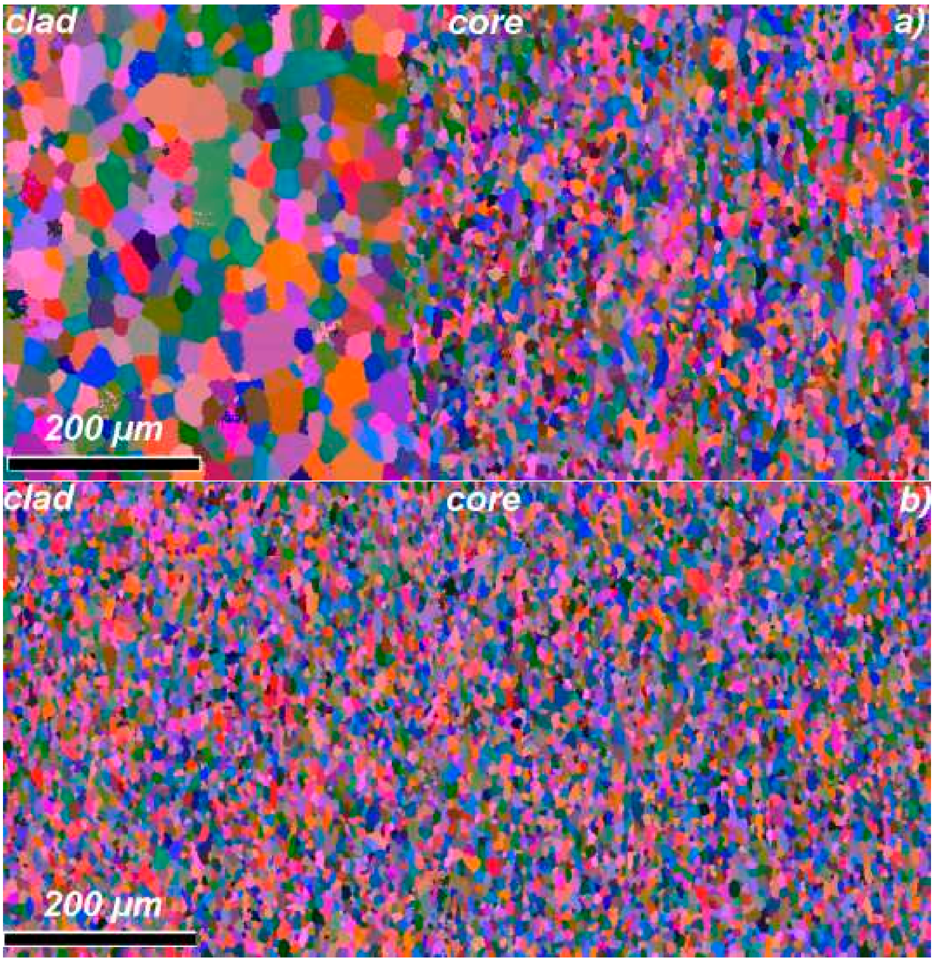

Fig. 3. The grain structures determined by EBSD in the longitudinal section in (a) 71% and (b) 90% cold rolled sheets after 1 hour at 500°C. The RD is vertical.

The cold rolled sheets were annealed for 1 hour at different temperatures and the annealed microstructures after 1 hour at 500°C following 71% and 90% thickness reduction are shown in Fig. 3. The sheets were recrystallized, with the cladding having a coarser grain size than the core alloy, while the cladding and core grain sizes decrease with increasing cold work. For brevity the remaining part of the paper will consider only sheet cold rolled 90%. While the sheet is recrystallized for all heat treatment conditions, the annealing temperature has a strong influence on the grain sizes developed, and this is shown in Fig. 4. The core alloy grain size increases very slowly over the whole annealing temperature range, while the grain size of the cladding increases more significantly, particularly above 500°C. In the 5000 series alloys the grain size has a strong influence on the yield strength of the alloys, and the stress-strain curves after annealing reflect this, as shown in Fig. 5. The yield strength decreases significantly with annealing, Fig. 6, as the sheet is recrystallized and the grains coarsen, and the stress-strain curves exhibit serrated flow, with an initial yield point elongation.

