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Effects of Cold Rolling Parameters on Sagging Behavior for Three Layer Al-Si/Al-Mn(Zn)/Al-Si Brazing Sheets

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The effects of intermediate annealing (IA) and the final cold rolling (CR) condition on the microstructure and sagging resistance during brazing were investigated using three layer clad sheets composed of the Al-7.5 wt.%Si alloy (filler, thickness: 10 μm)/Al-1.3 wt.%Mn based alloy (core, 80 μm)/Al-7.5 wt.%Si alloy (filler, 10 μm). Also, the effect of 1.2~2 wt.% Zn addition into the core on the sagging resistance of the clad sheets was determined. It was revealed that all the clad sheets fabricated by the optimum condition (IA at 690 K and CR to 20~45%) show excellent sagging resistance with a limited erosion due to the formation of a coarsely recrystallized grain structure in the core during brazing. It was also revealed that the recrystallization behavior of the Al-1.3 wt.%Mn based alloy is hardly affected by the addition of 1.2~2 wt.%Zn during the brazing cycle. Therefore, the sagging resistance of the clad sheets is found to be governed not by the Zn content added in the Al-1.3wt.%Mn based core, but by the intermediate annealing and final cold rolling condition.

Keywords : Al clad sheet, cold rolling, Zn addition, brazing, sagging resistance

1. INTRODUCTION

The use of aluminum-based alloys for automotive heat exchanger units has increased markedly in recent years in response to the need to reduce the weight of automobiles. Moreover, advanced types of automotive condensers, such as the parallel flow type condenser (PFC), have been developed to meet the increased demand for improved thermal efficiency [1]. The PFC is generally produced by assembling Al brazing sheets with multiport Al tubes using a brazing method. The brazing sheet used for the PFC is a three layer clad sheet, typically consisting of an Al-Mn core alloy clad on both sides with an Al-Si filler alloy. The clad sheet is fabricated by a sheet rolling process, and the entire thickness of a finally rolled clad sheet is usually about 100 μm. Therefore, in order to avoid the collapse of the assembly during the brazing process, the thin core material should have a high resistance against deformation during the brazing cycle, generally referred to as sagging resistance [2]. A Zn added Al-Mn alloy is considered to be a potential core material for a clad sheet, since it can allow enhanced corrosion resistance to the PFC owing to a sacrificial anode effect of Zn [3]. In this study, the effects of Zn addition into the Al-Mn core and cold rolling parameters on the microstructure and sagging resistance are investigated using three layer clad sheets composed of Al-7.5 wt.%Si alloy (filler, thickness: 10 μm)/Al-1.3 wt.%Mn alloy containing 0, 1.2 and 2 wt.%Zn (core, thickness: 80 μm)/Al-7.5 wt.%Si alloy (filler, thickness: 10 μm).

2. EXPERIMENTAL PROCEDURE

The clad sheets were produced to 100 μm thickness by laboratory fabrication, through casting, hot rolling and cold rolling. Above all, Al-1.3 wt.%Mn based core alloys with the addition of 0, 1.2 and 2 wt.%Zn were cast and homogenized at 773 K for 8 h. Al-7.5 wt.%Si filler alloys were cast and homogenized at 773 K for 1h. The chemical composition of as-cast materials is presented in Table 1. Filler alloys were hot rolled to a thickness of 2 mm (reduction rate: 90%) and clad to both sides of the core alloys having a thickness of 16 mm. The clad materials were hot rolled to a thickness of 2 mm and were then cold rolled to thicknesses in the range of 111~182 mm, followed by intermediate annealing (IA) at 540 or 690 K for 1h. After intermediate annealing, the clad materials were finally cold rolled to the thickness of 100 mm, the reduction rate of the final cold rolling (CR) varying in the range of 10 to 45%. The intermediate annealing condition was chosen by a restoration characteristic of the core alloys. Fig. 1 shows Vickers hardness values after annealing at temperatures in the range from 470 to 750 K for 1 h of three kinds

Table 1. Chemical composition of experimental alloys (wt.%)

		Mn	Si	Zn	Cu	Fe	Al
Core alloy	without Zn	1.28	0.41	0.00	0.13	0.36	Bal.
	with 1.2%Zn	1.32	0.55	1.22	0.13	0.25	Bal.
	with 2%Zn	1.34	0.52	2.04	0.14	0.27	Bal.
Filler alloy		0.09	7.53	0.19	0.17	0.29	Bal.

