Aluminum Sheet Material Technology Supporting the Weight Reduction of a Car Body

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ABSTRACT: Process routes for 5000 series aluminum alloy sheet produced with TBC(twin-belt casting) have been successfully trialed, and applicability for inner structural parts of automobile was studied. The TBC 5000 sheet has finer microstructure than conventional DC processed 5000 series aluminum alloy sheet, resulting from the process characteristics. Optimization of composition and fine microstructure results in superior formability to DC5182 sheets. Moreover, the TBC 5000 sheet shows good performance in SCC resistance, adhesive bonding and coating tests, showing the ability for the application to hood-frame of car.

KEY WORDS:(Standardized) Materials, Aluminum Alloy, Casting (Free) Body, Twin-belt Casting, Hood Frame [D3]

1. Introduction

In order to prevent global warming, the demanding for automotive weight reduction to increase fuel efficiency remains high. Aluminum alloys are light and easy of recycling, and therefore expected to be used as materials in automotive parts for replacing steel. However, aluminum alloy sheets are inferior in formability to steel sheets and are also more expensive, and are therefore needed to be developed further. In addition, environmentally friendly production methods with minimal energy use are requested to fabricate materials for mass-produced automobiles. Thin-strip casting can be considered as a production method that meets these needs, and research and development has been in progress. Aluminum alloy sheets fabricated by twin-roll casting (TRC) with an extremely high cooling rate during solidification, are being applied for small and narrow components(1). By contrast, aluminum alloy sheets fabricated by twin-belt casting (TBC) with an optimal cooling rate have fine intermetallic compounds and recrystallized grains, and is therefore expected to have excellent formability. Also, TBC is able to fabricate aluminum alloy sheets for large members due to minimal size restriction(2). Therefore, 5000-series aluminum alloy sheets produced using TBC were developed and applied for hood frames. This paper will discuss the results of this development.

2. Development Goals

In order to make it possible to apply a material fabricated with the environmentally friendly and low-energy use method to automotive hood frames, an alloy’s chemical composition was designed and material properties were evaluated. The goal of this study is to develop 5000-series aluminum alloy sheets for inner parts, which were fabricated by thin-strip casting and have superior formability and stress corrosion cracking (SCC) resistance than conventional materials.

3. Twin-belt Casting (TBC)

Fig. 1 compares the processes for TBC with conventional direct chill (DC) casting. Because the cooling rate during solidification can be optimally controlled in the TBC process, it is possible to get uniform casting quality with minimal segregation. It is also a simple process in comparison to DC casting, omitting the procedures from cutting to hot rolling. Specially, omission of the high-temperature homogenization and hot rolling make this process to be an energy-saving production method(2).

![Fig. 1 The production processes of Aluminum alloy sheet for TBC and DC.](image)

4. Material Development

4.1 Target Properties

Among conventional 5000-series inner sheet materials, 5182 aluminum alloy with high strength and 5052 aluminum alloy with good shape fixability, have been used for frame members et al. However, a material that combined high strength with good formability would be easier to handle, and the effect of mass-
production could be expected if the material was used in greater volumes. Yield strength was set at 110-140 MPa in order to keep good shape fixability. Table 1 shows the target properties of the developing material with good formability and resistance to SCC.

Table 1 The target properties for the developed material

| categories          | items | target            | <reference>          |
|---------------------|-------|-------------------|---------------------|
| Mechanical properties| UTS   | $\geq 230$ MPa    | 204 MPa (5052)      |
|                     |       |                   | 260 MPa (5182)      |
|                     | YS    | 110 ~ 140 MPa     | 101 MPa (5052)      |
|                     |       |                   | 118 MPa (5182)      |
|                     | EL    | $\geq 25\%$       | 27.5 (5052)         |
|                     |       |                   | 29 (5182)           |
| SCC property        |       | SCC free          |                     |

4.2 Study of Main Components

Fig. 2 shows the correlation between Mg content and mechanical properties. It was possible to obtain the target strength at 3.0mass% or more Mg. From the relationship between Mg content and susceptibility to SCC, Mg content of 3.5mass% or less was desirable from the viewpoint of resistance to SCC. For this reason, the Mg content was set at 3.0mass% $\leq$ Mg $\leq$ 3.5 mass%.

4.3 Results for Material Fabrication Trial (1st Trial)

A material with composition of Al-3.37Mg-0.15Mn-0.20Fe-0.08Si (mass%) was trialed firstly on a production line. The results are shown in Fig. 3. The material had ultimate tensile strength and elongation which satisfied the target values, but its yield strength is higher than the target range. So, it is necessary to reduce the yield strength.