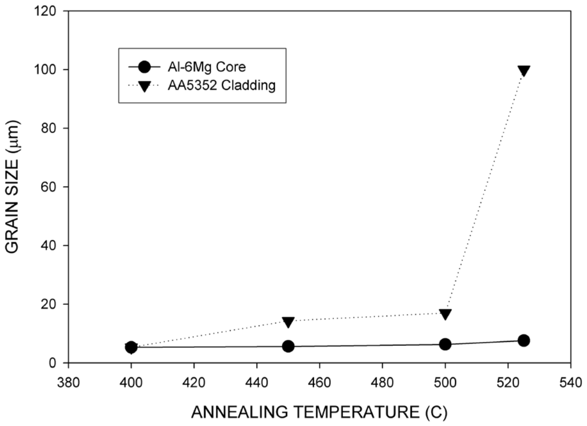

Fig. 4. Variation in grain size with annealing temperature.

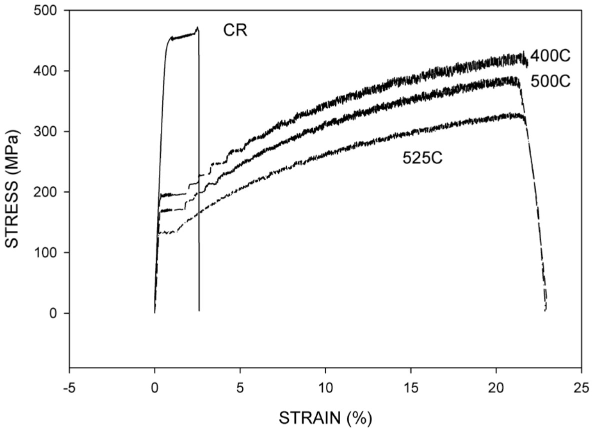

Fig. 5. Stress-strain curves after annealing at different temperatures.

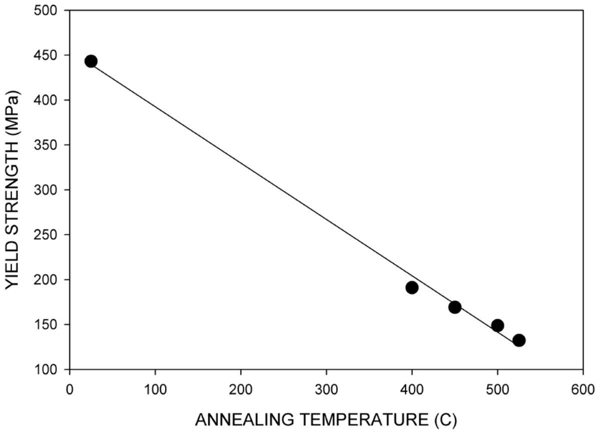

Fig. 6. Yield strength after annealing at different temperatures. The line is only meant to guide the eye.

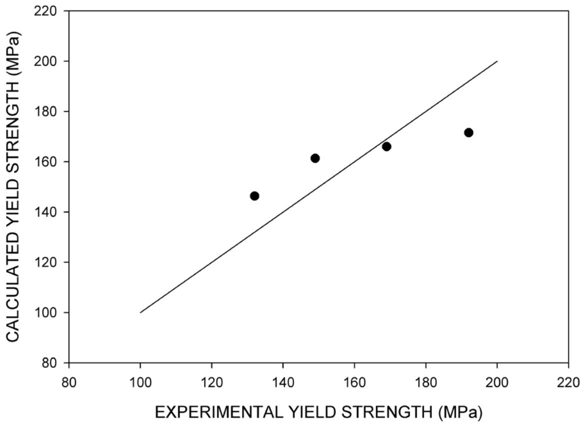

Fig. 7. Comparison of calculated and experimental yield strengths for different grain sizes of core and cladding.

4. Discussion

The low strength cladding greatly assisted the fabrication of the high Mg core, in agreement with previous studies [7]. The interface is free of coarse oxide films, and maintains its integrity through both hot and cold rolling. In addition, there is no indication of porosity formation during annealing up to 525°C, which is important because high Mg alloys are susceptible to hydrogen gas issues. The toughness, as measured by the notch-yield ratio is consistent with other Mg alloys of equivalent strength. The yield strength is the lowest stress at which appreciable plasticity can occur, and the larger the gap between the notched strength and the yield strength, the greater is the ability of the material to deform in the presence of a stress raiser. The high notch-yield ratio of the present sheet indicates that it should have good fracture toughness.

Annealing cold rolled sheet at low temperatures produces very fine grains in both the cladding and the core, typically around 5µm. The core alloy, with its high Mn dispersoid content, maintains a fine grain size up to the highest annealing temperature studied, while the cladding exhibits slow grain growth up to 500°C and then coarsens extensively above this temperature. The cladding alloy has much lower dispersoid content, so its grain size stability will be much less than that of the core alloy. As the grain size of the sheet coarsens the yield strength decreases. The stress-strain curves exhibit a Lüders elongation, and extensive serrated flow, typical of high Mg alloys due to Mg solute pinning. The Lüders elongation decreases with increasing grain size, in agreement with data on other aluminum alloys [8], so the global plasticity of the clad sheet is consistent with monolithic Al-Mg alloys.