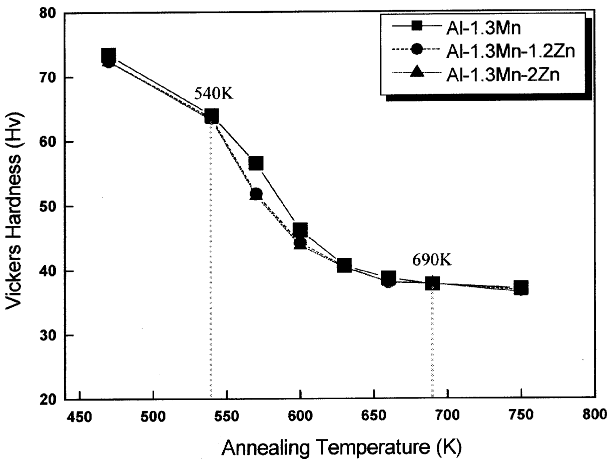

Fig. 1. Change of Vickers hardness with annealing temperature for each core alloy.

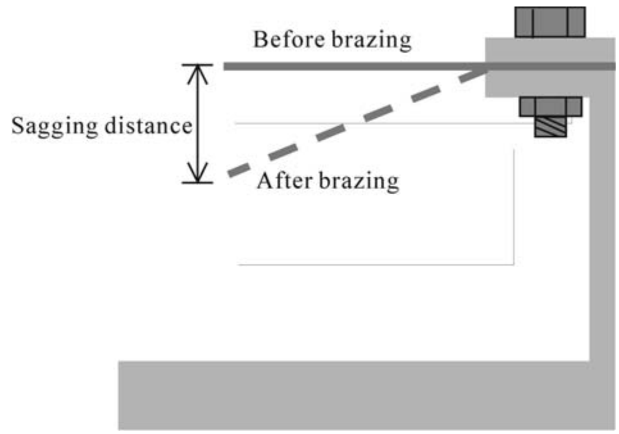

Fig. 2. Schematic view of sagging test rig and illustration of how to measure the sagging distance.

of core alloys that were cold rolled to a thickness reduction of 94%. As shown in this figure, there is no remarkable difference in the restoration characteristic between the three kinds of core alloy; that is the recrystallization behavior of the Al-1.3 wt.%Mn based alloy is almost insensitive to the addition of 1.2~2 wt.%Zn. Up to around 570 K, the hardness shows a high value, indicating an absence or incompletion of recrystallization. When the annealing temperature exceeds about 620 K, a low value of hardness is exhibited owing to the full recrystallization. In accordance with this result, two IA temperatures were chosen; one was 540 K (within incompletely recrystallized region) and the other was 690 K (within fully recrystallized region).

The sagging resistance of the clad sheet was evaluated by measuring the sagging distance [3]. Fig. 2 shows the schematic view of a sagging test rig and an illustration of how to measure the sagging distance. The specimens were taken parallel to the rolling direction. One end of the specimen was fixed during the brazing cycle. The free length and the width of the specimen were 35 mm and 22 mm, respectively. The sagging distance is defined by the deflection of the free end of the specimen after the brazing cycle. The sagging test was performed under a nitrogen atmosphere using a fluoride salt flux. The brazing cycle was as follows:

R.T.→798K: 75 K/min, 798→850 K: 12 K/min, 850→878 K: 6 K/min, 878→688 K: cooled in a furnace, followed by rapid cooling to R.T.

The microstructure was characterized by using an optical microscope (OM), a transmission electron microscope (TEM), a scanning electron microscope (SEM) and an energy dispersive spectrometer (EDS).

