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Effects of annealing process on sagging resistance of cold-rolled three-layer Al alloy clad sheets

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Abstract: The effects of annealing process on the hardness, microstructure, Si diffusion, and the sagging resistance of cold-rolled 4343/3003/4343 Al alloy clad sheets and their 3003 Al alloy core sheets were experimentally investigated through hardness tests, EBSD observations, EDS analysis, and sagging test. The results showed that with the increase of annealing temperature, the hardness of both clad sheet and core sheet decreased, while the sagging resistances of both clad and core sheets achieved maximum values after annealing at 380 °C for 1 h. After annealing at 380 °C, the clad layer contained fine and equiaxed recrystallized grains; the core layer was composed of fully recrystallized coarse grains elongated along the rolling direction. The Si diffusion from the clad layer to the core zone was limited. After annealing at a higher temperature of 440 °C or 550 °C, the sagging resistance of clad sheets worsened precipitously. The grains in the clad layer grew up, obscuring the interface between the clad and core layer; the recrystallized grains in the core layer became finer. Significant amount of Si penetrated into the core layer through the accelerated diffusion. Compared with the microstructure refinement, Si diffusion is the main factor influencing the sagging resistance.

Key words: aluminum alloy; microstructure; annealing; Si diffusion; sagging resistance

1 Introduction

Multi-layer aluminum brazing sheets featuring low density, high thermal conductivity, and excellent corrosion resistance are becoming predominant for producing the fins of automotive heat exchangers [1,2]. Aluminum heat exchangers are generally produced by brazing aluminum brazing sheets and multiport Al tubes at 600 to 610 °C. The cold-rolled 4343/3003/4343 Al alloy clad sheets, with a clad/core layered structure, are the most widely used aluminum brazing materials for heat exchangers. The 4343 alloy clad layer made from an Al−Si hypo-eutectic alloy with a low melting point of 570−610 °C, completely melts and forms a brazed joint with multiport Al tube during brazing. The 3003 alloy core layer made from an Al−Mn alloy has a higher melting point of 630−650 °C and provides the structural rigidity during the high temperature brazing [3]. The ever stringent regulations of automotive fuel economy standards call for more aggressive mass reduction in vehicular components, including a thinner aluminum brazing sheet [4,5]. This change will post a serious challenge for the manufacturing as the weaker heat exchanges may collapse during brazing [6].

To improve the high temperature mechanical strength of aluminum sheets, also termed sagging resistance, many studies have focused on the deformation mechanisms during brazing. Researchers suspected that the Si diffusion and microstructure were factors affecting the sagging resistance of the aluminum sheet. GAO et al [7] simulated the brazing process of aluminum sheets and confirmed the Si diffusion into the core layer by EPMA. TURRIFF et al [3] investigated the microstructure evolution induced by Si diffusion and observed the formation of coarse Al−Si eutectic phase during brazing. The research conducted by RYU et al [8] and NOH et al [9] indicated that Si content in the core alloy worsened the sagging resistance. It could be concluded that Si diffusion had a negative impact on the sagging resistance.

QIN et al [10] evaluated the brazability of an Al−Mn cold-rolled sheet and found that recrystallized coarse grains could reduce the grain boundary slip which

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was beneficial to the sagging resistance. After investigating the microstructure evolution of three-layered aluminum brazing sheets, KIM et al [11] revealed that Si diffusion in the recrystallized coarse grains was reduced compared with that in a deformed microstructure. Besides, the coarse grains were less prone to grain erosion, which further improved collapse resistance [12−15]. Nevertheless, the exact reason of collapse during brazing is still unclear and there lacks systematic study in the literature. The current research aimed at addressing the influence of different annealing processes on the sagging resistance of 4343/3003/4343 aluminum clad sheets via microstructure evolution and Si diffusion. The sagging resistance of 3003 core sheets was compared with the 4343/3003/4343 clad sheets, so that a comprehensive understanding of the deformation mechanism in the brazing process can be established and the main factor affecting the sagging resistance can be revealed.