Table 2: Tensile properties and grain sizes after annealing.

	YS (MPa)	UTS (MPa)	Elongation (%)	Grain size (length × thickness)
400°C 1h	192	349	24.5	clad : 5.8μm × 4.0μm core : 5.6μm × 3.9μm
450°C 1h	169	319	24.5	clad : 14.3μm × 11.6μm core : 5.7μm × 4.3μm
500°C 1h	149	285	24.0	clad : 18.7μm × 14.5μm core : 6.7μm × 4.9μm
525°C 1h	132	269	24.4	clad : around 100μm core : 7.4μm × 5.9μm

Since we essentially have a three layer laminate, and hence a composite sheet, the yield strength should be given, assuming iso-strain conditions, by the Rule of Mixtures, ROM:

$$\sigma_S = f_{CL}(\sigma_{CL}) + (1 - f_{CL})\sigma_{CR} \tag{1}$$

where σ_S is the yield strength of the sheet, σ_{CL} is the yield strength of the cladding, σ_{CR} is the yield strength of the core and f_{CL} = 0.2, is the volume fraction of the cladding. Unfortunately we do not have yield strength data for the monolithic alloys used in the package, but previously published data in the literature [8] can be used to get an estimate of the strengths involved. The yield strengths of the components of the package will depend on grain size and alloy composition. In reference [8] the alloy AA5052 was considered and this alloy has a Mg level of 2.5 wt.%, compared with 2.2 wt.% Mg in AA5352 used in the cladding. The strengths of the two components will be given by the Hall-Petch relationship

$$\sigma_Y = \sigma_0 + k(d)^{-\frac{1}{2}} \tag{2}$$

where σ_Y is the yield strength of the particular component, σ_0 is the friction stress, d is the grain size and k is a constant. The yield strengths of the clad sheet for the different grain sizes are given in Table 2, and to consider the present data in terms of Eq. 1 values are needed of σ_0 and k for the two components of the clad sheet. However, the situation is further complicated by the inhomogeneous yielding, since the Petch slope, k, is strongly strain dependent [8], so the effective Petch relationship will depend on the plasticity distribution during initial yielding. Assuming that yield initiates in the lower strength cladding, the frictional stress for AA5052 from reference [8] is σ_0 = 35MPa, and the Petch slope for initial yielding is k = 0.23Mn $m^{-3/2}$. The Mg level of the cladding alloy is slightly lower in Mg, and considering a Mg solution strengthening coefficient of σ_{Mg} = 16 (wt.% Mg), a value of σ_0 = 30MPa is a reasonable estimate. Therefore, these values can be used to calculate σ_{CL} for the different cladding grain sizes. For the core Al-6 wt.% Mg alloy, a pure Mg alloy has σ_0 = 90MPa, but the present alloy contains 0.6 wt.% Mn, which may provide additional strengthening, both in terms of solute and dispersoid strengthening. However, in a 5 wt.% Mn alloy Mn did not contribute to the frictional stress except at the very high Mn level of 0.7 wt.%, when it added 15MPa [8]. Considering the very limited data from this study a first order approximation of σ_0 = 90MPa is a reasonable value to take. There is no information for the k_{6Mg} value of Al-6 wt.% Mg, but reference [8] gave k in the range 0.15 to 0.25 for an Al-5 wt.% Mg with a range of Mn levels. If an average value of k_{6Mg} = 0.2 is used, the following Petch relationships can be used to calculate the strength contributions from the cladding and the core for the different grain sizes after the various annealing treatments.

$$\sigma_{CL} = 30 + 0.23(d)^{-\frac{1}{2}} \text{ and } \sigma_{CR} = 90 + 0.2(d)^{-\frac{1}{2}}$$

These strength values can then be used in Eq. 1 to obtain the clad sheet strength and compared with the experimental values in Table 2. The experimental data is very limited, so the results are an approximation, but as seen from Fig. 7, the trends are consistent with expectations.

5. Summary

High Mg aluminum alloys can be successfully clad using the Fusion^{TM} direct chill casting route and the clad ingots can be processed by conventional heat treatment together with hot and cold rolling. The strengths, ductility and toughness are comparable to monolithic alloys, and very fine grain size can also be obtained. The fine grain size has good thermal stability, making the clad sheet potential candidates for superplasticity, which will be studied in future work.

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