3. RESULTS AND DISCUSSION

3.1. Materials

TEM observation of as-cast and homogenized core alloys revealed no remarkable difference in the microstructure in accordance with Zn addition. Representative TEM micrographs of the as-cast and homogenized core alloys containing 2 wt.%Zn are shown in Fig. 3. In the homogenized alloy, a fine dispersoid is clearly visible within the grain. The EDS analysis result in Fig. 3 indicates that fine dispersoids are the intermetallic phases of Al-Mn-Si. The electrical conductivity of as-cast and homogenized core alloys was measured using a conductivity tester and the result is shown in Fig. 4. In this figure, the value of electrical conductivity is expressed in percent age of the International Annealed Copper Standard (%IACS). The %IACS electrical conductivity of the homogenized alloy is much higher than that of the as-cast one for all the alloy compositions, implying that precipitation would occur during homogenization. Moreover, as shown in Fig. 4, the difference in the %IACS between the homogenized and as-cast alloy is almost constant irrespective of the alloy composition. These facts indicate that the fine Al-Mn-Si based dispersoids observed in the homogenized alloy developed

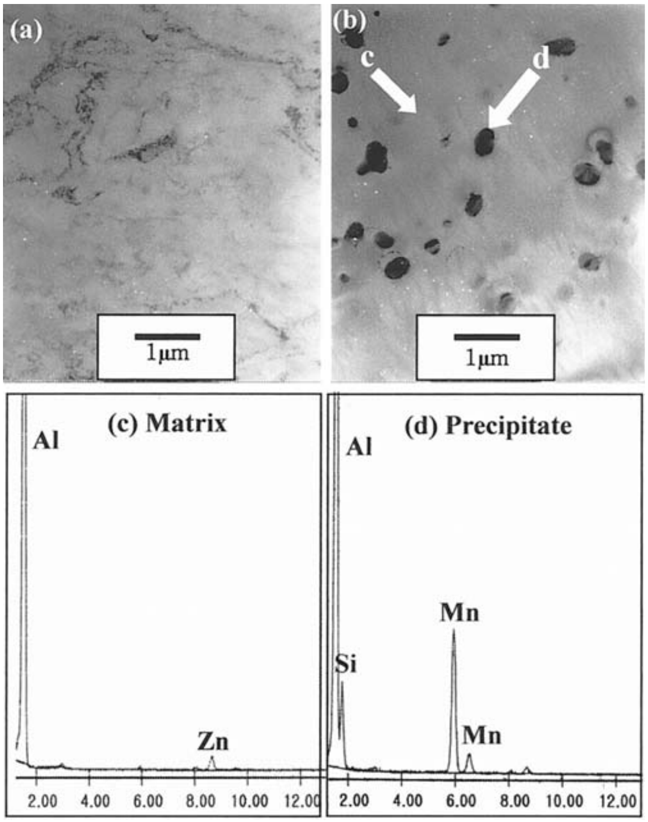

Fig. 3. TEM images ((a), (b)) and EDS analysis ((c), (d)) of as-cast (a) and homogenized ((b)-(d)) Al-1.3Mn-2Zn core alloy.

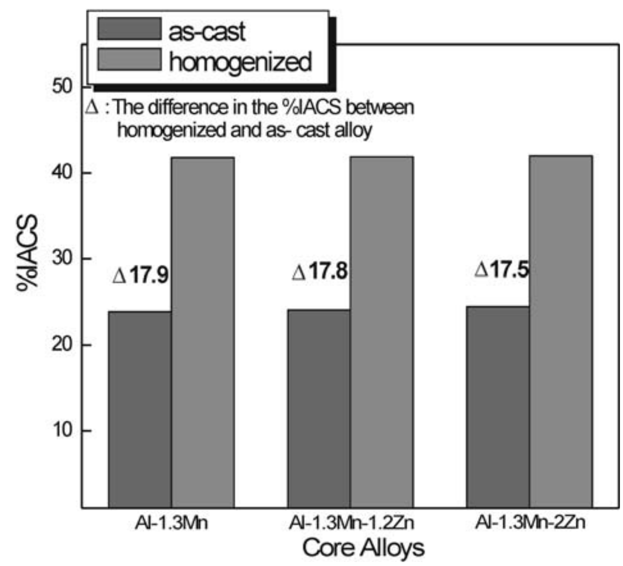

Fig. 4. %IACS for the as-cast and homogenized core alloys.

during the homogenization, and the precipitation seems to hardly be affected by the addition of 1.2~2 wt.%Zn.