4.4 Study of Methods for Reducing Yield Strength

Focusing on the rapid cooling rate that is a characteristic of TBC, the additive elements of the material were optimized. As shown in Fig. 2, Mg as an additive element has a more significant effect on ultimate tensile strength than on yield strength. Therefore, adjusting the additive amount of Mg would not be effective, and the development of the alloy therefore focused on Mn.

Mn is normally added to 5000-series aluminum alloys in order to prevent coarsening of recrystallized grains during annealing process and to realize solid solution strengthening. There is a clear correlation between grain size and yield strength, and it was considered that if there was no change in the recrystallized grain size (coarsening) when the amount of Mn was reduced, yield strength would only be reduced by decreasing solid solution strengthening, and it would therefore be possible to reduce yield strength without significantly affecting ultimate tensile strength.

Recrystallization nuclei in metal materials are reported to normally occur in areas where there is a high degree of change in crystal orientation, such as the grain boundaries prior to working, the vicinity of coarse dispersion particles, deformation bands, and shear bands. Industrial-use aluminum alloy materials are known to contain a considerable volume fraction of intermetallic compounds as coarse dispersion particles. During annealing of 5000-series alloys, intermetallic compounds of Fe, Mn et al. act as recrystallization nucleation sites, and recrystallization occurred in the form of grain growth on these recrystallization nuclei. The size and state (space between particles) of the intermetallic compounds particles significantly affects the recrystallization microstructure. With regard to size, particles with the size of about dislocation cells (approximately 1µm and above) are effective for nucleation sites. The recrystallization microstructure will become refined in proportion to the amount of intermetallic compounds which act effectively as recrystallization nuclei. It was therefore considered that the key to adjust yield strength was whether or not a sufficient amount of intermetallic compounds for recrystallization was gotten when the additive amount of Mn was reduced from the 1st trial material. Laboratory tests were therefore conducted in order to study the states of intermetallic compounds when the additive amount of Mn was varied, based on the 1st trial material.

4.5 Laboratory Tests

Fig. 4 shows the microstructures of intermetallic compounds in Al-3.5Mg-0.2Fe (mass%) base alloys when the Mn content varies from 0mass% to 0.13mass%. These results indicate that the state of the intermetallic compounds is stable in the rapidly solidified test materials regardless of their Mn content. Fig. 5 shows the density of intermetallic compounds with approximately 1µm and above, the size considered to be effective for acting as recrystallization nucleation sites. The number of

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effective intermetallic compounds per unit area is basically the same at around 6,000/mm$^2$ as Mn content is in the range of 0mass%–0.13mass%. The microstructure of recrystallized grains was examined, but no changes in the grain size with different Mn contents were observed. Fig. 6 shows photographs of the microstructures. These test results suggested that if the Mn content decreased from the 1st trial material, it would be possible to reduce yield strength without change of the grain size. The 2nd trial was therefore done for a material without Mn content, and its mechanical properties were evaluated.

Fig. 4 The microstructures showing intermetallic compounds in 0mass%Mn, 0.1mass%Mn and 0.13mass%Mn containing alloy respectively. ( The red arrows show the Al-Fe intermetallic compounds )

Fig. 5 The measured density of intermetallic compounds in alloys with different Mn contents.

Fig. 6 The grain structures in 0mass%Mn, 0.1mass%Mn and 0.13mass%Mn containing alloys.

4.6 Results for Trial Material (2nd Trial)  
Fig. 7 compares the mechanical properties and grain size of the 2nd trial material with 1st trial material fabricated by production line. No effect on the grain size was observed with the removal of the 0.15mass% Mn when the material was twin belt cast, a method with rapid solidification. In addition, the target mechanical properties were achieved by the composition Al-3.37%Mg-0.2%Fe-0.08Si(mass%), without Mn. So, Mn was excluded from effective additive elements.

Fig. 7 The grain size and mechanical properties of the 2nd trial material(unit of Mn content: mass% )

5. Properties of the Developed Material  
Properties of the TBC 5000-series aluminum alloy without Mn fabricated on the production line were evaluated, compared with those of conventional DC 5000-series aluminum alloys.