2 Experimental

The aluminum clad sheet was manufactured by Nantong Hengxiu Aluminum Heat Transfer Materials Co., Ltd., and consisted of an AA3003 core and an AA4343 clad on each side. The chemical compositions of the raw material are shown in Table 1. After hot-rolling and cold-rolling, the three-layer aluminum was reduced by over 99% to a thickness of 0.15 mm in the normal direction (ND) with a cladding ratio of 8% on each side. Because of high rolling reduction, the 4343/3003/4343 clad sheet contained heavily deformed grains elongated in the rolling direction (RD), which is hard to be confirmed by electron backscatter diffraction and optical microscopy.

Table 1 Chemical compositions of 4343/3003/4343 clad sheet

Sheet	Mass fraction						
	Si	Fe	Mn	Cu	Zn	Zr	Al
Core/3003+1.5%Zn	0.4	0.5	1.3	0.1	1.5	0.1	Bal.
Clad/4343	8.0	0.1	0.2	0.1	−	−	Bal.

To separate the effect of Si diffusion on the sagging resistance during brazing, the 4343/3003/4343 clad sheet was electropolished to remove the 4343 clad layer in a solution of 30% (volume fraction) nitric acid and methanol at −30 °C and 12 V. The electropolished specimen without Si diffusion was designated as 3003 core sheet, and the specimen without electrolytic polishing was referred to as 4343/3003/4343 clad sheet.

Both the 3003 core sheet and the 4343/3003/4343 clad sheet were annealed at 380, 440, 550 °C for 1, 2, 3 h, respectively, and then water-quenched to room temperature. After annealing, the hardness on the RD−ND cross section of the samples was tested by an HX−500 microhardness tester. Since the hardness was measured in the core zone of 4343/3003/4343 clad sheet, the 4343 clad layers were removed by electrolytic polishing after annealing.

The cold-rolled 4343/3003/4343 clad sheet and the specimens annealed for 1 h at various temperatures were held at 610 °C for 10 min to simulate the brazing process. The samples were cut into rectangle specimens of 90 mm long and 30 mm wide, whose length direction is parallel to the RD. The schematic of the sagging test is shown in Fig. 1. One end of the specimen was fixed and the other end of 50 mm long was free. The sagging distance was defined as the deflection of the free end after brazing. The sagging test was performed in a heating furnace, which had been held at 610 °C for 20 min to diminish temperature variation.

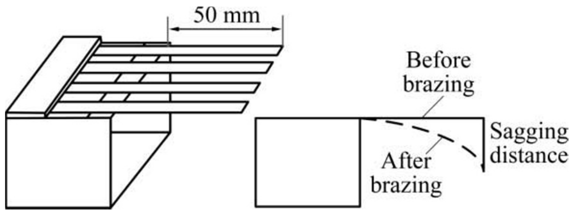

Fig. 1 Schematic view of sagging test rig

A set of microscopy techniques were used to characterize the microstructure evolution of both 4343/3003/4343 clad sheet and 3003 core sheet after annealing and brazing (sagging test). Samples were ground mechanically and polished in a 1 μm diamond polish. Etching was carried out by immersing samples in a 0.5% HF solution for 60 s. Then, the microstructures on the RD−ND cross sections of different aluminum clad sheets were observed by optical microscope (OM) and scanning electron microscope (SEM) QUANTA FEG−250. Electron backscatter diffraction (EBSD) was used to quantify the grain size after annealing and brazing. The Si diffusion before and after brazing was monitored by energy dispersive spectrometer (EDS). To observe the fine precipitated particles, the samples were twin-jet electropolished (at −20 °C, 15 V) with a solution of 33% HNO_3 in methanol and observed under a transmission electron microscope (TEM).

3 Experimental results

3.1 Hardness of annealing clad sheets and core sheets

Figure 2 exhibits the Vickers microhardness of 4343/3003/4343 clad sheet and 3003 core sheet as a function of annealing temperature and annealing time. Both specimens displayed similar trend of hardness evolution. The hardness of cold-rolled clad sheet was HV 93.8. After annealing, the hardness values of