Fig. 5 shows an example of the optical micrograph of the cross sectional microstructure of the clad sheet, finally cold rolled to 30% reduction rate after intermediate annealing at 690 K. It was shown that the interface between the filler (cladding) and core alloy is clearly defined and each cladding thickness is equal to 10% of the total sheet thickness that is approximately 100 μm. The cladding is characterized by a uniform distribution of silicon particles (indicated by an arrow in Fig. 5), while the core contains some finer dispersoids. According to the EDS analysis, most of the dispersoids correspond to Al-Mn-Si based intermetallics.

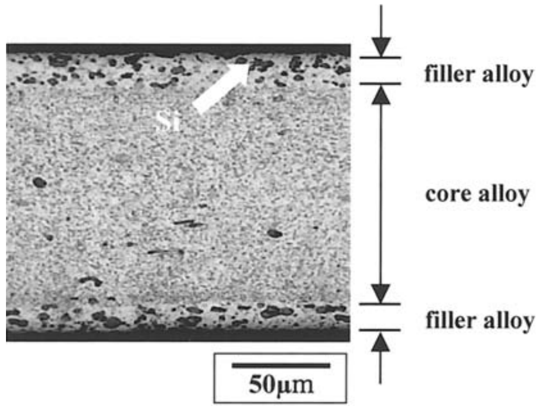

Fig. 5. Cross sectional microstructure of clad sheet (core alloy: Al-1.3Mn-2Zn, intermediate annealed at 690 K and subsequently cold rolled to 30%).

3.2. Sagging behavior

Fig. 6 shows the sagging test result for each clad sheet according to the reduction rate of the final cold rolling (CR).

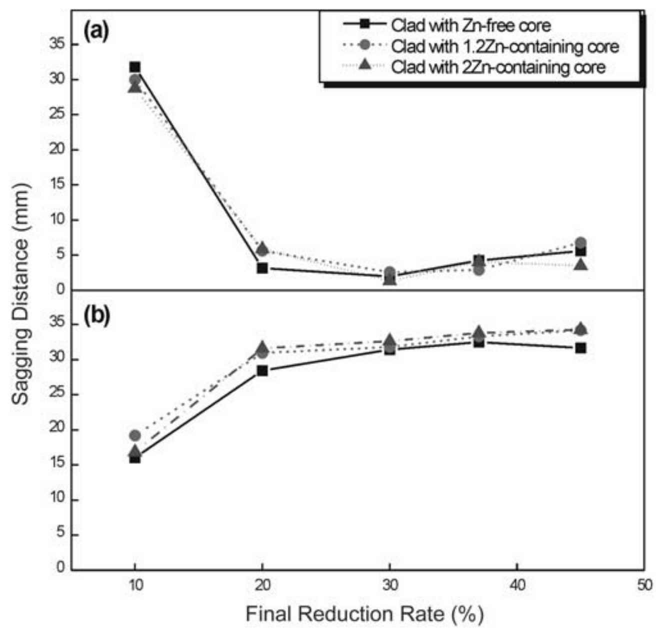

Fig. 6. Change of sagging distance with final reduction rate for each clad specimen intermediate annealed at (a) 690 K and (b) 540 K.

For all the clad specimens intermediate annealed at 690 K, a high sagging distance is observed when CR is performed to 10%, although the sagging distance decreases rapidly if CR is carried out to 20% and over. In the case of the clad specimens intermediate annealed at 540 K, a relatively low sagging distance is obtained when CR is done to 10%, whereas the sagging distance increases if CR is performed to and over 20%, irrespective of the composition of the core alloy. Therefore, it is obvious from Fig. 6 that although the sagging distance varies with both intermediate annealing and final cold rolling conditions, there exists no distinct difference in sagging distance in accordance with the alloy composition of the core at a given intermediate annealing and CR condition. In other words, the addition of 1.2~2 wt.%Zn into the Al-1.3 wt.%Mn based core has almost no influence on the sagging behavior of the clad sheet.