5.1 Microstructures  
Fig. 8 shows grain structures of the developed TBC 5000-series aluminum alloy with those of conventional DC5182 and DC5052. Despite the fact that it contains only minimal Mn and Cr, the grain size of the TBC 5000-series aluminum alloy is finer than those of the conventional alloys. The dispersion state of the intermetallic compounds in these materials was therefore studied, and their size was measured. The results are shown in Fig. 9 and Fig. 10. The density of the intermetallic compounds particles which are effective as recrystallization nucleation sites is higher in the TBC 5000-series aluminum alloy than in the conventional alloys. Specially, the density of 1-2µm particles is extremely high. It is considered that the high density of intermetallic compounds increased the number of recrystallization nucleation site and inhibited grain growth, resulting in fine grain
microstructures. This is an effect of the rapid solidification achieved by the TBC.

![Microstructures of TBC5000, DC5182, and DC5052](image)

Fig. 8 The comparison of grain structure and composition between TBC5000 material and conventional DC5000 material (unit of element content: mass %).

![Intermetallic compounds in TBC5000 and DC5000](image)

Fig. 9 The microstructure showing intermetallic compounds in TBC5000 and DC5000.

![Size distribution of intermetallic compounds](image)

Fig. 10 The size distribution of intermetallic compounds in TBC5000 and conventional DC5000 materials.

5.2 Formability

Evaluated results of the stretchability and drawability in the developed TBC 5000-series aluminum alloy will be discussed.

(1) Stretchability

Fig. 11 shows the stretchability evaluated by dome testing with a 100mm diameter hemispherical punch. The test piece with dimension of 200mm square was lubricated by stamping oil prior to testing. The blank holding force was 68.6 KN. The TBC 5000-series aluminum alloy has higher limit dome height (LDH) than the DC 5182 aluminum alloy, both alloys have equivalent elongation in tensile testing. In order to explain the reason, necking sections and fracture surfaces were observed. Fig. 12 shows the microstructures of necking section and SEM photos of fracture surface in the TBC 5000 and DC 5182 aluminum alloys. The microstructures of necking section shows stronger shear bands in the DC 5182 aluminum alloy, but these are weaker in the TBC 5000-series aluminum alloy. In addition, the fracture surface of the TBC 5000-series aluminum shows finer dimples comparing with the DC 5182(5).

Generally fracture behavior of 5000-series aluminum alloy is considered as follows:

Necking → Formation and propagation of shear bands → Occurrence of voids in boundary between secondary phase particles and matrix → Linking-up of voids along shear bands → Fracture

So, the voids are considered to be closely related to the fracture. The material in which voids do not formed easily has the following characteristics:

1) Low-Mg alloys: Less shear bands → Suppress voids linking-up
2) Fine grains: Hinder shear bands propagating → Suppress voids linking-up
3) Fine secondary phase particles: Suppress voids occurring

The TBC 5000-series aluminum alloy has lower Mg, and finer grains and particles, so it has higher limiting dome height than the DC5182 aluminum alloy.(6)

![Limiting dome height of TBC5000 and conventional DC5000 materials](image)

Fig. 11 Limiting dome height of TBC5000 and conventional DC5000 materials.

![Cross-sections of necking and fracture surface](image)

Fig. 12 Cross-sections of necking and fracture surface in TBC5000 and DC5182 materials after stretching testing.

(2) Drawability

Fig. 13 shows limiting deep drawing ratio (LDR) which represents drawability, and Lankford value (r value) for the developed and conventional alloys. LDR was measured by cylinder deep drawing testing with 33Φ-3R punch, 37.8Φ-3R die, and a lubricant, a blank holding force of 4.9 KN. It is known that metal sheets with high Lankford values generally
has better drawability\(^{(7)}\). A mild correlation between the Lankford value and drawability can be observed in the developed TBC 5000-series aluminum alloy and the conventional DC 5182 and DC 5052 aluminum alloys. The developed alloy has higher Lankford value and drawability than the other alloys. SEM-EBSD was used to measure the crystal orientation distribution in order to clarify the reason for the better drawability of the TBC 5000-series alloy.

Fig. 14 shows the measuring results of the crystal orientation distribution along longitudinal sections. The TBC 5000-series aluminum alloy has less \{100\} orientation grains and more rolling texture characteristic \{112\}, \{110\}, and \{111\} orientation grains than the conventional alloys. It is the reason why the developed material has higher Lankford value and limiting drawing ratio than the conventional alloys.

![Graph showing the correlation between limiting drawing ratio and Lankford value in TBC5000 and DC5182 materials.](image)

The correlation between limiting drawing ratio and Lankford value in TBC5000 and DC5182 materials.