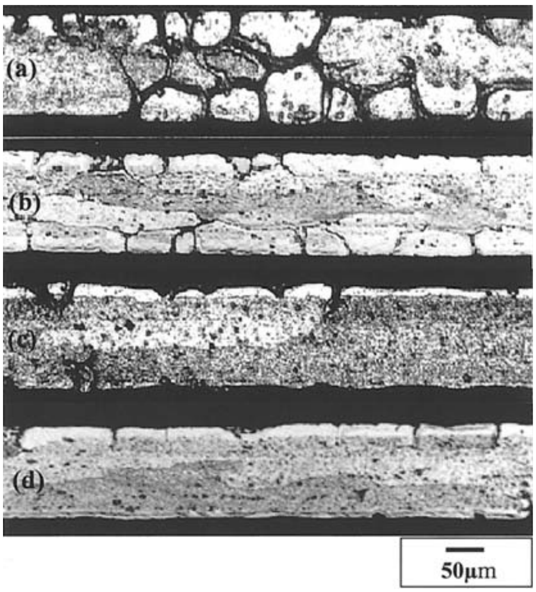

Fig. 7. Cross sectional microstructures after brazing for the clad specimen, intermediate annealed at/cold rolled to (a) 690K/10%, (b) 540K/30%, (c) 690K/30%, and (d) 540K/10%. (a) and (c): Zn-free core; (b) and (d): 2%Zn containing core.

The cross sectional microstructure of the post-brazed specimens changed in accordance with the sagging test result. That is, for the specimens showing a high sagging distance (specimens intermediate annealed at/cold rolled to 690 K/10% and 540 K/20~45%), a wide range of eroded areas was observed as illustrated in Figs. 7(a) and (b). In contrast, for the specimens having a very low (specimens intermediate annealed at 690 K/cold rolled to 20~45%) or relatively low sagging distance (specimens intermediate annealed at 540 K/cold rolled to 10%), a few (Fig. 7(c)) or a narrow range of eroded areas (Fig. 7(d)) is observed, respectively. Fig. 8 illustrates a SEM image and EDS mapping of silicon for the specimen in Fig. 7(a). From this figure, a eutectic structure containing silicon is clearly visible in the core after brazing, indicating that the eroded area is formed by a penetration of filler alloy into the core during brazing.

In order to quantify the degree of erosion, average erosion depth (AED) was measured using the following equation:

$$AED = t_0 - S/L$$

where, t_0 is the core thickness before brazing, S is the non-eroded area of the core after brazing and L is the unit length of the core. The values of AED measured by an image analyzer are plotted in Fig. 9. Comparing Fig. 9 with Fig. 6, the value of AED changes in accordance with that of sagging distance for the clad specimens. This fact indicates that the sagging characteristic of the clad sheets is directly affected by erosion behavior.

The difference in erosion behavior with intermediate annealing and final cold rolling conditions for the clad sheets may be attributable to the microstructure characteristics of the core alloys during brazing [4], since the clad ratio and brazing cycle are constant for all the specimens. Therefore, in order to determine the microstructure of the post-brazed core alloys in detail, core alloys without cladding (bare alloys) were subjected to the same brazing treatment as in the previously described procedure after being fabricated

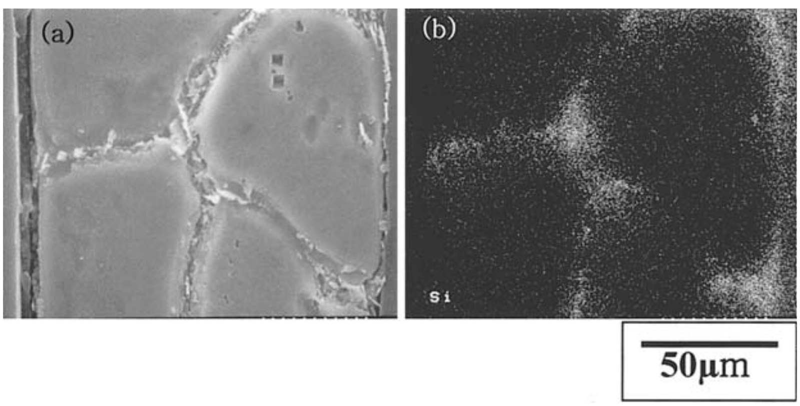

Fig. 8. (a) SEM image and (b) EDS mapping of Si for the specimen in Fig. 7(a).