![Table showing area fraction of the grains with main orientations in TBC5000 and conventional DC5000 materials.](image)

|                | TBC5000 | DC5182 |
|----------------|---------|--------|
| \{100\}       | 11.5    | 12.8   |
| \{112\}       | 41.2    | 40.4   |
| \{110\}       | 18.1    | 16.2   |
| \{111\}       | 14.1    | 11.5   |
| Others         | 15.1    | 19.1   |

5.3 SCC Resistance

Fig. 15 shows the results of SCC testing on the developed TBC 5000-series and the conventional DC 5182 aluminum alloy. SCC testing was conducted by the U-bend and passing current procedures. Samples were taken from sheets given cold rolling at 30% reduction and sensitized at 393 K for 168 hr. Then, they were bent into U shape and immersed in 3.5% NaCl solution at a current density of 6.2 mA/cm\(^2\). The time to failure was taken as the SCC lifetime.

Although the TBC 5000-series aluminum alloy was tested for longer than the DC 5182 aluminum alloy, no SCC fractures occurred, and the material was therefore judged to have excellent SCC resistance.

![Image showing the result of SCC testing for TBC5000 and DC5182 materials.](image)

Fig. 15 The result of SCC testing for TBC5000 and DC5182 materials.

5.4 Adhesive bonding and coating performance

Adhesive bonding and coating performance of the developed alloy was evaluated. These properties are significantly influenced by thickness of oxide film on the surface of material, and deteriorate if oxide film is too thick. Auger electron spectroscopy was therefore used to measure the thickness of oxide films. It was found that oxide film on the surface of the TBC 5000-series aluminum alloy was thinner than that on the surface of the conventional DC 5182 aluminum alloy, and also contained less Mg concentration (Fig. 17).

![Image showing the Auger analyzed chart showing the thickness of oxide films on the surface of TBC5000 and conventional DC5182 materials.](image)

Fig. 17 The Auger analyzed chart showing the thickness of oxide films on the surface of TBC5000 and conventional DC5182 materials.
So, it was presumed that adhesive bonding and coating performance in the developed alloy would be equivalent to the conventional alloy. The evaluation results showed that the developed alloy’s adhesion strength, fracture morphology, and coating adhesion were not inferior to those of the conventional alloy.

5.5 Construction and Performance of Hood Parts

(1) Construction of hood parts Fig. 18 shows construction of a hood manufactured from the developed TBC 5000 aluminum alloy. The hood is mainly composed of six kinds of parts: A skin, a frame, stiffeners, a reinforcement, a striker, and a patch. This construction was examined from the viewpoint of regulation adaptability, appearance quality, strength and stiffness, formability, cost, and weight of parts.

Fig. 18 The components configuration of the hood.

Fig. 19 shows a cross-section of the hood assembly. The hood skin and the hood frame are joined by hem-bending of the skin panel. In addition, the hood is applied with a structural adhesive for reinforcement and good seal performance. SPR is used to join the frame and the stiffeners or the reinforce. The frame and the striker are connected using bolts after the contact surfaces are insulated by a structural adhesive to prevent electrolytic corrosion.

Fig. 19 The sketch of the cross-section of the hood assembly.

The bake-hardening 6000-series aluminum alloy sheet is used for the skin, one of the larger components due to good appearance quality. The developed TBC 5000 was used for the frame, another large component which is not necessary for paint bake response. Other 5000-series aluminum alloy sheets were used for the stiffeners and the reinforce. The striker was manufactured from steel, and the patch from a rubber-based mass material. The patch was added on the hood skin surface in order to comply with the regulations (pedestrian protection performance) when aluminum sheets are used for hoods.

(2) Evaluation on the parts The properties of the hood in which the TBC 5000-series aluminum alloy was used for the frame were evaluated, and were found to satisfy all in-house criteria. The hood also satisfied the criterion for the important regulation adaptability: pedestrian protection performance in each country.

6. Conclusions

A Mn-free 5000-series aluminum alloy with fine grain structures has been developed using TBC. The developed alloy realizes high ultimate tensile strength at low yield strength, and has superior formability and SCC resistance to conventional alloys. In addition, the alloy has the adhesive bonding and coating performance similar to conventional alloys, and its properties satisfy all performances of hood frames. Much of the properties of the developed alloy was realized through the rapid solidification of TBC. The developed TBC-5000 series aluminum alloy is expected to be widely used for further automotive weight savings in the future.

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