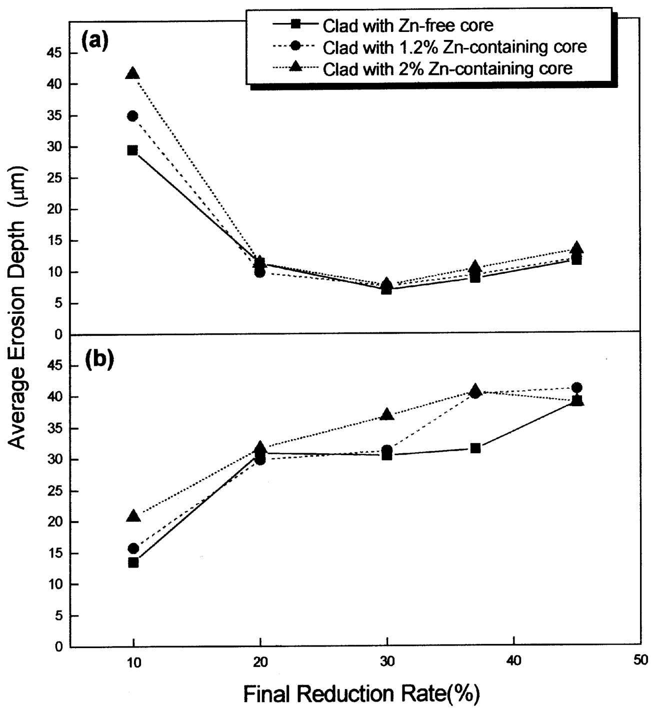

Fig. 9. Change of average erosion depth with final reduction rate for each clad specimen intermediate annealed at (a) 690 K and (b) 540 K.

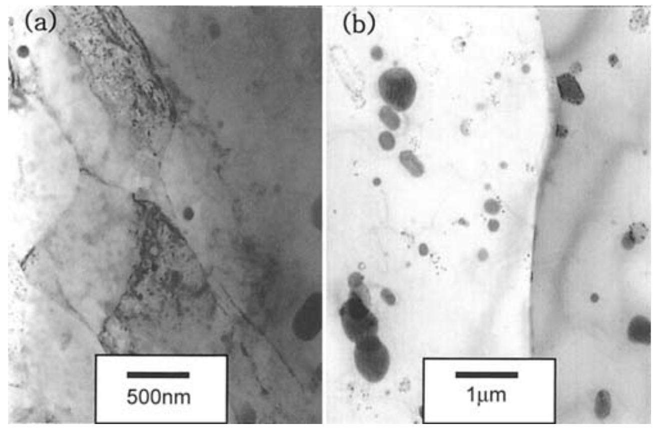

Fig. 10. TEM images of brazing treated bare specimens with 2%Zn, intermediate annealed at/cold rolled to (a) 690 K/10% and (b) 690 K/30%.

under the same intermediate annealing and final cold rolling conditions as the clad materials. The observation of the parallel sectional microstructure of the brazing-treated specimens indicates a distinct variation in grain structure depending on the intermediate annealing and final cold rolling conditions, whereas there is almost no change in grain structure in accordance with the Zn content. For all the core specimens intermediate annealed at 690 K/cold rolled to 10%, there exists a non-recrystallized structure, such as dislocation cells and subgrains after the brazing treatment, as illustrated in Fig. 10(a). In contrast, in the core specimens intermediate annealed at 690 K/cold rolled to 20~45%, a fully recrystallized structure with a coarse grain (above 200 μm in mean grain size) is developed after the brazing treatment, as shown in Figs. 10(b) and 11(a). In the case of the core specimens intermediate annealed at 540 K, a fully recrystallized structure is observed after the brazing treatment irrespective of the final cold rolling condition, and the mean grain size of the recrystallized grain decreases from about 130 to 55 μm when the value of CR increases from 10 to 45% (see Figs. 11(b)-(d)).

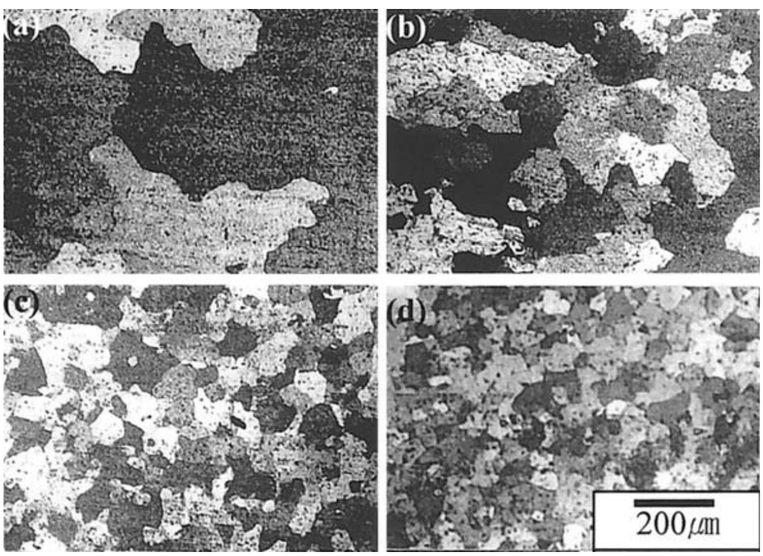

Fig. 11. Parallel sectional microstructures of brazing treated bare specimens with 2%Zn, intermediate annealed at/cold rolled to (a) 690 K/30%, (b) 540 K/10%, (c) 540 K/30%, and (d) 540 K/45%.

From these experimental results, it is obvious that the recrystallization characteristic of the core alloy during brazing is mostly affected not by the Zn content but by the intermediate annealing and final cold rolling condition. It is, therefore, suggested that the conditions of intermediate annealing and final cold rolling are important controlling factors for obtaining a desired brazing sheet having an enhanced resistance against sagging, which is governed by the erosion behavior through recrystallization characteristics of the core alloy during brazing. For all the clad sheets fabricated by the optimum condition (intermediate annealed at 690 K/cold rolled to 20~45%), sagging distance is low (less than 7 mm); in other words, sagging resistance (brazeability) is high, AED is small (less than 12 μm) and the brazed core possesses a coarsely recrystallized grain structure (over 200 μm in mean grain size). In contrast, if the clad sheets are subjected to final cold reduction lower than the optimum range after intermediate annealing at 690 K, recrystallization in the core is not completed during brazing due to a smaller driving force for recrystallization. In this case, a penetration of filler alloy into the core occurs easily along the subgrain boundaries in the core, which increases AED, and hence increases sagging distance (decreases sagging resistance). When the clad sheets are fabricated by using the condition of intermediate annealing at 540 K and cold rolled to 20~45%, the lower intermediate annealing temperature and the higher cold reduction rate may provide a finely recrystallized grain structure (55~70 μm in mean grain size) in the core during brazing due to an increased nucleation site for recrystallization. Such a fine grain structure, namely, an increased grain boundary area in the core, could promote filler penetration into the core along the grain boundaries, which increases AED, and hence increases sagging distance. For the clad sheets fabricated by using the condition of intermediate annealing at 540 K and cold rolled to 10%, relatively coarse grain structure (120~130 μm in mean grain size) could be developed in the core during brazing, and, as a result, relatively low AED and a low sagging distance may be achieved.

4. CONCLUSIONS

Three layer clad sheets composed of Al-7.5 wt.%Si alloy (filler, thickness: 10 μm)/Al-1.3 wt.%Mn based alloy containing 0, 1.2 and 2 wt.%Zn (core, 80 μm)/Al-7.5 wt.%Si alloy (filler, 10 μm) were fabricated with various intermediate annealing (IA) and final cold rolling (CR) conditions. All the clad sheets fabricated by the optimum condition (IA at 690 K and CR to 20~45%) showed an excellent sagging resistance with a limited erosion due to the formation of a coarsely recrystallized grain structure in the core during brazing. It was also revealed that the recrystallization behavior of the Al-1.3 wt.%Mn based alloy is hardly affected by the addition of 1.2~2 wt.%Zn during the brazing cycle. Therefore, the sagging resistance of the clad sheets is found to be governed not by the Zn content added in the Al-1.3 wt.%Mn based core, but by the intermediate annealing and final cold rolling condition.

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